What Happened and Will Happen with Biofuels? Review and Prospects for Non-Conventional Biofuels in California and the U.S.: Supply, Cost, and Potential GHG Reductions

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16. Abstract

This paper examines past and future trends for non-conventional biofuels in transportation in the next decade and beyond in California and the U.S., drawing on existing literature. It finds policy was geared toward expanding use of technology-ready biofuels in the 2010s; hydroprocessed renewable diesel from lipid feedstocks and biogas were beneficiaries alongside conventional ethanol and biodiesel. Cellulosic ventures largely failed due to lack of technological readiness, high cost, and an uncertain and insufficient policy environment. Policy goals for competitive cellulosic fuels remain, yet fuels from technologies already in the market may suffice to meet low carbon fuel policy targets, at least in California until 2030, considerably more oilcrop-based biofuels. How much biofuel will be needed there and elsewhere to meet climate targets hinges critically on the pace and scope of zero emission vehicle, and particularly electric vehicle, rollout. Analysis of unintended market consequences like indirect land use change has evolved over the decade but remains uncertain; current policy structures do not comprehensively safeguard against increased emissions. Market activity for non-conventional fuels has targeted biojet. Pioneer plants using new conversion technologies, if successful, will take some time to scale. Technoeconomic analyses (TEAs) for such non-conventional fuels point to no clear biofuel conversion technology winner as yet, given uncertainties. TEAs are evolving to reduce uncertainty by concentrating more on robust returns in the face of uncertain policies, potential additional cost-cutting for new technologies given what is known about processes involved, and potential revenue-raising through new coproducts or shifting product slates. Policies are needed to make initial financing more secure. Additional policy and societal attention to appropriate use of biomass, and land more generally, in a low carbon future is needed to clarify likely feedstock supply for biofuels that will enhance climate goals with low risk of unintended consequences.

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Disclaimer

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December 2021

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EXECUTIVE SUMMARY

Low carbon biofuels using cellulosic materials failed to materialize at commercial scale in the decade 2010-2020. Behind the failure was, among other factors, a drop in oil prices that made it more difficult for biofuels to become cost-competitive; persistent uncertainty about the magnitude and longevity of policy incentives that aimed to create demand "pull," especially from the U.S. Renewable Fuel Standard (RFS), but also for California's Low Carbon Fuel Standard (LCFS) as it faced several legal cases; a challenging financing environment post-Great Recession; and a string technical and financial failures for pioneer cellulosic enterprise, which only made financing more difficult. The U.S. policy package pushed a "go big" rollout for cellulosic fuels. The U.S. government, via its policy, deemed cellulosic ethanol in particular technically ready for commercialization—that is, construction of larger scale stand-alone plants for which policy would ensure a market, meaning government funded R&D in effect ceased. The go-big approach precluded early recognition of technical barriers to commercial scale production not visible in smaller pilot and demonstration facilities, and logistical barriers such as feedstock sourcing and collection, which would require new contractual arrangements. The difficulties ended up hampering commissioning most of the handful of pioneer plants that made it to construction in the 2010s, and sidelining or significantly shifting business strategy in terms of location, product line, and/or conversion technology for others.

While the market-based policy incentives in place from the RFS and LCFS would have benefited any liquid cellulosic fuels that emerged, they also promoted the conventional biofuel market and expanded its demand. Conventional biofuels' large contribution to compliance with these policies as implemented meant liquid cellulosic fuels were not required to meet compliance. The RFS and LCFS especially incentivized more use of biomass-based diesel in the U.S. and California, respectively. Hydrotreated lipid-based renewable diesel (RD) use in California expanded rapidly, and is expected to remain a key LCFS compliance fuel for some time. Biogas as transport fuel also expanded after 2013, when the RFS recognized this as a cellulosic fuel, under RFS and LCFS indirect accounting mechanisms, where contracts for biogas delivered to the pipeline match volumes delivered to natural gas vehicles. A relatively small natural gas fleet, relatively small volumes of residue feedstocks for biogas given transport demand realities, and a changing policy context that looks toward transport electrification for the future may limit growth for natural gas for transport. However, expanding crediting for biogas-to-electricity for electric vehicle (EV) fueling—already eligible in the LCFS—may open up substantial opportunities. Since 2016, RFS implementation has been increasingly uncertain, while the LCFS program has expanded to other states and set targets out to 2030 and beyond, emerging as a primary driver behind nonconventional biofuel investment.

Perspectives on 2020 to 2030 for California, as the major low carbon fuel player in the country, are relevant for the U.S. market. Fuel types currently under broad commercialization and already used in California can likely suffice for its LCFS compliance, meaning lower carbon new fuels like cellulosics, while eligible and incentivized, are not needed to meet the policy target in this timeframe. Fat-based RD use continues to grow, with announcements of capacity for the next five years expanding dramatically in the U.S. and globally. With no apparent technical barrier, RD will likely be available as needed for LCFS compliance. Less RD would be required if California experiences a highly successful EV rollout or significant market uptake of new opportunities like carbon capture and sequestration or very low carbon biogas.

Policy activity beyond California is broadening market demand for low carbon fuels, which could start to dilute the reliance of low carbon fuel investors on the LCFS and provide additional outlets for low carbon fuels. Other LCFS jurisdictions like Oregon and British Columbia, plus soon Washington and Canada, are behind California in EV rollout, and therefore more reliant on liquid low carbon fuels. British Columbia already shows signs of significant RD growth, and the process has started in Oregon. U.S.-wide EV rollout, which has received more attention in 2021 under the new administration, will lag California; a substantial portion of vehicle fleet is likely to remain reliant on liquid fuels for some time. The current policy environment incentivizes biomass-based diesel: in addition to benefits from the LCFS, it also benefits from the RFS as its marginal compliance fuel and receives a blender's tax credit in the U.S. How national transport decarbonization policies take shape, and especially the RFS post-2022 re-set, will help determine how large a player RD will be in the U.S. in the next decade.

Nonconventional low carbon liquid biofuel development continues to face high costs, according to academic studies. Serious technical barriers remain for all considered conversion processes. Most studies find viability even for an nth plant depends on policy support. Technoeconomic analyses (TEAs) have grown more sophisticated since the early 2010s, a likely necessary precursor for broader investment and action. TEAs started incorporating more rigorous uncertainty analysis and policy incentives to glean likelihood of conditions meeting product breakeven prices. Coproducts, biorefinery location and configuration, as well as adjustments to the technologies themselves are all being considered in research investigating how to lower costs and make these fuels financially viable while remaining low carbon. However, actual production mostly remains in the experimental phase, and winner(s) remain unclear after a decade of work. Because climate goals and policies demand near-term carbon reductions, existing technologies will continue to be used as the newer ones are developed.

The burgeoning commercial activity surrounding alternative jet fuel provides a contrast. Indeed, the pioneer cellulosic plants moving to production tend to target jet fuel. Produced fuel volumes are and will be low for some time, but the aviation sector will need low carbon liquid hydrocarbons for a decarbonized future and various actors have shown interest, allowing some market pull to develop under only modest policy support thus far beyond the military. U.S. policy support looks set to increase under the new administration. Most current commercial biojet uses the hydrotreated lipid production process similar to RD's and draws on the same feedstocks; it is poised to expand most in the market. For the cellulosic fuels, even if current efforts are successful, only modest expansion is feasible before 2030 because of the time it would reasonably take to build new production plants. Any cellulosic technology breakthroughs for biojet would likely be transferrable to on-road fuels for heavy duty sector not able to electrify (or not yet), if more or lower carbon fuels are needed there.

The current policy outlook prioritizes residue feedstock use for RD. The draw is not only from California, but other LCFS jurisdictions on the west coast of North America, Canada, and European markets. Growth rates depend to some extent on how much currently uncollected residue oil could be brought into the supply chain under these incentives, how long that would take, and feedstock dynamics when/where residues are not available. Alternatively, growth could mean biofuel demand crowds out other end uses for residue oils, leaving the cheapest oil to backfill unmet demand. Crop-based oils like soy and canola, already used for biofuel production, seem the most likely to fill gaps in the short run; additional crop oils might also emerge as feedstocks. Algae as a lipid feedstock remains uneconomical. Additional planting could occur either to obtain feedstocks directly or to backfill demand from oils diverted to feedstock use. The potential for markedly greater use of agricultural land for feedstock could meet with pushback on environmental and equity grounds for concerns that the resulting shifts in land use would increase GHG emissions and raise food prices. Similar concerns led the EU to cap crop use for renewable energy crediting under its policies. Early studies of land use change emissions due to biofuels had mixed and widely varying results; more has been learned and published, but estimates continue to vary by modeling system, and academic disagreement about appropriate modeling structures, parameters, as well as interpretation of actual land use change to date from empirical studies also continues. More work to date has been done on first-generation crop-based systems, but the discussion spills over to all land-using feedstocks. The debate has left controversy about how to use estimates in policy and some reluctance for policies to address the issue, in effect dismissing the risks of increased emissions from biofuels against potential for forgoing any carbon-saving opportunities they hold.

Beyond 2030, studies have outlined in broad terms what low carbon fuel use might look like to align with climate goals. Electrification, once it becomes cost competitive with gasoline vehicles, would increasingly take over the light duty sector. Internal combustion engines, and biofuels with them, would move into a shrinking portion of the legacy vehicle fleet. For heavy duty, the picture is less clear. Lower duty cycles of trucking will likely electrify. But portions of long-haul trucking, as well as shipping and aviation that requires higher energy density fuels will likely not. Low carbon liquid biofuels are one option, especially to the extent that the carbon in production can be captured and sequestered. Other options being pursued and discussed include liquid drop-in fuels from industrial waste gas for all duty cycles and low carbon hydrogen for heavy-duty fuel cell vehicles, especially for on-road uses. These options, much like liquid cellulosic fuels, have significant cost and technology hurdles to overcome. They are farther away from commercialization that some cellulosic processes which have commercial facilities near completion. In the case of hydrogen, penetration of fuel cell heavy-duty vehicles and fueling infrastructure pose additional challenges, making it likely a longer-term effort.

All to say, liquid biofuels will probably face some competition within the heavy-duty sector. The uncertainties associated with any given low carbon fuel technology have led to a portfolio approach whereby many different possible technologies, both within biofuels and for non-biomass alternatives, are being pursued. Policy to enhance R&D and commercial readiness, as well as to incentivize market activity in development and uptake of a fuel that meets the desired criteria while remaining technology neutral, is preferred. Some technology pathways will turn into dead ends. Others may be turned toward non-fuel low carbon uses, as was seen when many of the 2010s cellulosic ventures shifted towards higher value chemicals or nutraceuticals. In short, commercial development to date reinforces that the market can be agile and direct end products towards the most profitable markets as conversion technologies mature. Once volumes rise enough for technology basics are mastered, if products are needed for decarbonization in a particular end use—e.g., transportation, policy can incentivize it. For liquid biofuels, a longer-term end-use in aviation and some shipping seems likely, making it less likely that investment in the next decade will result in stranded assets. Hydrogen's role in the heavy-duty on-road sector, on the other hand, may depend on the extent to which the economy as a whole turns to hydrogen as a low carbon fuel.

Liquid biofuel technologies will also likely compete amongst themselves for biomass, and against other end uses, such as electricity production. For example, low carbon hydrogen would likely be produced via solar- or wind-powered electrolysis or gasification of appropriately sourced biomass. Biomass also can be used for electricity, either via direct combustion, via gasification, or when already in gaseous form, as is the case for biomethane from landfills, wastewater plants, or livestock manure. These end uses taken together—bioenergy—may well compete in turn against alternative approaches to maximize carbon gains from the biomass, via, for example, enhanced land management.

Ultimately, policy for liquid biofuels, or bioenergy more broadly, for climate goals must be fully integrated into economywide carbon-lowering strategies, especially for the land sector. A debate continues over whether biomass to be used for liquid fuels (or other energy) is limited to relying on waste and end-of-life materials that cannot scale (Moriarty and Honnery 2019), or can be literally cultivated to enhance carbon profiles of soil while displacing petroleum products (Field et al. 2020), and if so in what volumes. All bioenergy shares the issue of how to source biomass without unintended consequences and given other necessary land uses. Policy to address potential consequences thus far, however, has focused mostly on biofuels used in transportation, in the land use change discussion. More recently, efforts to reward farmers for carbon-saving activity have gained momentum, and also entered the low carbon fuels policy discussion. Measurement and administrative challenges remain, as well as a clearer conceptual vision for how on-farm actions and their beyond-farm consequences should be addressed and integrated. Policy and society need a consensus on the literal ground rules that, once set, clarify the scope for bioenergy. The EU has placed caps on crop-based biofuels, and phase-out of feedstocks deemed to be at high risk of ILUC emissions; this sends a more definitive signal to investors than do the estimates for land use change emissions incorporated in policy in the U.S., which would at the least need updating for current conditions. More broadly, identifying and regulating the conditions under which biomass feedstocks are most likely to enhance GHG emissions reductions and least likely to trigger more emissions, in a framework that considers other ecosystem uses, is a policy step that is well overdue.

Current policies like the RFS and LCFS can generate more biofuel demand, as discussed above. But they so far have fallen short in driving cellulosic fuel innovations. The U.S. has applied a suite of additional policies to move these biofuels forward, to lower capital required (e.g., loan guarantees), guarantee offtake via government procurement (often the military), and technology development, e.g., R&D that now spans the gamut of feedstock development and logistics, to conversion technology, to coproduct development, to final fuel distribution. Technoeconomic analysis now more fully embraces stochastics in prices, policies, and carbon ratings, making results more business-relevant. The track record of the 2010s may make "go slow" progress in new low carbon biofuel commercialization inevitable for the 2020s, necessitating a track record of commercial success for early facilities before investment flows. Policy focus on R&D and more intermediate-scale plants for new technologies, a step missed in the 2010s, could yield dividends in terms of uncovering any additional unforeseen technical barriers. R&D, plus tracking early commercial or pre-commercial developments, are key to reducing the uncertainties that characterize advanced biofuels. Policy approaches like reverse auctions or contracts-for-difference, to guarantee a minimum price for future production volumes could help overcome financing woes that hamper projects in a way that embraces competition in the policy push and allows the learning-by-doing that only comes with production.

1 Introduction

Alternative fuel transportation policies like the Renewable Fuel Standard (RFS2) in the U.S. or the Low Carbon Fuel Standard (LCFS) in California and similar policies elsewhere were meant to foster development of biofuels beyond conventional corn starch ethanol and lipid-based (mostly soy) biodiesel in the 2010s, but the industry instead sputtered. Over the decade, pioneer plants built to produce cellulosic ethanol or drop-in hydrocarbons foundered under technical and financial difficulties, were largely idled and sold off, and sometimes dismantled. Hoped-for volumes of cellulosic fuels that could lower GHG emissions on a large scale and spark a new economic sector simply did not materialize even though policy incentives were considerable.

The cellulosic ethanol that was produced in the U.S. came from technologies "bolted on" to a few existing corn ethanol plants using corn kernel fiber as a feedstock. This approach, however, remained in commercial infancy, producing relatively small volumes and faced administrative hurdles to earning policy incentives. While these initial bolt-on efforts could theoretically have spurred learning about feedstock handling process or conversion engineering or chemistry that would prove transitional to breakthrough approaches to large-scale cellulosic fuels (Morrison et al. 2016), no such acceleration of industry development is yet evident. Several pioneer plants for drop-in cellulosic fuels applying a variety of technologies primarily to be used in aviation, are under construction, and not yet proven at commercial scale. The primary new liquid biofuel to emerge in the marketplace over the period was a drop-in fuel, hydroprocessed esters and fatty acid renewable diesel (hereafter HEFA RD), which shares feedstocks with traditional biodiesel.[1] Biogas also became a more prominent transportation fuel, injected to the pipeline and dispensed to natural gas vehicles, recorded via contracts between biogas producers and natural gas stations. However, both HEFA RD and biogas are thought to have limited scale-up as extremely low carbon transport fuels. Non-crop byproducts with a lower carbon footprint—like tallow, used cooking oil, and corn oil, as used for HEFA RD or biogas from landfills or animal manure—are limited by the finite sectors they depend on. Use of crops as feedstocks raises concerns about competition with food and land conversion to agriculture, as seen in the EU debate leading to caps on food and feed crop feedstocks for biofuels. While technological improvements and sectoral growth can boost feedstock availability, market links make backfilling residue lipid demand with higher carbon oils, like palm, or expanding livestock operations due to biogas profitability possible market responses that would risk additional emissions. In short, the supply response from residues is likely to fall far short of projected long-term needs for low carbon biofuels.

Moreover, there remains disagreement whether enough biomass to fill the huge projected need for liquid biofuels can be reliably sourced out into midcentury and beyond without causing more emissions or food price increases through market-related effects. The best use of

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[1] Renewable diesel can be made in a stand-alone facility, the majority of existing commercial activity, or via coprocessing in an oil refinery, which has faced some technical challenges but is underway in small volumes. For more, see (Witcover and Williams 2020).

particular biomass resources or their land base from a societal perspective, moreover, is far from settled. The stakeholder consensus that supported liquid biofuels a decade ago on climate, energy security, and rural development grounds eroded in the 2010s, helped along by the poor cellulosic fuel track record, and, importantly, a stronger push, especially in California, for electrification of as much of the fleet as possible, made more realistic by recent declines in battery cost for electric vehicles (EVs).

At the same time, biofuels play an outsized role in compliance with existing low carbon fuel policies as the predominant low carbon fuel available in commercial volumes. With incrementally lowering carbon footprints and more volumes of byproduct-based fuels coming online, their dominance is expected to continue for at least the next decade. Liquid biofuel benefits from some legacy advantages—a familiar production technology in the case of conventional ethanol and biodiesel, and more broadly, compatibility with the internal combustion engines that make up the bulk of existing vehicle fleets, at least to some modest blend rate with petroleum fuels. Biofuels provide near-term carbon reductions at a time of climate crisis. Looking ahead, liquid biofuels are still seen by most modeling as critical to long-term decarbonization of the economy due to the difficulty of moving to lower carbon energy for the transportation modes that require the highest energy density—especially aviation, some marine, and likely some long-haul trucking. For these sectors, liquid hydrocarbons like biofuels are likely to be needed in large volumes (Fulton et al. 2015), although hydrogen from biomass or zero-carbon electricity sources may also play a role, especially in trucking (A. Brown et al. 2021).

Going into the 2020s, existing liquid biofuels and biogas—with some carbon-lowering improvements—look set to continue to benefit from policy incentives already in place, as does electrification, pushed by additional policy initiatives. Other as-yet-unproved fuels, or conventional fuels with lower carbon intensity due to carbon-capture-and-sequestration, may also emerge, assisted by the incentives under LCFS-like programs and others like tax credits, but the timing and cost of their commercial appearance at scale is still hazy.

Will 2020 to 2030 look any different for non-conventional biofuels—biofuels other than starch-based ethanol and fatty acid methyl ester (FAME) biodiesel, using feedstock that doesn't compete for arable land—compared to the last decade? This white paper synthesizes existing literature to outline factors likely to shape trends for non-conventional biofuels in the next decade and beyond with the hindsight of their below-expectations track record over the last decade. The focus is California with its ambitious GHG reduction targets for transportation under its Low Carbon Fuel Standard (LCFS) and Sustainable Freight initiatives, among others, but the discussion is relevant for the U.S. as well. The focus is biofuels used in on-road transportation like cellulosic ethanol and drop-in hydrocarbons, and technologies using biochemical and thermochemical conversion processes as well as hydrotreated lipid renewable diesel, although some of these could also transfer to produce low carbon biojet (a subset of alternative jet fuel, or AJF; sustainable aviation fuel (SAF) when sustainably sourced and produced). Similarly, analysis touches on technologies that currently target jet fuel that could also yield on-road biofuels. Technoeconomic analyses (TEA) of novel conversion technologies and their evolution for liquid hydrocarbon biofuels as successful pioneer plants failed to emerge are used to shed light on likely future trends.

The remainder of this paper is structured as follows. Section 2 overviews biofuel policy and developments from 2010 to 2020. Section 3 presents alternative views (scenarios) of the state of biofuels in 2030, with implications for biofuels to 2050. Section 4 examines the current state of and prospects for non-conventional biofuel supply, as well as trends in technoeconomic cost analysis. Section 5 describes principal policies' impact, and Section 6 offers conclusions.

2 Biofuel Trends 2010-2020

This section first lays out the primary policy drivers that were meant to lead to spark growing commercial activity for nonconventional fuels, detailing how the incentive structure instead favored other fuels. It then describes what fuels indeed did appear in the decade under those policy incentives. It ends outlining and summarizing the key factors that hindered nonconventional fuel development in the 2010s.

2.1 Primary Policy Drivers

U.S. policy in the 2010s aimed for a take-off in low-carbon cellulosic biofuels alongside modest increases in use of biomass-based diesel substitutes and, for corn ethanol, up to "blendwall" levels of about 10% by volume in retail gasoline, via the RFS2, established under the Energy Independence and Security Act of 2007. The RFS2 updated the 2005 RFS; implementation by the U.S. Environmental Protection Agency (EPA) began in 2010. While the RFS2 targeted cellulosic fuel growth, its broader objectives were lower reliance on (largely imported) petroleum use for transport, and greater use of (largely likely domestically produced) biofuel that would help domestic agriculture, encouraging biofuels that met carbon intensity requirements so as to lower GHG emissions from transport. Under the RFS2, petroleum fuel refiners and importers must use a certain amount of renewable fuels, set annually in a series of nested mandates. Corn starch ethanol use was limited to 15 billion gallons, biomass-based diesel had a minimum requirement of 1 billion gallons, and cellulosic fuel had its own submandate that ramped up use to 16 billion gallons by 2022.[2] Beyond 2022, the EPA has more leeway to set mandates.

In practice, the U.S. expanded use of conventional and FAME biodiesel use, but only a small fraction of the envisioned use of cellulosic and other biofuels emerged that met the 50% carbon intensity (CI) reduction requirements for the policy's advanced fuel category. The shift was triggered by EPA's severe cutbacks of required cellulosic volumes each year due to lack of

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[2] Eligible renewable fuels to meet each tier of the RFS2 mandate nest also had to reduce GHG emissions per unit of energy (carbon intensity, or CI) by set amounts compared to 2005 petroleum fuels. The cellulosic fuel needed to meet at least a 60% CI reduction; the biomass-based diesel, at least a 50% CI reduction; and other renewable fuels (including corn ethanol) at least a 20% CI reduction. The residual to reach the full mandated quantities, 36 billion gallons in 2020, could be from any renewable fuel meeting at least a 50% CI reduction, which the policy termed "advanced fuels" (U.S. EPA 2010).

availability, a circumstance written into the statute. Largely to accommodate the decline in the cellulosic contribution to the overall mandate, required volumes for other categories were reduced starting in 2014 (Figure 1).

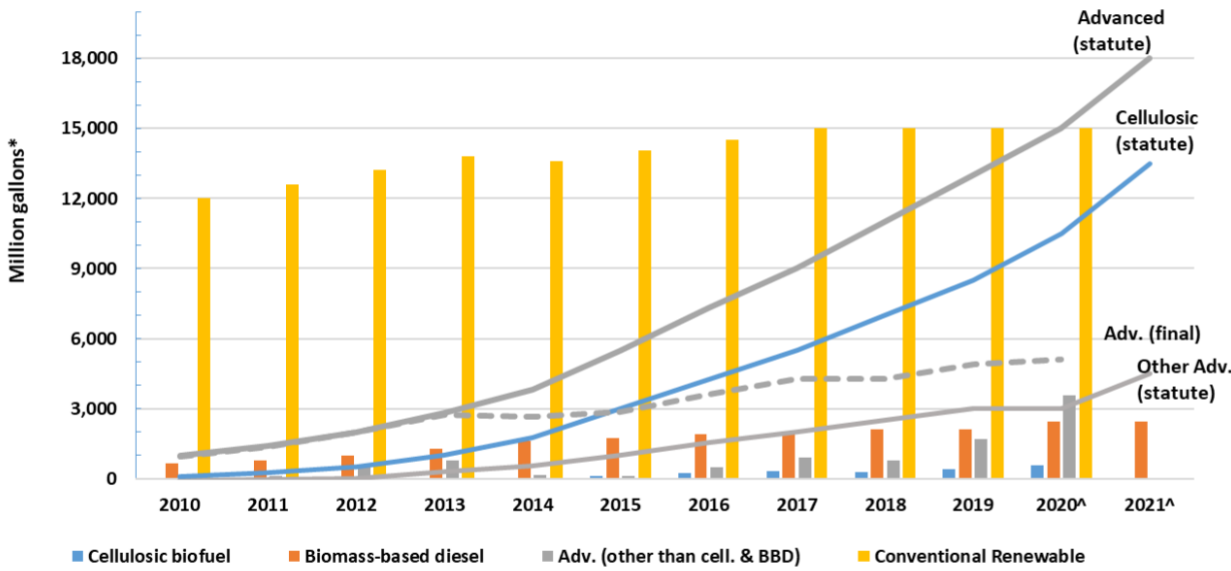

Figure 1. RFS Volume Standards: implemented (columns) and statutory levels (lines). *Gallons for biomass-based diesel; ethanol-equivalent gallons for other mandates. "Adv. (other than cell. & BBD)" and "Other Adv. (statute)" refer to residual advanced fuel after adjusting for ethanol-equivalent gallons covered through the cellulosic and biomass-based diesel mandates, with the statutory line indicating the statutory minimum of 1 billion gallons. Source: (Bracmort 2020)

The RFS2 was not the only policy tool incentivizing biofuels during the 2010s: tax credits were extended for blending biomass-based diesel and producing cellulosic fuels, and federal grants, loan guarantees, and tax benefits for stand-alone biorefineries pioneering new cellulose conversion technologies were all available. But the RFS2 was the most sweeping of these, as it worked directly in the fuel market to raise costs for fossil fuels and transfer that value to lower them for lower carbon fuels, to bridge the cost competitiveness gap. The assumption was apparently that cellulosic ethanol was technologically ready for commercialization, and only lacked a market for deployment in large volumes, which the RFS2 aimed to create; government-funded R&D largely focused on other technologies (Lynd 2017).

In California, a separate policy also focused on lower GHG emissions from transportation fuels also debuted in the 2010s: the LCFS. The policy sets an annual target for CI reductions averaged over the entire transport fuel pool, and initially aimed for a 10% CI reduction from 2010 levels by 2020. The LCFS is more flexible than the RFS2 in that it does not mandate use of any particular alternative fuel; carbon reductions can come from any alternative fuel. Moreover, the LCFS incentivizes incremental carbon reductions anywhere along an alternative fuel's supply chain, unlike the RFS2, which instituted threshold CI reduction requirements for eligibility (see Figure 1, above). Like the RFS2, the LCFS works by raising costs for fossil fuels, and any fuel with emissions higher than the annual CI standard (generating LCFS deficits), while fuels that reduce emissions beyond the standard generate LCFS credits, which can be sold to cover deficits, thus transferring value to lower carbon fuels (Figure 2).

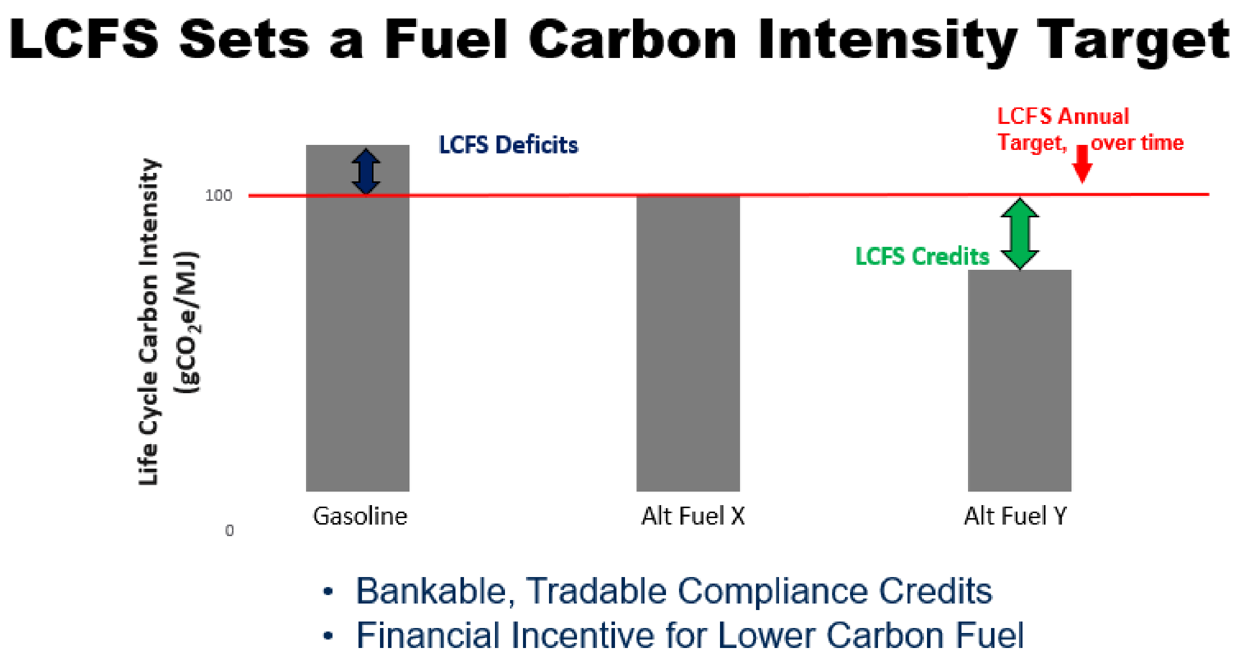

Figure 2. Schematic of LCFS market-based mechanism.

The increased compliance flexibility in the LCFS thus opened more possibilities than the RFS2 to financially reward lowering conventional fuels' CI scores in a smaller but still substantial market—roughly 10% of the U.S. total. Modest initial LCFS targets grew more stringent later in the decade. Going into the program, California expected to see increasing volumes of cellulosic ethanol over time under the LCFS; since the incentive stacked with the RFS2 incentives, California could essentially piggyback on RFS2 compliance if fuel producers shipped to the state to take advantage of both incentives. However, the lack of mandates for particular fuels in the LCFS left open possibilities that unforeseen lower carbon fuel types or processes could emerge.

The RFS2 faced challenges throughout the 2010s that diluted its importance as a market driver. Court rulings resulted in after-the-fact changes to mandated fuel amounts (Bracmort 2020). As the 2010s proceeded, there were delays in setting the annual mandate that left it unclear what even current requirements looked like. The EPA failed to follow through on court rulings requiring redress of earlier waived biofuel quantities. Perhaps above all, exemptions from RFS2 requirements for small refineries surged after 2016, effectively lowering required volumes in all mandate categories. Required volumes for 2021 and the shape of the program post-2022 both remain uncertain, pending EPA action under the new administration (Bracmort 2020); in its current form, it looks likely to do little to incentivize non-conventional biofuel development.

The LCFS also had court challenges to contend with especially in the first part of the decade, that increased uncertainty about policy longevity and about the robustness of this incentive for alternative fuel investment (Witcover 2018; Lade, Cynthia Lin Lawell, and Smith 2018). LCFS target declines were delayed and the program required re-adoption in 2016 in response to court rulings (Yeh et al. 2016). Still, the LCFS was on surer footing going into 2020 than either the RFS2 or it had been previously: California had extended its LCFS with a 20% CI reduction target for 2030, and resolved most of its most pressing legal challenges. Other jurisdictions replicated the policy, adding to the robustness of an aggregate signal that more, lower carbon fuels would be needed in the future. British Columbia in 2010, Oregon in 2015, and Brazil in 2019, all adopted similar policies, Canada is developing one to take effect in December 2022, and Washington state enacted one in 2021 to take effect in 2023.[3] Toward decade's end, the California LCFS set a schedule of targets to 2030. At the same time, other LCFS programs—in British Columbia and Oregon, as well as Canada—laid out targets for 2030 and, in Oregon's case, 2035, making these the most important low carbon fuel policy driver. Targets announced through and beyond 2030 increase the certainty of a long-lived investment signal (Figure 3). An LCFS has entered the policy discussion in other jurisdictions as well, like New York, New Mexico, and Minnesota, and, under the new administration, at the U.S. federal level.

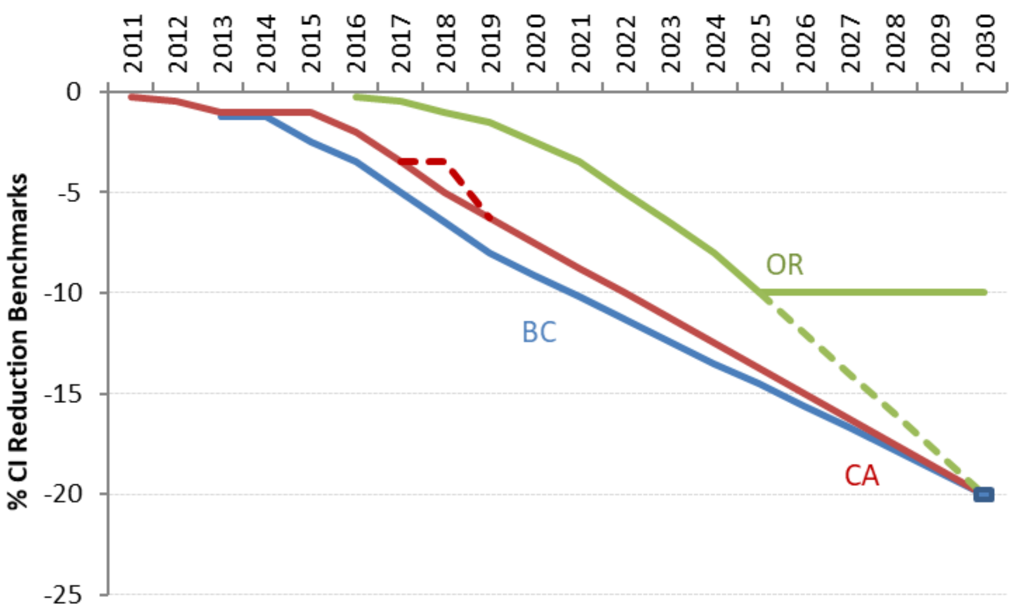

Figure 3. Annual targets for Low Carbon Fuel Intensity Standards in California, British Columbia, and Oregon. The red dashed line depicts the freeze applied to diesel fuel reductions in California due to a court case. The green dashed line indicates Oregon's announced 2030 target of 20% CI reduction; the 2025 10% CI reduction target is in effect thereafter until Oregon determines specific annual targets from 2025-2030 and to hit 25% in 2035. Washington targets

[3] These are the BC-LCFS in BC, Clean Fuels Program (CFP) in Oregon and Washington, RenovaBio in Brazil, and Clean Fuel Standard (CFS) in Canada. The EU's Fuel Quality Directive is based on similar principles, and the region's commitment to advanced biofuels was renewed under Renewable Energy Directive II announcing 2030 targets, with increased credit for fuels made from certain types of residue.

will be set during an upcoming rulemaking, targeting 20% CI reduction below 2017 levels by 2038.

The policies all acknowledge that greater use of biomass as feedstock may prompt conversion of additional land around the world to agriculture, with higher GHG emissions and/or lower biodiversity ("indirect land use change", or "iLUC"), as well as potential impacts on food prices. Existing low carbon fuel policies worldwide have varying approaches to iLUC. Policies in the U.S.—California, Oregon, and the RFS2—sought to address these concerns by adding an estimate of a biofuel's impact on global emissions to its carbon intensity score for policy evaluation (Witcover, Yeh, and Sperling 2013). In the EU, years of debate ultimately led to caps on contributions to renewable mandates from fuels made from food and feed crops under its Renewable Energy Directive and CI reductions under its LCFS-like Fuel Quality Directive, an added phase-out for crops deemed to be at high risk from iLUC by 2030,[4] with a need to certify use beyond the cap for crop-based feedstocks as low risk (Giuntoli 2018). BC included placeholder language for iLUC in its regulation, but has not implemented any restrictions. Canada's proposal to address iLUC in its LCFS-like program, the CFS, is based on source certification coupled with the high-risk restrictions mirroring the EU approach but without its food and feed-based feedstock caps. Brazil's RenovaBio policy also relies on source-country certifications.

Early modeling studies highlighted a potential for high GHG emissions from biofuel-induced land use change (Searchinger et al. 2008; Fargione et al. 2008). Several regulatory agencies implementing CI-based alternative fuel policies, like the California Air Resources Board (CARB), the US EPA, and the EU Joint Research Council, sponsored their own modeling efforts using different modeling frameworks to estimate iLUC emissions, settling on regulatory values of iLUC emissions that were considerably lower than the early studies but still substantial, and variable across studies (Witcover, Yeh, and Sperling 2013). Another hallmark of studies undertaking systematic sensitivity analysis was wide uncertainty ranges on the estimated values (Hertel et al. 2010; Plevin et al. 2010), leaving higher values as plausible if not likely. Over the next decade, model modifications in the primary modeling systems used generally led to lower iLUC emission estimates (Scully et al. 2021b). The modeling shifts incorporated important real-world realities into the modeling framework, such as better representations of the livestock and land sectors, which allowed more of an economic response and hence lower iLUC estimates (Taheripour, Hertel, and Tyner 2011; Taheripour, Zhao, and Tyner 2017). Other studies, however, raised questions over whether the primary model used for the California program takes adequate account of model uncertainty (Plevin et al. 2015). Discussion about robustness of results is still playing out in the literature (Malins, Plevin, and Edwards 2020; Taheripour, Mueller, and Kwon 2021). Even with efforts to align different modeling structures in terms of input parameters and assumptions as much as possible, gaps in modeling results persist (CORSIA 2019). The nature of the ongoing discussion is evinced in a recent study, comment, and

[4] Biofuels using crops as feedstocks that expanded more than 1% annually post 2008, with 10% of that expansion into high carbon areas, are classified as high risk. Palm oil was the sole assessed high-risk feedstock for iLUC by the EU (European Commission 2019).

reply to comment on iLUC estimates (Scully et al. 2021a; Spawn-Lee et al. 2021; Scully et al. 2021b). While the focus in this exchange is on corn ethanol CI, the modeling issues discussed impact other biofuel iLUC estimates.

Non-governmental organizations focused on environmental impact from transportation have expressed concern about land use impacts of biofuels, especially for crop-based biofuels, but not exclusively so; they voice strategies emphasizing electrification where possible, exploration of clean hydrogen-based electro fuels, and careful feedstock sourcing for biofuels so as to not trigger unwanted impacts (Transport & Environment 2021a; Searle 2019; Baek et al. 2021).

To date no policy has grappled with indirect land use change topic comprehensively to ensure that careful feedstock sourcing in terms of amounts and locations to safeguard against market-related impacts that might come with large-scale biomass use. Policies like those in the U.S. that attribute iLUC emissions to biofuels based on their feedstock have incentives that reflect the uncertainty of iLUC emissions. Attributing estimated iLUC emissions to fuels can help safeguard against overuse of biofuels that rely heavily on land by decreasing the policy incentive to produce them, but that incentive still exists and this iLUC approach does not safeguard against risk of feedstock use beyond modeled amounts or account for multiple land use conversions within the modeled period. This could mean missing some carbon sequestration, but also carbon emissions that are less readily reversed once land is converted. The EU policy has some safeguards in place in its eligibility caps for food- and feed-based biofuels, and further safeguards for high-iLUC risk feedstocks, but the risk assessment is made on broad global patterns for the specific feedstock and high carbon areas. While this may limit the most egregious potential for GHG emissions, it also overlooks substitution impacts on markets other than the feedstocks themselves that could be associated with substantial emissions.

The existing policies emerged in the absence of comprehensive GHG accounting and accountability globally in the land sector; policy tools would ideally transparently reflect policymakers' and society's risk levels about too much, or too little, bioenergy use given the potential consequences (Witcover, Yeh, and Sperling 2013). Identifying feedstocks as at low risk of prompting ILUC impacts, is a promising approach, but requires site-specific detail beyond what is seen in the current EU approach (Mouratiadou et al. 2020; Searle and Giuntoli 2018). The environmental impact from backfilling biomass diverted to make fuel remain a concern that any scaled biofuels effort must comprehensively address. How to encourage land use that sequesters additional carbon without triggering unwanted market impacts continues to be central to the question of the key role for biofuels in transport decarbonization, and indeed to bioenergy more broadly (Field et al. 2020). We return to this topic in the context of the next later in the report.

2.2 Production and Use Trends 2010-2020

Some cellulosic fuels did appear in the 2010s. There was a small increase in cellulosic U.S. ethanol use reported under the RFS2, peaking near 10 million gallons in 2017 (Figure 4).[5] California received several times more starting in 2019 when 54 million gallons was used; this accounted for about 5% of California's ethanol use (CARB 2020).[6] Larger planned U.S. cellulosic ethanol facilities with corn straw as a feedstock failed. Only one, POET's plant, began producing at any substantial volume, and never got to scale before closing in late 2020. Others went bankrupt (Abengoa's Kansas site) or were sold off (Dupont's facility in Iowa and INEOS Bio's plant in Florida). The handful of successful cellulosic ethanol production came from "bolt-on" technologies using corn kernel fiber at corn ethanol plants and required relatively small investments to modestly boost facility output (Witcover and Williams 2018). Two larger facilities producing in Brazil use sugarcane straw (bagasse) as a feedstock, but remain well below nameplate capacity as they work on technical challenges (Mendes Souza et al. 2019). Lanzatech pursued gasification technologies to produce ethanol from cellulose and other feedstocks, but with an unfavorable market perceived in the U.S., it moved early efforts to build pioneer facilities overseas, and retargeted its end-product market further to process ethanol into drop-in jet fuel and diesel (Bagby 2020).

Biogas became eligible as a cellulosic fuel under the RFS in 2013, and has filled over 90% of the policy's dramatically lowered annual cellulosic mandate since then (Figure 4). Around the same time, the LCFS clarified biogas injected into a common carrier pipeline and contracted for by natural gas dispensers for transport use could earn credits via indirect accounting (book-and-claim) methods. By 2019, biogas contracts to fuel natural gas vehicles covered 39% of on-road natural gas use nationally (Coalition for Renewable Natural Gas and NGV America 2020), and 77% in California (NGV America and Coalition for Renewable Natural Gas 2020). Most LCFS biogas has come from landfills throughout North America, although in the late 2010s California began to see rapid growth in animal manure biogas, which has a negative CI score in the LCFS due to how the system accounts for diverted methane emissions. Without biogas' success, the policy pressure for liquid biofuels to meet targets might have been greater (and at least LCFS credits scarcer sooner).

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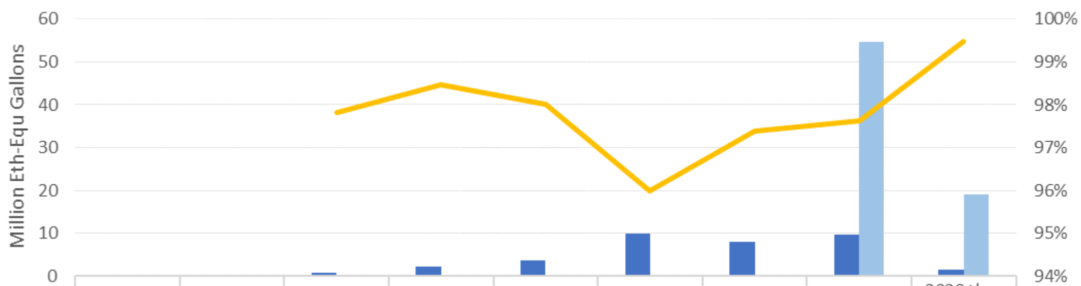
[5] Data do not permit isolating the source of the drop in RFS2 cellulosic ethanol volumes from 2017 to 2018.

[6] While RFS and LCFS incentives can stack, some cellulosic ethanol conversion technologies related to corn kernel fiber are only certified under the LCFS, and not the RFS. This is the likely cause of substantial cellulosic ethanol use in California not reported in the RFS. Data do not show how much, if any, of RFS-reported cellulosic ethanol was used in California, and counted toward LCFS volumes.



Gallons	2012	2013	2014	2015	2016	2017	2018	2019	2020 thru Sep*
Cellulosic Ethanol	20,069	-	728,509	2,181,096	3,805,246	10,047,034	8,158,168	9,815,841	1,646,168
Cell eth (CA LCFS)								54,565,145	19,182,032
Cell Biogas			32,587,883	139,859,145	188,556,549	240,577,439	304,190,030	404,306,969	320,572,942
US D3 % biogas			97.8%	98.5%	98.0%	96.0%	97.4%	97.6%	99.5%

Cellulosic Ethanol   Cell eth (CA LCFS)   Cell Biogas   US D3 % biogas   * thru Mar for CA

Figure 4. Cellulosic fuels reported under the U.S. RFS and CA LCFS (ethanol-equivalent gallons). D3 refers to D3 RINS, the tradable instrument for recording cellulosic biofuel use used for compliance with the RFS cellulosic submandate. Sources: (CARB 2020; US EPA 2020).

One non-conventional fuel emerged from 2010s' biofuel policy regime as a standout: HEFA RD. A drop-in fuel to blend with or displace on-road diesel altogether, HEFA RD does not require modifications to delivery infrastructure or vehicle engines to blend at higher rates, as do ethanol and FAME biodiesel. U.S. HEFA RD use was negligible at the beginning of the decade, but by 2019, nearly 800 million gallons was reported under the RFS. About 80% of that amount was used in California, accounting for over 16% of its liquid diesel pool that year. Residue feedstocks like used cooking oil, tallow, and distiller's corn oil from ethanol production contribute the lion's share of the California HEFA RD because they receive a low carbon intensity score under the LCFS. Residual oil use, however, is ultimately capped by the size of the processes of which the oils are residues. How much residue oil supply can be brought into supply chains how quickly, moreover, was and is not well known; the logistics of aggregating dispersed supply is one of the challenges. The LCFS market is revealing, at least, what volumes are feasible in the short run. Starting in 2018, non-residue HEFA RD, largely soy-based, began to arrive in California, suggesting HEFA RD expansion is currently outpacing growth in residue feedstock supply. In 2020 through September, about 15% of HEFA RD in the LCFS was principally soy.

Other drop-in cellulosic renewable diesel conversion technologies also saw some commercial activity in the 2010s. KiOR attempted to build a pioneer facility using catalytic cracking to biocrude. Ensyn, expanding an existing renewable heating oil business, sought to produce a biocrude from woody biomass using pyrolysis technology, to be further upgraded and processed alongside petroleum fuel. KiOR went bankrupt. Complications and costs related to upgrading has left Ensyn still not producing biocrude destined for on-road transportation fuel. Fulcrum and Red Rock both pursued drop-in diesel substitutes from a Fischer-Tropsch biomass gasification process. Both eventually targeted jet fuel as the primary output and are constructing and close to moving into operation for their first-of-a-kind facilities.

A 2016-2017 study overviewing companies with announced U.S. cellulosic fuel production intentions found many moving away from U.S. transport fuels as their core business. Reasons cited included shifts in or broadening of target markets, projects put on hold due to lack of financing, a decision to try overseas first, consolidation and drop-outs of efforts, uncertainty about the size and value of the market, and the mid-decade dip in oil prices, which made alternative fuels less competitive (Witcover and Williams 2018). The study highlighted a downturn from earlier similar assessments especially in cellulosic ethanol production, but this was somewhat compensated in energy terms by HEFA RD capacity expansion that was not expected. The study highlighted dangers of taking announcements of "advanced biofuel" capacity as indicative of actual near-term capacity at nameplate values: to do so overlooks a variety of potential complications both technical and financial in nature that arose during virtually every stage of plant development and during commissioning, when operations were slated to ramp-up to nameplate capacity. Not accounting for potential cost increases associated with unknowns at final stages of moving to scale with pioneer technology, and the rise in costs per gallon that accompanies smaller production levels, threw off assessments of expected capital requirements and operating expenses (total, and normalized per gallon) for the new facilities, both key metrics for investors.

The U.S. government shifted tactics in the latter part of the decade in recognition of the nonconventional biofuel industry's difficulties. More funding emphasis was placed on biomass supply chains and biomass handling research, and the scope for loans was expanded to bioproducts in general, beyond just biofuels. Technological advances in other bioproducts might create synergies toward the desired goal of low carbon biofuels cost competitive with petroleum fuels, while improving the business model.

2.3 Key Factors Hindering Development, 2010-2020

The factors hindering cellulosic fuel development over the decade were several, coming from policy, technical and financial arenas, complicated by other fuel market developments. Loan guarantee policies encouraged cellulosic pioneer plants to go large in order to reap economies of scale and make a difference in the huge-volume transportation fuel market. Cellulosic ethanol, seemed closer to commercialization than other technologies. The government largely bypassed cellulosic ethanol in R&D, apparently assuming it was adequately developed technically to move from demonstration plans to full-scale plants and ready for commercial roll-out (Lynd 2017). The RFS2 and LCFS turned out better suited to enlarge markets for existing fuels, albeit at times with incrementally lower CI values via tweaks in conversion processes and technologies (Morrison et al. 2016), but within limits, as the policies do not target new infrastructure needed for significantly higher blends of conventional biofuels. Investments that would only pay off in the longer term if at all and with continued policy support, were made more risky by the court challenges to both the RFS2 and LCFS, especially to the cellulosic mandate implemented under the RFS2.

Moreover, the size of needed incentive was far from clear. Problems with early ventures led to unplanned capital investments and significant delays in planned construction and commissioning activities (Witcover and Williams 2018). One after another, pioneer facilities encountered difficulties: yields from new conversion technologies for drop-in fuel fell well short of targets (KiOR), and issues with large quantities of biomass feedstock hamstrung production for cellulosic ethanol at commercial sized facilities (e.g., technical difficulties at INEOS Bio's Florida facility, POET's slow ramp-up at its Iowa facility, and fire issues with stored feedstock for Dupont's Iowa facility).[7] The technical challenges point to insufficient experience with the technology at a medium scale, smaller than large commercial plants that would realize scale economies, that would uncover technical glitches associated with scale-up from demonstration plants, and allow for learning-by-doing and innovation (Lynd 2017). Falling and volatile oil prices in mid-decade compounded the cost problem, meaning even lower costs or higher incentives for new technologies would be needed to compete with petroleum fuels. The U.S. military bought small volumes of newer biofuels for testing, and awarded funds to supplement private investment for several pioneer facilities in mid-decade (US GAO 2015). These efforts were important to industry development—in fact, two of the early awardees are among pioneer companies still aiming to produce commercial quantities of fuel (with military interest in jet fuel), they were insufficient to kick off an industry. Successful military demonstration use of HEFA RD may have increased commercial confidence in the fuel.

As already described, bankruptcies and facility sales ensued, leaving a track record of failure. Alongside a generally unfavorable investment environment in the wake of the Great Recession, policy uncertainty, and lower oil prices, the failed starts severely complicated efforts to raise additional capital for cellulosic fuel efforts. Environmental NGO support of transport biofuel policies ebbed amid persistent uncertainty and controversy over land use impacts of bioenergy in terms of emissions and higher food prices, especially in Europe, but also in the U.S., where concerns centered on potential for corn expansion with unwanted environmental consequences, if policy supported very high ethanol blends. VW's Dieselgate emissions scandal and increasing optimism about EV cost and efficiency, at least for passenger cars, fed into the general trend. Public and private investment in novel biofuels in the U.S. peaked in 2012, declining later; similar trends occurred globally (Witcover and Williams 2018; Lynd 2017).

At the end of the decade, HEFA RD and biogas were the new players in the biofuels arena, prompted by policies that also promoted lower carbon crop ethanol and biodiesel. The most prominent nonconventional conversion technologies for large-scale, low carbon production—cellulosic ethanol, or drop-in renewable diesels via the biomass-to-liquid gasification and Fischer Tropsch process or pyrolysis followed by hydrotreatment—remained too expensive to compete with petroleum fuels in the marketplace given the level of relatively new policy support for alternative and historical subsidies for petroleum fuels, plagued by difficulties, or, in the case of Fischer Tropsch, still building pioneer facilities long on the drawing board. The companies pursuing Fischer Tropsch, among them the two Defense Department fund awardees mentioned above -- also target biojet fuel as the main output rather than off-road fuel. Additional technologies under development, such as cellulosic ethanol via gasification and gas

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[7] Outside the U.S. there were similar issues; Beta Renewables' Italian facility face difficulties handling uneven feedstock quality (Lane 2017), and the two operating facilities in Brazil are still ramping up due to pre-treatment challenges (Mendes Souza et al. 2019).

fermentation (Lanzatech process), are also more targeted to biojet, through additional processing, and open to feedstocks beyond low carbon biomass (British Airways 2021).

3 Biofuel Prospects 2020–2030 (and beyond?)

This section overviews hurdles still facing biofuel development in the 2020s, and examines likely biofuel trajectories in California and beyond, given the current policy environment.

3.1 Overview

Current policy approaches point to nonconventional biofuels making modest headway at best in the 2020s. HEFA RD, with no technical blending limit, is positioned to expand relatively easily to displace diesel fuel on-road demand; FTC labeling rules for blends above 5% are a small hurdle. HEFA RD's rapid expansion in California to nearly 620 million gallons (mg) (CARB 2020) indicate no serious technical demand barriers, the policy support being sufficient to overcome cost barriers. Volumes of the lowest CI-rated HEFA RD—from residual oils—may be constrained by feedstock supply, however (Kotrba 2019). Significant policy incentives should bring new sources of low CI residual oils for HEFA RD to market, such as used cooking oil in countries where it is not yet collected, or other residuals still unthought of. The timing for new feedstock supply chains to be established and the volumes involved, however, are uncertain. Moreover, many residues have existing market uses, that, if diverted will require backfilling. For example, used cooking oil is used as animal feed; if more goes to biofuel, a land-based substitute (e.g., corn) is possible. The market dynamic should be evaluated in an emissions assessment (Searle 2020). Sufficient draws on "residual" feedstocks could also raise their value enough to prompt expansion of the primary activity, at which point market impacts should be assessed for indirect emissions, and possibly higher CI ratings (Smith 2021).

If lower CI oils are not readily available at the necessary scale, higher CI crop-based fuels may still be attractive with sufficient incentives. They recently appeared in California: in late 2018 into 2020, between 10 and 25 million gallons of higher CI HEFA RD, likely soy,[8] entered the state per quarter, climbing from 4% to almost 15% of RD fuel supply (CARB 2020). Crop-based oils, soy or others, could expand production due to a continued incentive.[9] Other LCFS jurisdictions lag California in their CI reduction schedules or ignore iLUC impacts. Higher CI rated RD might be in demand there longer into the future, if supply of low-CI residual oils is insufficient. There

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[8] Based on analysis to ascertain CI rating plus certified pathway data from the program.

[9] In the case of U.S. soybeans, additional planting in response to incentives is complicated by the nature of the industry. Historically about two-thirds of the crop value is derived from soybean meal for feed, so those prices drove planting decisions; only a third of value came from soybean oil. However, when soybean oil prices have increased, oil production has driven crushing decisions, such as when prices exceeded 50% of total in 2011 and 2012 (Informa Economics 2015). Less substitutability for U.S. soy than EU oilseeds with palm oil, known to cause deforestation in southeast Asia, are behind generally lower iLUC estimates for U.S. soy than EU oils. Model differences noted above still lead to substantial gaps in modeling U.S. soy, in part due to different assumptions about peatland coverage and conversion to agriculture.

are, however, potential brakes on RD growth, such as feedstock price increases or a lower LCFS credit price due to additional low CI fuels coming on.

Fischer-Tropsch process drop-in renewable diesel from cellulosic residues is the most commercially advanced of non-HEFA liquid biofuel conversion technologies. Fulcrum's 11 mg/year cellulosic fuel pioneer plant using municipal solid waste is slated to open in Nevada in 2021. Fulcrum is also the farthest along in announcing additional facilities, in Indiana and the UK (Fulcrum Bioenergy, Inc. 2021), which would provide more volume and learning opportunities. The pioneer plant experienced considerable delay; expectations in the mid-2010s were for a Nevada plant to open in 2018, and eight plants by 2022 (Sapp 2016). Red Rock's first 16.1 mg/year Fischer-Tropsch plant to produce cellulosic fuel using woody biomass left over from timber harvest or thinnings from forest management as a feedstock was also expected to open soon, in Oregon in 2022. However, the project recently ran out of money and is turning to bonds while redesigning to expand output by 15%; given the redesign, construction of the facility is reportedly over halfway complete (Sapp 2021).[10] The company received DoE money in 2013, eyeing cost-competitive fuel by 2015.

Even if these cellulosic fuel pioneer plants successfully open and ramp production to nameplate capacity without further delay, each facility can take several years to site, construct, and commission before being able to deliver at capacity, expected to be up to ~30 mg/year. In the 2030 timeframe, therefore, cellulosic biofuel volumes from this process will likely be modest. Those volumes would still make an important contribution to lower carbon goals; the learning behind the achievement of several fully functioning facilities would have greater import in terms of technology development, potentially bringing down per unit costs, that would then improve prospects for lower carbon biofuels beyond 2030. Other conversion technologies for cellulose, while being actively pursued as discussed in the prior section, have proved more elusive.

3.2 California Example: HEFA Renewable Diesel and EVs to 2030

California, a decade into its ambitious push towards transport decarbonization, offers a microcosm of what might be possible elsewhere. Studies looking forward to 2030 in California LCFS compliance at a 20% CI reduction target (from 2010 levels and from a 2021 target of 8.75%) find HEFA RD likely to play a strong role. They find that the size of the demand pull for HEFA RD from this source will be primarily shaped by state's roll-out of EVs. If fast, demand for HEFA RD is lower, if slow, higher. This is because while HEFA RD is used as a diesel substitute (heavy duty), and most electrification in the near term will be substituting for gasoline (light duty), demand for the two and with other alternative fuels are linked via LCFS design. The LCFS incentivizes enough alternative fuel to meet targets via CI reductions that can occur either in the gasoline pool or the diesel pool. California will continue to vigorously pursue electrification goals, with state policies like the ZEV mandate bolstered by the LCFS, and additional low carbon fuel needed to meet LCFS targets will likely come from HEFA RD (Alden 2020), given trends

[10] The reference does not specify the metric for assessing extent of construction (e.g., capital expenditure, construction time, etc.).

already seen in the program. According to the state target scoping exercise for 2030, from the recent 620 mg used in California, HEFA RD volumes could increase up to 1.5 billion gallons (bg) by 2030 (CARB 2018). An environmental-NGO sponsored study found a more modest 750mg peak for HEFA RD in 2025; EV penetration assumptions permitted declining reliance on RD thereafter (Malins 2018). An academic study exploring impact of on-road fuel demand uncertainty to LCFS compliance found a much wider range of possible HEFA RD volumes for 2030, from 760mg – 5 bg, or up to 75% of the liquid diesel pool (Bushnell et al. 2020). In this study, with a rapid EV roll-out, between 760mg and 1.3 bg would be needed. With a slower EV roll-out, 1.7bg - 5bg would be needed. In each case, the range of fuels is determined by how much overall transport demand there is in the state, with high and low ranges extrapolated from historical demand.[11]

HEFA RD demand could be lower due to other factors as well, like California's newer policies to electrify transport including for heavier duty cycles could, if significant fleet penetration is achieved by 2030. Also, in the past, the California Air Resources Board (CARB), the implementing agency, has opened up additional LCFS credit generation opportunities, including off-road electricity sources (such as existing light rail), alternative jet fuel, and use of book-and-claim accounting to credit biogas and low- or zero-, or negative-carbon electricity use, which, if taken up or expanded, would also dampen the need for HEFA RD for compliance. Biogas in particular may have an impact: the uptick in announcement for and use of very negative CI manure biogas reported in the program has been marked, not only showing signs of displacing higher CI landfill gas as an end fuel, but moving beyond the limited natural gas transport market as a source fuel for electricity for EVs.

3.3 Beyond California

California's LCFS is not alone. Additional low carbon fuel policies globally have helped drive announcements about expanded HEFA RD production capacity, attractive due to its drop-in status and ability to further process into biojet fuel. HEFA RD output in the U.S. could triple from 2019 levels by 2022 to just under 2 bg, and expand beyond 3 bg to 5 bg if announced projects reach fruition (US EIA 2021). Unlike for other nonconventional fuels, HEFA RD production processes are now technologically mature, so delay would likely be from some other issue, like feedstock supply or insufficient demand. Even if announced capacity falls considerably short in the short run, since final investment decisions have not been made in all cases, higher volumes are expected to come online in response to global demand by 2030; this occurring in so soon a timeframe would likely outstrip supply of the lowest-CI-rated feedstocks from residual oils and fats and expand production using crop feedstocks like soy and canola (Alden 2020), a trend already visible. The recent RD capacity announcements appear to be having an impact on soybean oil prices, pushing them beyond usual levels to parity with meal over this year (Irwin and Janzen 2021), where they are more likely to influence crushing decisions and soybean demand. As mentioned above, persistent higher credit prices will also

[11] The study framed the analysis using state-agency assumptions about CI scores and other CI-lowering activity in the 2020s, such as some carbon capture and sequestration and/or cellulosic fuel. RD demand could be higher if these assumptions are not met and other carbon lowering activities do not come online.

likely incentivize additional feedstock development; the exact mix of crop and non-crop oils that end up as HEFA RD remains unknown.

Looking to the medium term, policies elsewhere will likely be slower to electrify than California and may not have California's ambition or objectives, especially in the 2030 timeframe. In Brazil for example, an historically strong role for ethanol plus a relatively high cost of electricity may hamper EV expansion at least in the medium run; explorations are also under way for ethanol-powered fuel-cell vehicles (Argus 2021). Brazil's LCFS-like RenovaBio, moreover, does not reward electricity as a transport fuel. Under the regulation, Brazil's traditional focus on ethanol use is foreseen to expand 67% to 50 billion liters by 2030; biodiesel use is expected to more than double to 13 billion liters (Mendes Souza et al. 2019).

If HEFA RD and electricity are enough to satisfy current alternative fuel policies, there is less policy incentive to develop other, currently more expensive new technologies commercially. Lower carbon fuels would still be rewarded, but not as much. Under a dynamic that rewards very low carbon fuels without explicitly creating a market for them, and in a context where significant technological hurdles still remain, R&D for sustainably sourced cost-effective low carbon biofuels plays a critical role. If R&D uncovers technological solutions achievable at a reasonable cost given policy incentives, policy pull can help generate a market. The U.S. target cost of low-carbon drop-in biofuels by 2030 is still $2.50 per gallon gasoline equivalent (GGE). The government is actively funding bioenergy projects to try to reach that goal, including conversion technologies but going beyond them to study bottlenecks and technical issues surrounding feedstock supply and handling, or role for coproducts. EU and India also have policies that may create some kind of market for emerging low carbon biofuels (A. Brown et al. 2020). The EU prioritized waste and residue-based fuels for its 2030 targets, while limiting food-based biofuels, and, importantly for HEFA RD use in Europe and the incentive for other nonconventional biofuels, placing a soft cap on the contribution of UCO and tallow, among others, as feedstocks at 1.7% of advanced fuel targets (Transport & Environment 2021b). It is revisiting targets in light of the 2019 European Green Deal for climate neutrality by 2050 (Bolla 2020), which might result in a greater push for low carbon fuel development. India outlined a policy in 2018 that included a push to develop advanced biofuels and biogas from cellulosic sources and residues, albeit alongside expanding allowable conventional biofuel feedstocks to include sugarcane juice, sugar beet, and corn (Gupta, Puri, and Ramakumar 2020).

As mentioned earlier, existing commercial activity for potentially low carbon drop-in biofuels turned from an on-road focus to alternative jet fuel (AJF). ICAO (International Civil Aviation Organization) has recognized sustainably sourced AJF, SAF, as critical to aviation decarbonization. The carbon assessment includes iLUC, and favors nonfood-based fuels. If there are successes in lowering cost for cellulosic biofuel conversion processes for SAF, they could spill over to benefit on-road lower carbon fuels as well, as the technologies are often similar and can target either end use. The market and policy climate could determine the best end use; currently, the policy incentive for SAF in California and the U.S. falls short of that for on-road renewable diesel, and SAF volumes have been small. In the long run, absent a significant change in aviation transport, SAF is likely to be important to the decarbonization of aviation and be needed in large volumes. SAF activity is still nascent, however, and ICAO aspirational goals can also be met via carbon offsets. The policy push for SAF in North America was not particularly strong through the 2010s. While there is more interest now under the new U.S. administration, with a target named of 3 billion gallons of SAF in use by 2030, and in Europe, where mandates have been set, scaling up will be challenging, especially for technologies using cellulosic feedstocks. And as already seen, pioneer plants for a few key cellulosic conversion technologies of interest, whether targeting SAF or on-road, will likely need to build a track record of successful feedstock procurement, production, and offtake before additional commercial activity looks financially attractive to investors, especially given the failures and setbacks of the 2010s, so that sector expansion can proceed at pace.

4 Nonconventional Biofuel Supply

Nonconventional fuel conversion technologies include those discussed most above, namely Fischer-Tropsch gasification biomass-to-liquid processes, fermentation for cellulosic ethanol, and pyrolysis followed by upgrading and hydroprocessing plus less well studied technologies like hydrothermal liquefaction (HTL) and power-to-liquid (PtL), also known as e-fuels. For a description of the most discussed technologies, see (Witcover and Williams 2020). HTL uses high temperature and pressure to generate biocrude, that can be processed into jet, diesel, or marine fuels. The process can use, but need not involve, a catalyst. While HTL has a long history as a concept, it did not advance beyond pilot stage in the 2010s. Part of its attractiveness now is its ability to process wet biomass, without need for drying, and ability to handle any type of biomass (Rudra 2019), bypassing some of the feedstock pretreatment difficulties that have and continue to hamper cellulosic ethanol.[12] PtL converts hydrogen and carbon dioxide into synthetic liquid fuels. To be low carbon, the process requires renewable electricity to generate the hydrogen via electrolysis, and a low-carbon CO2 source (captured emissions or direct air capture); a FT or other process is then used to produce the biocrude, which can be further processed for jet or diesel fuels (ICAO 2019). Fuels from algae, another low carbon feedstock that holds the hope of bypassing land use concerns, also remains cost prohibitive (Chisti 2019) and faces environmental concerns such as emissions and potential damage from high fertilizer use. Despite the high hopes placed on algae fuels with R&D in the 2010s from both private and public sectors, it is still far away from entering the marketplace, and generally considered a 3rd generation fuel, that is, only available farther in the future.

It is clear from commercial trends that the technologies are not currently cost competitive, but could they be? Past and some current analyses have suggested potential profitability for a mature industry—the “nth plant,” at least with modest policy incentives (see, e.g., Brown 2018; Witcover and Williams 2020; McGarvey and Tyner 2018). A recent review of the technoeconomic analysis literature for nth plant found production cost estimates for several prominent conversion technologies—cellulosic ethanol, biomass-to-liquid (gasification and Fischer Tropsch process), and fast pyrolysis followed by hydrotreatment—to average at or

[12] This attribute may make it promising for algae-based biofuels.

below $4/gge (gasoline-gallon equivalent) (Witcover and Williams 2020) (Figure 5), not that different than the $3.70/gge for commercially successful HEFA RD.

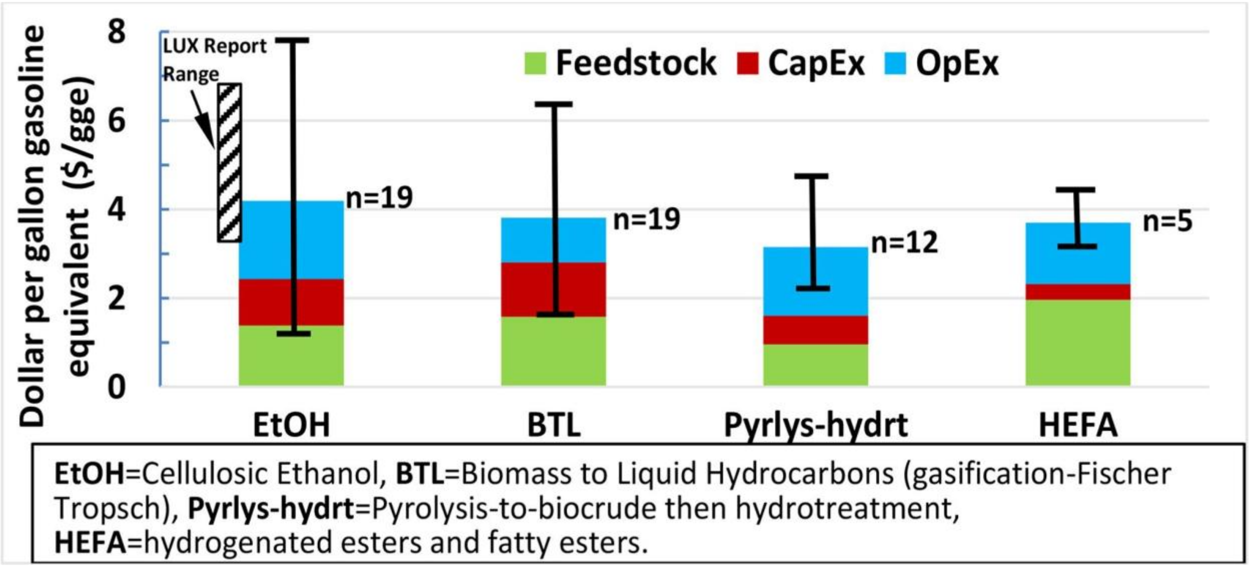

Figure 5. Cellulosic and residual oil biofuel costs, average and range from TEA literature, 2016 $. Source: (Witcover and Williams 2020)

While these estimates point to pyrolysis having the lowest average production cost among the non-commercial fuels for the (relatively small) set of TEAs analyzed ($3.25/gge), the wide range of estimates and lack of practical large-scale experience with the technologies makes this assessment not definitive. Moreover, adjusting the analysis to estimate first-of-a-kind pioneer plants, with higher capital costs and lower production facilities, move the first-wave cellulosic biorefinery more definitively out of the range of profitability, without more substantial and sustained policy incentives (T. R. Brown 2018; Witcover and Williams 2020). A recent study synthesizing a range of technoeconomic analysis research determined that production costs of drop-in cellulosic biofuels were approximately double those of fossil fuels, or ~$5-6/gallon (Kargbo, Harris, and Phan 2021). A third study comparing conversion technologies for drop-in fuels (AJFs, more specifically), found HEFA technology the least costly, followed by FT gasification; pyrolysis, which has not been investigated in this space, was not included (Pavlenko, Searle, and Christensen 2019) (Figure 6). The fermentation-based pathways using cellulosic feedstocks and PtL were both more expensive, due to additional processing of intermediate sugar products into the final fuel. Cost-savings may be difficult to find, either due to expected feedstock price increases along with demand (where the feedstock cost component dominates) or need for capital intensive equipment. Comparative studies along these lines have been hampered by the differing or obscured assumptions in the TEA literature, regarding key parameters like financing term, ramp-up rates, and yield at critical points along the production process (T. R. Brown 2015).

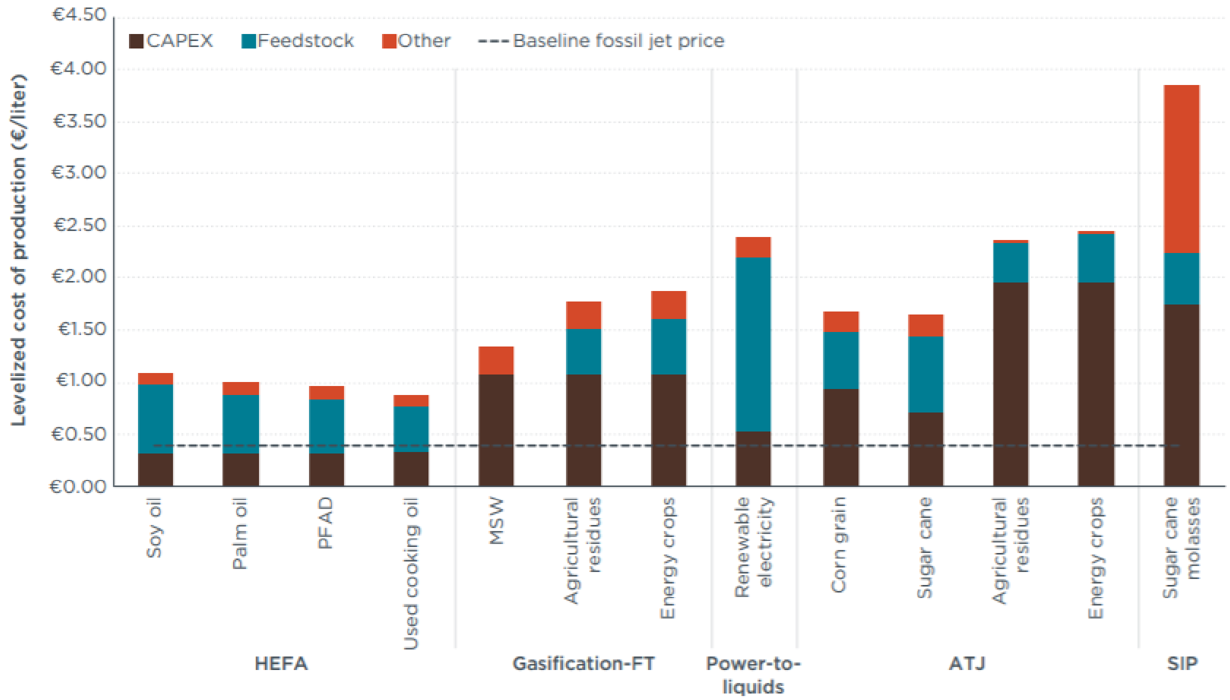

Figure 6. Levelized cost of production for biofuel (alternative jet fuel) pathways, 2018 Euros (average 2018 exchange rate, 1.18 Euros/USD). ATJ is Alcohol-to-Jet, involving processing ethanol or isobutanol. SIP is synthesized isoparrafins, involving farnesene as an intermediate product for sugar feedstocks and final drop-in fuel. Source: (Pavlenko, Searle, and Christensen 2019)

A separate analysis of cellulosic ethanol concluded that the industry continues to stagnate under high production costs and a range of technical and non-technical barriers, including difficulty to finance projects and lack of sustained, certain policy signal (Padella, O'Connell, and Prussi 2019).

A takeaway from these studies is that widespread commercialization of cellulosic biofuels will remain elusive over the next decade due to high costs, persistent technical issues that are difficult to address absent a lower cost environment or more opportunities to learn through more production, and difficult financing due to cellulosic's track record of business failures.

Forward-looking assessments of cellulosic biofuels generally deem those furthest along on the technological readiness scale (see Figure 7) or building on well-established processes most promising.

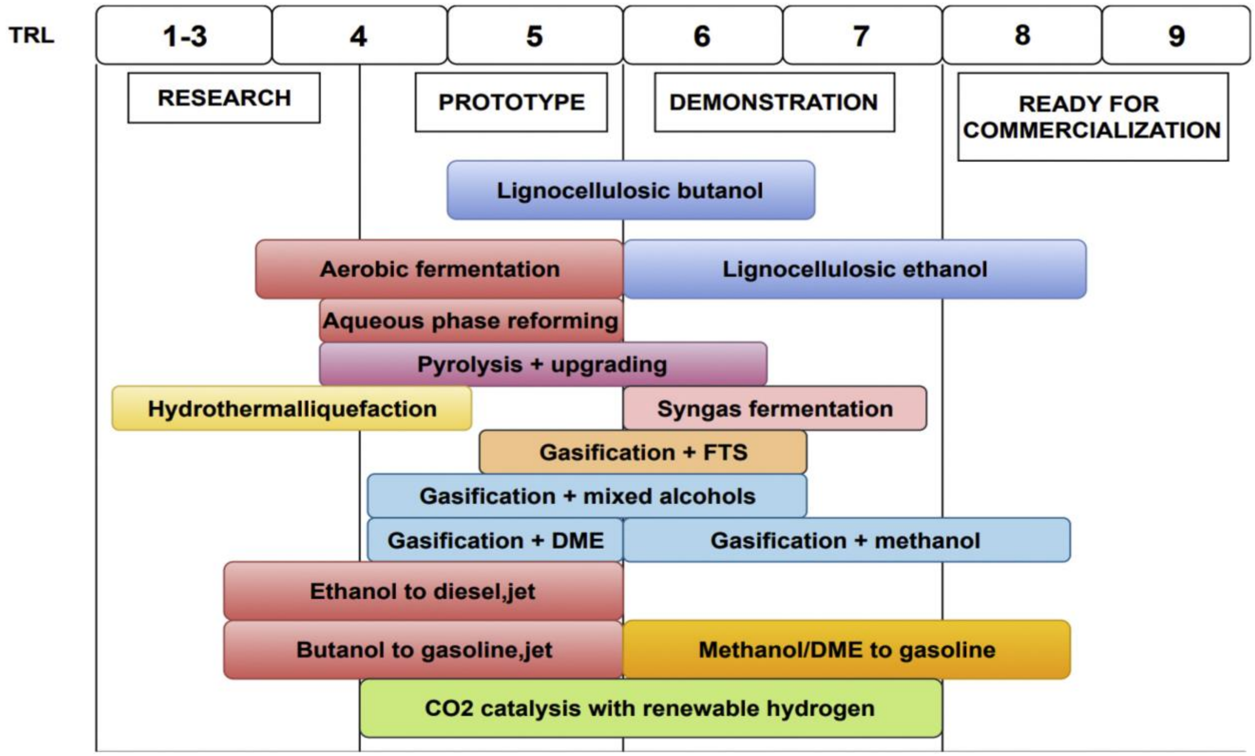

Figure 7. Technological readiness assessments for biofuel conversion technologies. Source: (Kargbo, Harris, and Phan 2021), adapted from (E4Tech 2017, 4).

This was the case for a recent study on biofuel technical potential in the UK to 2030, which found Fischer Tropsch and fast pyrolysis—the best understood technologies—to be the most likely to scale despite the considerable technical and cost challenges they currently face. Some newer technologies, like the catalytic conversion of cellulosic-based alcohols, might also be able to scale quickly due to the ability to extrapolate learnings from first generation biofuel production (E4Tech 2017, 4).

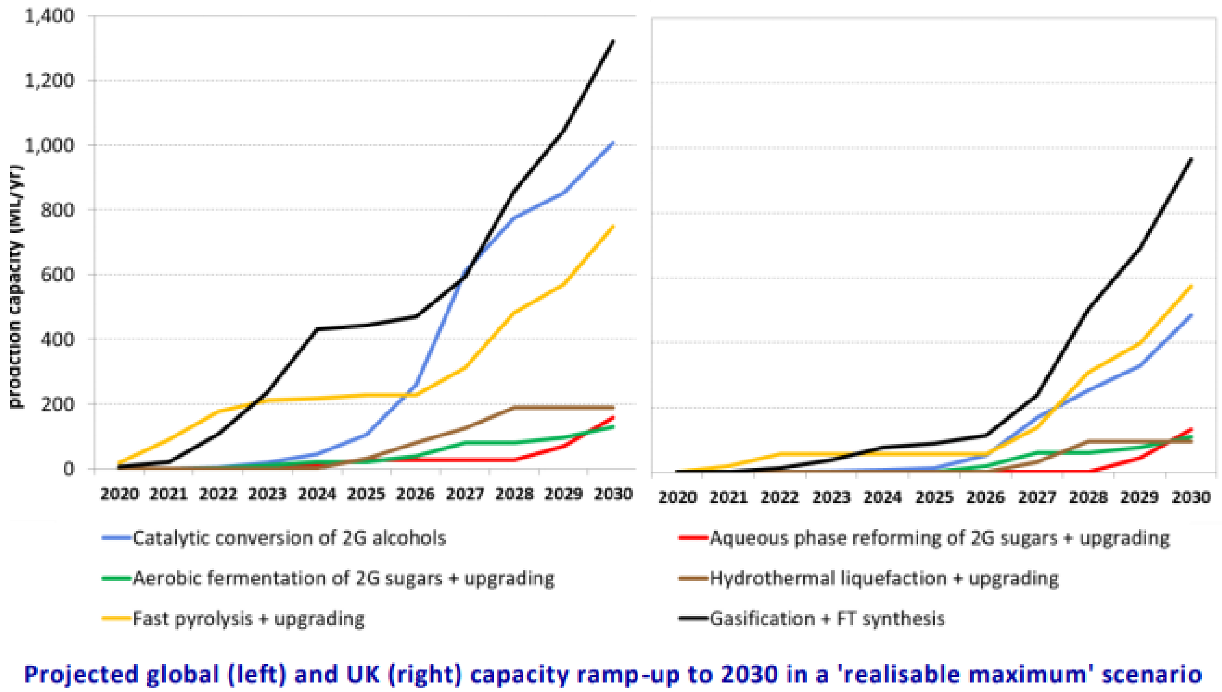

Figure 8. Assessment of potential 2nd generation biofuel capacity to 2030, global and UK.
Source: (E4Tech 2017, 4)

Fischer-Tropsch cellulosic fuels were assessed as most-likely-to-scale-soon among drop-in nonconventional biofuels in another study (Figure 9). A higher cost in TEAs was compensated for by longer experience with the generic technology. Growing practical experience with biomass as a feedstock was another factor: of 114 operating FT plants using biomass globally, 17% target liquid fuels (Kargbo, Harris, and Phan 2021). Figure 10 summarizes some of the technical challenges faced by newer drop-in technologies. Company leaders for each are also listed, underlining that commercial activity is continuing. Of the start date for pioneer plants projected in 2017, those for the most technologically ready—Fischer Tropsch and fast pyrolysis—seem to be on target. As mentioned already, Fulcrum still aims for a 2021 fall start. Although upgrading difficulties have stymied fast pyrolysis activity in the U.S., Pyrocell announced start of production in September 2021 for a 780,000 gallon/yr plant in Sweden (Setra Group 2021). A caveat is that the commissioning time to full capacity is critical, and still unknown. Gevo, known for its alcohol-to-jet process, in 2021 announced a plant to produce aviation fuel from agricultural residue in South Dakota; a 2023 start seems optimistic, given funding still needs to be secured. The outlook for hydtrothermal liquefaction (HtL) continues to be positive, with recent national lab work uncovering potential cost savings (Snowden-Swan et al. 2021), but with demonstration plants still to be built and interested firms encountering technical challenges (Halladay 2021), the 2026 start date while possible looks optimistic.

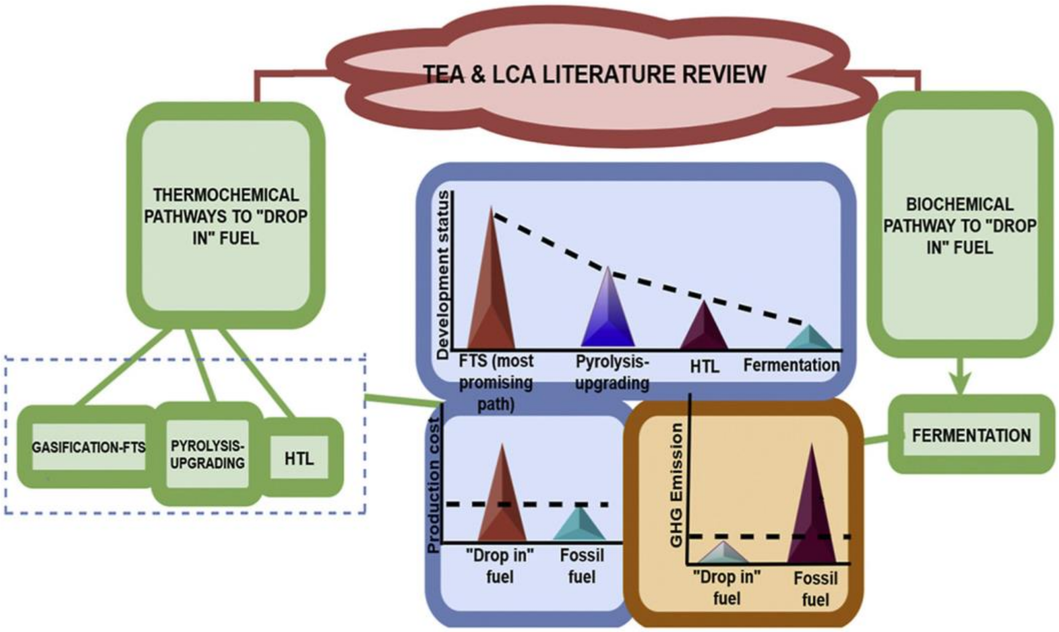

Figure 9. Drop-in cellulosic biofuel assessment for future commercialization. Source: (Kargbo, Harris, and Phan 2021)

Technology global commercialisation estimates, leading developers and key challenges

Technology	TRL (with 2G feedstocks)	Possible date for 1st commercial-scale plant	Leading developers	Key technical challenges
Gasification + FT synthesis	TRL 5-6	2020-2021	Kaidi, Joule, Fulcrum, Velocys	Consistent syngas quality, plant thermal integration
Fast pyrolysis + upgrading	TRL 5-6	2020-2022	Envergent, BTG, Cool Planet, CRI	Catalyst deactivation and coking, low carbon conversion
Catalytic conversion of 2G alcohols	TRL 5	2022-2023	Swedish Biofuels, Gevo, Sundrop	Reactor thermal control, catalyst deactivation and recycling to improve yields
Aerobic fermentation of 2G sugars + upgrading	TRL 5	2022-2024	Amyris, Global Bioenergies	Microbe adaptation to 2G sugars, low yields
Aqueous phase reforming of 2G sugars + upgrading	TRL 4-5	2023-2024	Virent/Tesoro	Catalyst selectivity, co-refining unproven
Hydrothermal liquefaction + upgrading	TRL 4	2024-2026	Licella, SCF Technologies, Biochemtex	Waste water recycling, carbon losses, co-refining unproven

Figure 10. Technology development levels, key companies, and challenges. Source: (E4Tech 2017, 4) See text for discussion for an update on possible commercialization dates.

Looking beyond the near term or next decade, there is no firm consensus about which, if any, of the nonconventional conversion technologies that have received the most attention to date might emerge in the future as a cost-effective solution for large-scale, low carbon biomass production. Work continues to develop and analyze these technologies, looking for ways to lower costs.

Indeed, ongoing TEA research more robustly characterizes and accounts for aspects of the business environment. (T. R. Brown 2018) analyzed profitability for cellulosic biorefineries under a variety of policy regimes and price volatility, and found a suite of policies necessary to sustain a mature-industry cost plant, but not sufficient to cover pioneer plant costs. (Michailos and Bridgwater 2019), examining alternative upgrading pathways for pyrolysis biocrude to jet fuel, found policy support like RFS RINs and tax credits, along with other advances, would be needed to make investment attractive.

Research to uncover cost-cutting adjustments to the basic conversion technology continue, including exploring hybrid technologies or integrated processes. For example, combining fast pyrolysis with catalytic hydrodeoxygenation (HDO) in a single reactor may sidestep some technical issues with pyrolysis bio-oil upgrading (Dabros et al. 2018). Investigating costs for combining fast pyrolysis and bio-oil gasification found this integration insufficient to be cost competitive, unless perhaps for larger facilities (Q. Li, Zhang, and Hu 2015). Use of catalysts in fast pyrolysis for partial upgrading on-site is also being actively investigated, while still in early days (Perkins, Bhaskar, and Konarova 2018). Applying a systems-level perspective to cost evaluation, rather than a ground up component-by-component approach common to some TEAs, netted a 12.1% cost savings from a baseline case for a cellulosic biorefinery in another study (L. Li and Ge 2017)

Scrutinizing the full biorefinery output portfolio, that is, potential coproducts for biofuels or alternative products, is also an active area. A study comparing biofuels and other biochemical outputs for fast pyrolysis found higher, lower risk returns for the non-biofuels (Hu et al. 2016). Coproduct revenue was also seen as critical for a potential transition of the bioeconomy away from transport fuels as electrification proceeds (T. R. Brown and Brown 2017). Another study found slow pyrolysis to produce biochar could outcompete fast pyrolysis to biochar and biofuel pathways under a sufficiently high carbon price, illustrating how policy environment can shift production process viability (Frank et al. 2020). For forest residue to sugar pathways, another study found coproduct revenue is essential for any viable business case (Brandt et al. 2020).

Biorefinery siting decisions have also received scrutiny. Regional variation in feedstock cost and policy environment can generate considerable variation in realized costs, as found in a study for pyrolysis siting in U.S. states (T. R. Brown et al. 2013), with results that correlated with early plant cellulosic plant locations. Supply chain configurations are also being analyzed. A hybrid model using a central biorefinery for nearby corn stover supply, with depots to pelletize feedstock further afield could lower capital investment by $.80 or more (Kim et al. 2018). Optimization modeling involving both economics and GHG impacts can uncover different centralized or distributed processing models, depending on site- and feedstock-specific characteristics (You and Wang 2011; Y. Li, Brown, and Hu 2014; Witcover and Williams 2020).

The sensitivity of TEA results to these factors reflect the still-very-nascent nature of the sector. For this reason, considerable shake-ups in outlook are likely to occur, making projecting a likely technology, cost, and scale still highly uncertain. Current trends in analysis are promising however. They should reduce uncertainty by concentrating more on robust returns in the face of uncertain policies, potential additional cost-cutting for new technologies given what is known about processes involved, and potential revenue-raising through new coproducts or shifting product slates. As ever, a predictable and stable policy signal is required to attract investment. Additional policy schemes to support financing, like Green Banks, or Contracts for Difference (Pavlenko et al. 2016) that would support early pioneer plants and enhance cost-savings through learning and increased volume, provide a way forward. The existing market activity targeting alternative aviation fuel should be leveraged to promote exploration of which of the next generation of technologies from cellulose, waste or air carbon, and e-fuels, hold the most promise. Removing a persistent source of uncertainty—feedstock reliability—requires more systematic work on available volumes of feedstocks truly low in carbon. Given that waste or residue products will not suffice for the volumes needed, coming to an understanding of where and how land can be used to provide the most climate benefit, with biofuels or other bioenergy being a possible use, is urgent. This will require an approach that looks beyond biofuels and bioenergy—a land-based strategy.

5 Conclusions

Low carbon biofuels using cellulosic materials failed to materialize at commercial scale in the decade 2010-2020. Behind the failure was, among other factors, a decline in oil prices that made it more difficult for biofuels to become cost-competitive; persistent uncertainty about the magnitude and longevity of policy incentives that aimed to create demand "pull," especially from the U.S. RFS, but also for California's LCFS as it faced several legal cases; a challenging financing environment post-Great Recession; and a string technical and financial failures for pioneer cellulosic enterprise, which only made financing more difficult. The U.S. policy package pushed a "go big" rollout for cellulosic fuels. Cellulosic ethanol in particular was deemed technically ready for commercialization—that is, construction of larger scale stand-alone plants for which policy would ensure a market, meaning government funded R&D in effect ceased. The go-big approach precluded early recognition of technical barriers to commercial scale production not visible in smaller pilot and demo facilities, and logistical barriers such as feedstock sourcing and collection, which would require new contractual arrangements. The difficulties ended up hampering commissioning most of the handful of pioneer plants that made it to construction in the 2010s, and sidelining or significantly shifting business strategy in terms of location, product line, and/or conversion technology for others.

In mid-decade, the U.S. Department of Energy increased R&D resources focused on supply chain issues from the biomass through to deployment, and broadened the focus. from biofuels to biochemicals and other bioproducts; they followed market trends that recognized that high-volume relatively low value fuels did not provide a glide path to profitability. DoE retained its cost-competitive low carbon fuel goal and its estimate of long-run costs edged up due to expectation of higher capital and feedstock costs, informed by on-the-ground realities that faced pioneer facilities.

Policy incentives could have benefited any cellulosic fuels that showed up on the scene, but more actively encouraged a considerable expansion of conventional biofuels. Starch ethanol benefited, especially in the period from the passage of the RFS in 2007 to hitting the E10 blendwall. E15 expansion faced regulatory hurdles for supply, and E85 required infrastructure improvements that never materialized, as well as appropriate vehicles. The RFS and LCFS also incentivized more use of biomass-based diesel in the U.S. and California, respectively. Hydrotreated lipid-based renewable diesel use in California expanded rapidly. New facilities were able to open and existing ones to expand capacity at relatively low cost, marking renewable diesel as a key LCFS compliance fuel likely for some time to come. Incremental improvements in carbon intensity of conventional fuels under the LCFS, and contracts for biogas to fuel natural gas vehicles via book-and-claim under the LCFS and contributing to the RFS' cellulosic submandate also contribute to policy compliance at relatively low cost. In contrast, cellulosic liquid fuels, still not proven at commercial scale, require large initial capital investment hurdles, long time lags before production, and no proven track record. This translates into uncertainty about if and when policy credits might be earned and about their future value. The other low carbon fuels that emerged on the scene at lower cost than cellulosic liquid fuels left less policy "room" to generate a large-scale market pull/demand that could spark investment. Cellulosic ethanol from corn kernel fiber produced via bolt-on conversion technologies at existing corn ethanol plants started to commercialize, but uptake has not been rapid. Since 2016, increased uncertainty about RFS implementation and future mandates further undermined investment.

Perspectives on the next decade, from 2020 to 2030 for California may shed light on broader market conditions. Under a tightening LCFS as a driver for investment in low carbon fuels, most studies see a modest expansion of new cellulosic fuels as possible, but trends already in place as more potent pathways for future compliance—biomass-based diesel and electric vehicles, as well as biogas. Amendments in the LCFS program complement separate policies pushing more EVs and in-state biomethane, and in the past have opened new credit generating opportunities. Successful EV rollout or market uptake of new opportunities can translate into less renewable diesel, or indeed other biofuel, required.

Academic literature points to high costs as a continuing issue for nonconventional low carbon biofuels. Serious technical barriers remain for all considered pathways and most studies find few design set-ups, even for an nth plant, that can be viable without policy support. TEAs have grown more sophisticated since the early 2010s, incorporating more rigorous uncertainty analysis and policy incentives to glean likelihood of conditions meeting product breakeven prices. Coproducts, biorefinery location and configuration, as well as adjustments to the technologies themselves are all being considered in research investigating how to lower costs and make these fuels financially viable, while remaining low carbon. However, much of this work remains in the experimental phase, and winner(s) remain unclear after a decade. Indeed, the industry trends evolved toward focus on non-fuel bioproducts, perhaps including biofuels in the portfolio.

Alternative jet fuel provides a bright spot in terms of ongoing commercial activity. Volumes are and will be low for some time but the aviation sector has need for low carbon liquid hydrocarbons for a decarbonized future and various actors have shown interest, allowing some market pull to develop without a lot of explicit policy support thus far, beyond start-up funding and offtake by the military, and modest LCFS and RFS incentives. Technology breakthroughs for biojet could translate into lower cost on-road biofuels in the medium term. With the likely need for biofuels in aviation in the long run, technologies may also receive more policy support and remain focused toward jet fuel.

Current policy is not set up to ensure that feedstock is sourced to be truly low in carbon, even for cellulosic fuels. The existing policy framework looks likely to promote residue feedstock (residue oils for RD) use to the point that other end uses will be crowded out and need backfilling with other products and that crop-based oils might be used in greater quantity, both raising the specter of unintended consequences (land use conversion emissions and/or pressure on food prices). The draw is not only from California, but European markets as well. Higher credit prices will likely to uncover new sources of supply; to the extent they compete with the crops or lower-CI crops are used, the risk of iLUC declines. A more comprehensive understanding of lipid feedstock supply is needed in the nearest term.

Biofuels play and are foreseen as filling a more direct and outsized role in the decarbonization of transportation across vehicle sized in the short run, and for freight/heavy duty sectors that cannot be electrified, including aviation, in the long run. Information about the unexpected cost dynamics and slower industry emergence is thus of vital interest to policymakers and others seeking to understand the likely success (and cost) of incentive programs, and balance the options for biomass in transportation in a low-carbon future. Different conversion technologies for biofuels will vie for identical biomass sources. Likewise, liquid biofuels may compete with electricity and hydrogen for biomass. The land, moreover, may have other, more climate friendly uses. The biofuel/bioenergy climate discussion has still to be fully integrated into economywide carbon-lowering strategies, especially for the land sector. Assessments of biomass potential supply must be viewed through this lens.

A debate continues: whether bioenergy is limited to relying on waste and end-of-life materials, that cannot scale (Moriarty and Honnery 2019), or can be literally cultivated to enhance carbon profiles of soil while displacing petroleum products (Field et al. 2020), and if so, how to meet the challenge of incentivizing this behavior while lowering the risk of unintended consequences. Developing policy frameworks that provide these incentives and safeguards will ease one of the most persistent challenges to biofuel development and investment—uncertainty over feedstock supply. Other challenges—to technology development at cost, financing, and appropriate end uses—remain, but may be more amenable to existing policy solutions. None will be overcome rapidly, perhaps buying society the time to address the difficult and less familiar land use questions that require new groupings of actors to resolve.

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