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Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities

Greenhouse gas (GHG) emissions from transportation recently surpassed those of the electricity sector in the United States and are expected to increase 60% globally by 2050 if no new climate mitigation actions are taken.[1] Keeping global temperature increases from pre-industrial levels below 2°C will require reducing emissions by around 50% by 2050 and 70% in 2100 compared with a business-as-usual (BAU) scenario.[2] For the transport sector to meet these ambitious goals, every major transport mode—including all new cars, trucks, ships, and aviation—will have to nearly decarbonize within several decades.

While electric vehicles that consume renewable electricity are a promising option for reducing emissions in road transport, aviation is widely seen as the transport sector that is most difficult to decarbonize. Even with continued improvements in aircraft technology and operations efficiency, the aviation sector could emit up to 1.8 billion tonnes CO_2e annually by 2050, three times what it emits today.[3] Electrifying commercial aircraft does not appear feasible in the 2050 time frame, except for short

1 Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2014: Synthesis Report," Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2014). http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

2 Ibid.

3 International Civil Aviation Organization (ICAO), "On Board A Sustainable Future" (2016). https://www.icao.int/environmental-protection/Documents/ICAO Environmental Report 2016.pdf

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haul flights.[4] One option to dramatically reduce the remaining emissions within the aviation sector is through the use of low-carbon alternative fuels that have near-zero carbon emissions in their upstream production.

This briefing paper summarizes available science on low-carbon fuel availability and the progress and challenges to the commercialization of alternative aviation fuels, then charts a course to widespread deployment of low-carbon jet fuel by mid- to late century. We identify the most urgent roadblocks to the long-term decarbonization of the aviation sector. Based on these findings, we provide recommendations on policy priorities globally for the next five to 10 years.

BACKGROUND

Low-carbon jet fuel is an essential component of decarbonization within the broader transport sector, and the impact can be substantial provided it works within the prevailing constraints. A primary key constraint that is evident from the literature is that long-term growth in low-carbon aviation fuels must work within a competitive market for feedstocks. Deploying low-carbon fuels to the aviation sector delivers climate benefits only if it works in concert with—and does not compete with—carbon reductions in road, rail, and marine transport. Liquid alternative fuels, whether biofuels or renewable power-to-liquids, are resource-intensive and their global potential is limited. Biomass in particular is used in many sectors (e.g., biofuels, bioplastics, industrial power plants, district heating systems), but in fact most of this resource still has traditional uses (e.g., household fires for heat and cooking, building materials).

Competition for low-carbon fuel resources will continue among the transport, heat, power, and material sectors. We expect traditional biomass use to decline, but at the same time bioenergy demand is ramping up. Countries across the world are increasing biofuel mandates. Europe has been aggressively pursuing biomass for renewable heat and power, and manufacturing companies are increasingly turning to bioplastics and other advanced biomaterials. In fact, some cellulosic biofuel companies have pivoted to producing biomaterials because of improved economics.[5] For the next few decades, these other applications will compete with transport biofuels for the available biomass resources.

Within the transport sector, competition is likely to be especially fierce in the years ahead. Virtually all biofuels are used in the road sector today, and this is likely to continue as long as cars and trucks continue to use liquid fuels because it is more profitable to produce road biofuel than aviation biofuel (more detail on fuel production economics below). Even in one of the most ambitious vehicle electrification scenarios from the International Energy Agency (IEA), the road sector is still expected to consume enough liquid fuels in 2050 to utilize most sustainable biomass that could be available for transport.

4 Dale Hall, Nikita Pavlenko, Nic Lutsey, *Beyond road vehicles: Survey of zero-emission technology options across the transport sector* (ICCT: Washington DC, 2018).https://www.theicct.org/sites/default/files/publications/Beyond_Road_ZEV_Working_Paper_20180718.pdf

5 Kevin Bullis, "Amyris Gives Up Making Biofuels: Update," *MIT Technology Review*, Feb 10, 2012, https://www.technologyreview.com/s/426866/amyris-gives-up-making-biofuels-update/; "Harnessing the power of biomass," Sweetwater Energy, accessed Sept. 26, 2018, http://sweetwater.us/

Figure 1 shows our projection of the maximum amount of low-carbon biomass that could be supplied for various uses in 2050 and how it is likely to be divided among uses, assuming aggressive vehicle electrification. For context, current global oil production is nearly 100 million barrels per day. The figure shows that demand in heat and power, plastics, and road vehicles is likely to draw the majority (83%) of available sustainable biomass, with only around 9% likely to be delivered to the aviation sector. This is mainly due to economics: It is less expensive to replace fossil fuels with biomass in other sectors than in aviation. Realistically, there may not be enough low-carbon bioenergy available to significantly decarbonize aviation fuel until well beyond 2050, unless road electrification far surpasses expectations and the stationary heat and power sectors also transition entirely to other low-carbon renewables such as solar, wind, and geothermal.

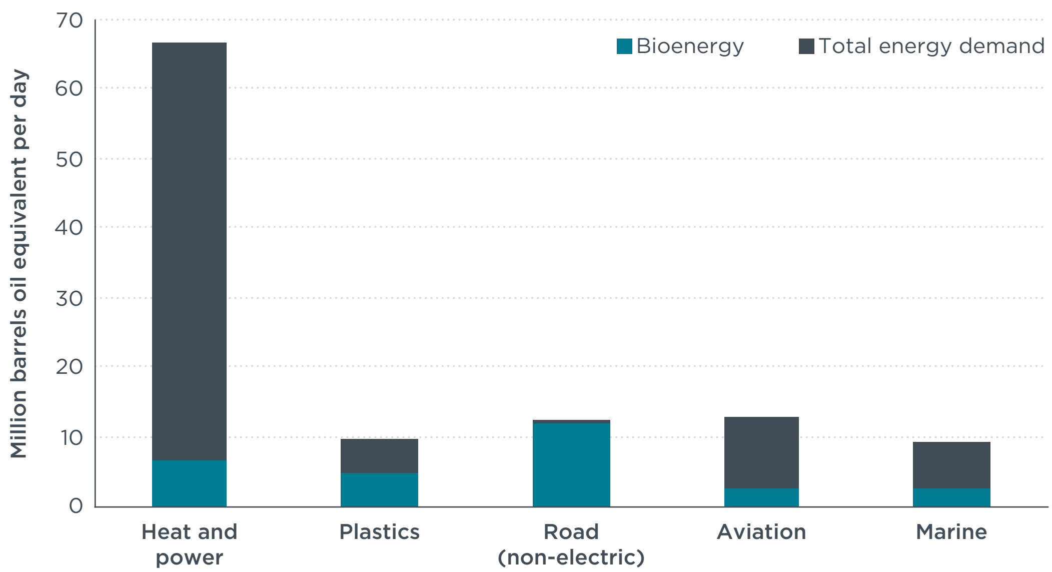

Figure 1. Maximum global low-carbon biomass supply for energy and plastic uses and projected bioenergy demand across sectors compared with total energy demand in 2050[6]

Beyond availability and competition constraints, bioenergy must be produced from low-carbon sources or no carbon gains will be achieved. Most biofuels (largely produced from food crops including grains, sugars, and vegetable oils) and biomass used in heat and power (wood) are strongly linked to land use change (the conversion of natural land to agriculture to supply growing demand for food and feed commodities). The resulting emissions substantially reduce, and in some cases even reverse,[7] the climate benefits of using these fuels instead of petroleum. Waste fats and oils such as tallow and used cooking oil can also indirectly cause land use change when used for biofuel if they are diverted from existing uses in livestock feed, soaps, and chemicals. It is thus not possible to decarbonize jet fuel using today's feedstocks.

6 Stephanie Searle, "Bioenergy can solve some of our climate problems, but not all of them at once," ICCT blog, Oct. 15, 2018, https://www.theicct.org/blog/staff/bioenergy-solve-some-climate-problems-not-all-once

7 For example, Hugo Valin, Daan Peters, Maarten van den Berg, Stefan Frank, Petr Havlik, Nicklas Forsell, & Carlo Hamelinck, *The land use change impact of biofuels consumed in the EU*: *Quantification of area and greenhouse gas impacts*, (Ecofys: Utrect, 2015) https://ec.europa.eu/energy/sites/ener/files/documents/Final Report_GLOBIOM_publication.pdf

Yet there is a substantial opportunity for greatly increased production of sustainable, low-carbon biomass-derived fuels for the transport sector. Low-carbon biofuel feedstocks with low land use change risk include cellulosic energy crops (e.g., switchgrass, Miscanthus, poplar) grown on unused land,[8] landfill-destined waste, and sustainably harvested crop and forestry residues (e.g., corn stover and small branches from logging).[9] Drop-in jet fuel produced from these feedstocks in advanced fuel conversion processes such as gasification and cellulosic alcohol-to-jet can deliver 80% to 90% reductions in fuel carbon intensity, and their production could be greatly increased in the upcoming decades.

Based on the above background on bioenergy limitations and trends in energy demand across sectors, we draw several conclusions. First, any long-term approach to decarbonizing jet fuel must involve both reducing liquid fuel demand across all sectors and transitioning to and ramping up a global sustainable biofuel industry. This means that it is critical to reduce aviation fuel demand using maximum feasible efficiency technology and best operational practices. Second, it is essential to carefully identify and promote feedstocks with low land-use impacts and high lifecycle GHG reductions based on the best available science. Third, it is necessary to understand the limitations in sustainable biomass supply globally and to the aviation sector in particular.

PROGRESS IN LOW-CARBON JET FUEL PRODUCTION

In 2018, we are in the very early days on the path to jet fuel decarbonization. A small handful of alternative jet fuel projects were announced between 2014 and 2018, and only one facility in the United States (AltAir in California) has produced significant volumes of alternative jet fuel that have been used in aircraft.[10] Most existing alternative jet fuel capacity is for hydro-processed esters and fatty acids (HEFA), using a mature technology that can only utilize oil and fat feedstocks. HEFA production relies on either virgin vegetable oils with high land-use change emissions or used cooking oil and waste fats. The waste fats supply globally is limited, leaving little room for future sustainable growth.

Technologies to convert the most sustainable feedstocks (cellulosic biomass, municipal solid waste, and renewable electricity) are still emerging. Two projects currently under construction, Fulcrum Bioenergy[11] and Red Rock Biofuels,[12] are planning to produce alternative jet fuel from municipal solid waste and forestry residues, respectively, using advanced technologies. Fulcrum Bioenergy and Red Rock Biofuels both gasify solid waste into syngas and then use the Fischer-Tropsch process to turn the syngas into liquid fuels. Syngas can also be fermented into liquid fuels, a technology pioneered by the company LanzaTech.[13]Although a promising technology, no large-scale gasification

8 Stephanie Searle, *Sustainability challenges of lignocellulosic bioenergy crops* (ICCT: Washington DC, 2018). https://www.theicct.org/sites/default/files/publications/Energy_Crop_Sustainability_briefing_20180226.pdf

9 Stephanie Searle, Chris Malins, *Availability of cellulosic wastes and residues in the EU* (ICCT: Washington DC, 2013). https://www.theicct.org/sites/default/files/publications/ICCT_EUcellulosic-waste-residues_20131022.pdf

10 Anastasia Kharina, "Will slow and steady win the race for alternative jet fuels?," ICCT blog, Oct. 9, 2018, https://www.theicct.org/blog/staff/will-slow-and-steady-win-race-alternative-jet-fuels

11 "Overview," Fulcrum Bioenergy, accessed Sept. 26, 2018, http://fulcrum-bioenergy.com/technology/

12 "Process Technology Platform," Red Rock Biofuels, accessed Sept. 26, 2018, https://www.redrockbio.com/technology.html

13 "Technical Overview," LanzaTech, accessed Nov. 2, 2018, http://www.lanzatech.com/innovation/technical-overview/

facilities have been built. This is the kind of technology needed for decarbonizing significant volumes of jet fuel.

Other advanced technologies that can process sustainable feedstocks are further from commercialization. Alcohol-to-jet (ATJ) pathways can convert cellulosic ethanol or other alcohols into drop-in jet fuel, but no companies have proposed commercial-scale cellulosic ATJ. Fast pyrolysis, another advanced biofuel technology, is not currently being pursued following a high-profile industry failure. Power-to-liquids is another promising technology that combines renewable hydrogen with CO_2 to produce drop-in liquid fuels. At present, costs are likely to be prohibitive for this technology, and using it risks indirectly increasing near-term fossil fuel use if renewable electricity is diverted from other uses.[14]

Importantly, most alternative jet fuel produced or in the pipeline today comes as a co-product of road fuel production. Hydroprocessing (used for HEFA) and Fischer-Tropsch synthesis both generate a product slate of various fuel types, similar to the way a conventional oil refinery produces an assortment of gasoline, diesel, kerosene, and other petroleum products. Alternative fuel refining processes generally produce the largest fraction of diesel or gasoline with smaller amounts of kerosene and "light ends" such as propane. Figure 2 shows the product slate for a few advanced fuel technologies. ATJ and a novel technology, synthesized isoparaffins (SIP), can produce mostly or entirely jet fuel, but hydroprocessing and Fischer-Tropsch synthesis generally produce mostly road fuel with only a small jet fuel component. These latter two technologies are mostly kept afloat through road fuel sales and policy incentives. The small amount of progress that has been made on sustainable jet fuels is thus heavily dependent on demand for road biofuels.

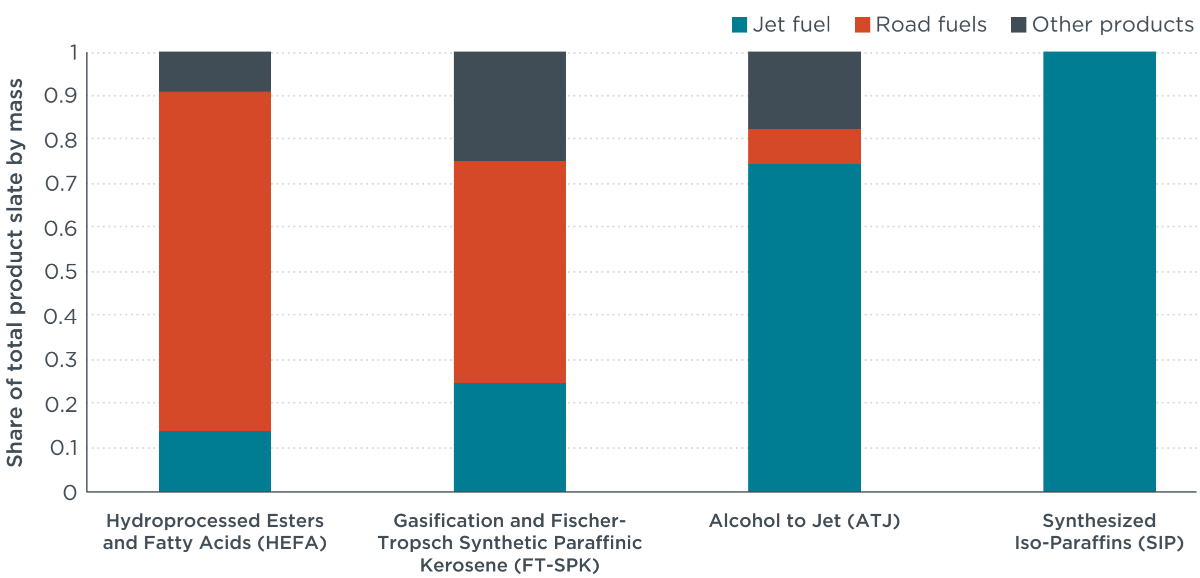

Figure 2. Product slates for four alternative jet fuel production pathways

14 Stephanie Searle, Adam Christensen, *Decarbonization potential of electrofuels in the European Union*, (ICCT: Washington, DC, 2018), https://www.theicct.org/publications/decarbonization-potential-electrofuels-eu

BARRIERS TO ADVANCED JET FUEL COMMERCIALIZATION

Although some progress has been made in alternative jet fuels, significant challenges remain for deep decarbonization of the sector. The bottleneck is not just in commercializing advanced fuel conversion processes; there are barriers up and down the alternative fuel production chain, from feedstock supply to fuel conversion, upgrading, blending, and delivery. In this section, we review the progress and remaining hurdles at each step.

Feedstock supply: There is high potential availability of sustainable feedstock, but there are barriers to its collection. Municipal solid waste, one of the most sustainable feedstocks, already has collection systems in place and is readily available for biofuel producers. Other major cellulosic waste and residues, including crop and forestry residues, often do not have mature supply chains in place. Crop and forestry residues must be harvested carefully to avoid loss of soil carbon and health, and farmers are sometimes resistant to selling any crop residues for fear of harming the next year's crop.[15] In some places, there is not enough time to harvest crop residues before planting the next crop.[16] In addition, these feedstocks are often contaminated with soil and are bulky and difficult to transport and store.[17] Most of the potential future production of sustainable biomass would come from cellulosic energy crops,[18] but this pathway has additional challenges. Establishing energy crop plantations requires large upfront investments that take several years to recoup. There is a chicken-and-egg problem: Farmers are unwilling to invest in energy crops without a mature cellulosic biofuel industry to buy them, and cellulosic biofuel producers cannot scale up without feedstock supply chains in place. For example, Biochemtex planned to run a cellulosic ethanol facility in Sardinia on locally grown energy crops,[19] which never materialized; the Sardinia facility later closed down. Once these challenges are overcome, sustainable cellulosic biomass could potentially be available in large quantities.

Power-to-liquids are not subject to these same constraints because they can be produced from wind, solar, and geothermal power rather than biomass. Power-to-liquids production can, however, compete with other uses of these renewables and will only offer strong net GHG benefits if produced from additional renewable power.

Fuel conversion technologies: Although several advanced alternative fuel technologies have been demonstrated successfully, technological problems still limit cost-effectiveness and throughput at larger facilities. There are challenges in grinding biomass before conversion: It is often contaminated with rocks and dirt that damage grinding blades and slow production. In gasification, tar buildup and corrosion

15 Toby Townsend et al., "Wheat straw availability for bioenergy in England," *Ener. Policy* 122: 349-357 doi: 10.1016/j.enpol.2018.07.053

16 Stephanie Searle, "The hardest part of cellulosic biofuels in India might be collecting the rice straw," ICCT blog, Oct. 11, 2018, https://www.theicct.org/blog/staff/hardest-part-cellulosic-biofuels-india-might-be-collecting-rice-straw

17 Chelsea Petrenko, "Short-term barriers to energy cropping," ICCT blog, Nov. 8, 2018, https://www.theicct.org/blog/staff/short-term-barriers-energy-cropping

18 Stephanie Searle et al., "A reassessment of global bioenergy potential in 2050," *Glob. Change Biol. Bioenergy*, 2014, 7(2): 328-336 doi: 10.1111/gcbb.12141

19 Stephanie Searle, Chelsea Petrenko, Ella Baz, Chris Malins, *Crops of the Biofrontier: in search of opportunities for sustainable energy cropping* (ICCT: Washington DC, 2016), https://www.theicct.org/sites/default/files/publications/Energy Crop White Paper vF.pdf

increase maintenance demands. Syngas fermentation has to halt if there is bacterial contamination. Achieving successful product yields has also been difficult. For example, KiOR, a pyrolysis company, never produced more than one-third of its target yields before filing for bankruptcy.[20] These processes also do not always produce finished fuels and instead require further upgrading, which adds complexity and cost.

The largest barrier to advanced alternative fuel technologies is economics. Cellulosic biofuel costs can range from around $4.50 per gasoline-equivalent gallon for small bolt-on corn kernel fiber ethanol facilities to $8.50 per gasoline-equivalent gallon for large gasification Fischer-Tropsch facilities using agricultural residues,[21] compared with typical wholesale kerosene prices of $1.50 to $3.00 per gallon in the United States.[22] Costs for first-of-a-kind facilities can be even higher. Design and construction of a first plant can take three or four years, and ramping up to full production can take five years or more, especially if a plant encounters the kinds of technological problems reviewed above.[23] These delays increase the average cost of producing each gallon for the time that a facility is operating. Design of a first-of-a-kind plant is also not always efficient and can cost 25% more than future plants.[24]

It is possible for advanced alternative fuel facilities to reduce costs with time. For most advanced alternative fuel production systems using wastes, residues, or energy crops, up to 70% of the levelized costs come from the upfront costs for equipment and facility construction, which can be reduced over time through technology learning.[25] For these kinds of technologies, some studies estimate costs can decline by 40% from pioneer plants to a mature industry.[26] In contrast, approximately 65% of levelized HEFA costs are the feedstock,[27] and these costs are unlikely to come down over time.[28] At present, the high and uncertain costs of first-of-a-kind plants for advanced technologies compared with HEFA are deterring investment. As the advanced fuel industry develops and costs come down, these technologies will likely be seen as more promising.

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20 Jim Lane, "KiOR: The Inside True Story of a Company Gone Wrong. Part 4, the Year of Living Disingenuously," *Biofuels Digest*, Sept. 18, 2016, https://www.biofuelsdigest.com/bdigest/2016/09/18/kior-the-inside-true-story-of-a-company-gone-wrong-part-4-the-year-of-living-disingenuously/

21 Nikita Pavlenko, Stephanie Searle, Brett Nelson, *A comparison of contracts for difference versus traditional financing schemes to support ultralow-carbon fuel production in California* (ICCT: Washington DC, 2017). https://www.theicct.org/sites/default/files/publications/CfD-Cost-Benefit-Report_ICCT_Working-Paper_vF_23012017.pdf

22 U.S. Energy Information Administration, "Data 1: U.S. Kerosene Wholesale/Resale Price by Refiners (Dollars per Gallon)," Spreadsheet (2018). https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMA_EPPK_PWG_NUS_DPG&f=M

23 Nik Pavlenko, "Failure to Launch: Why Advanced Biorefineries Are So Slow to Ramp Up Production," ICCT blog, Nov. 13, 2018, https://www.theicct.org/blog/staff/failure-to-launch-biorefineries-slow-ramp-up

24 U.S. Government Accountability Office, "Renewable Fuel Standard: Low Expected Production Volumes Make It Unlikely That Advanced Biofuels Can Meet Increasing Targets," Report to the Chairman, Subcommittee on Regulatory Affairs and Federal Management, Committee on Homeland Security and Government Affairs, U.S. Senate (2016). https://www.gao.gov/assets/690/681256.pdf

25 Nikita Pavlenko, *Assessing the Costs of Policy Support for Alternative Aviation Fuels* (ICCT: Washington DC, in press)

26 Ryan Swanson, Justinus Satrio, Robert Brown, *Techno-Economic Analysis of Biofuels Production Based on Gasification* (NREL: Goulden CO, 2010), https://www.nrel.gov/docs/fy11osti/46587.pdf

27 Nikita Pavlenko, *Assessing the Costs of Policy Support for Alternative Aviation Fuels* (ICCT: Washington DC, in press)

28 OECD/FAO, "OECD-FAO Agricultural Outlook 2015" (2015). https://doi.org/10.1787/agr_outlook-2015-en

Upgrading to drop-in jet fuel: Technology upgrades have been successfully demonstrated at small scale, and generally there are fewer technological challenges in this step compared with fuel conversion. The main challenge is added cost in maximizing the fraction of jet fuel produced. Hydroprocessing of fats and oils generally produces 10% to 15% HEFA jet fuel, although producers can also blend some of the road fraction from this process in jet fuel at low blend rates.[29] The HEFA fraction from hydroprocessing can be increased to 50%, but tilting the product slate toward jet fuel comes at a cost, adding up to 30 cents per gallon.[30] For cellulosic ethanol, it costs 25% more to upgrade to drop-in jet fuel compared with blending the ethanol in road gasoline.[31] In general, maximizing jet fuel production is feasible but somewhat costly.

Fuel blending and delivery to aircraft: Certification can be a hurdle for novel fuels, but this barrier is shrinking. Alternative fuels must be certified by ASTM, an international body, before they can be sold commercially. Only a handful of jet fuels have received this certification. One major barrier is that ASTM requires up to 235,000 gallons of new jet fuels to be tested, and it can be difficult for a new company to produce this much fuel. After considerable investment in testing by the U.S. Department of Defense, it is now getting easier for new producers to get certified. Less testing is required for new fuel types that are similar to already approved fuels.

Figure 3 shows the maximum amount of alternative jet fuel required by ASTM for certification depending on its similarity to already approved pathways. As shown in the chart, producers of new type fuels are required to test 235,110 gallons, compared with 10,110 gallons for fuels that are "similar" and just 110 gallons for fuels that are "very similar" to already approved pathways. This means that the more fuel types that have been approved, the easier it is for a wider variety of companies using slightly different technologies and feedstocks to attain certification. For example, LanzaTech had to undergo two of four ASTM testing rounds on its ATJ pathway, requiring only 110 gallons[32] because its product is very similar to an ATJ pathway already certified for Gevo.[33] The certification barrier will continue to be reduced as more fuel types are approved.

29 https://www.theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCT-Working-Paper_20180321_vF.pdf

30 Nik Pavlenko, "Can alternative jet fuels crowd out demand from the road sector?," ICCT blog, Oct. 24, 2018, https://www.theicct.org/blog/staff/can-alternative-jet-fuels-crowd-out-demand-road-sector

31 Tao, L., Markham, J.N., Haq, Z., and Biddy, M.J. (2017). Techno-Economic Analysis for Upgrading the Biomass-Derived Ethanol-to-Jet Blendstocks. Green Chemistry. DOI: 10.1039/c6gc02800d

32 LanzaTech, "Flying a Carbon Smart Future," (2017), https://www.iata.org/events/Documents/afs-2017/AFS17-Session2-Jennifer-Holmgren-Lanzatech.pdf

33 "Gevo's Alcohol to Jet Fuel Meets Approved ASTM Standard," Gevo News Release, accessed Sept. 27, 2018, http://ir.gevo.com/news-releases/news-release-details/gevos-alcohol-jet-fuel-meets-approved-astm-standard?field_nir_news_date_value[min]=

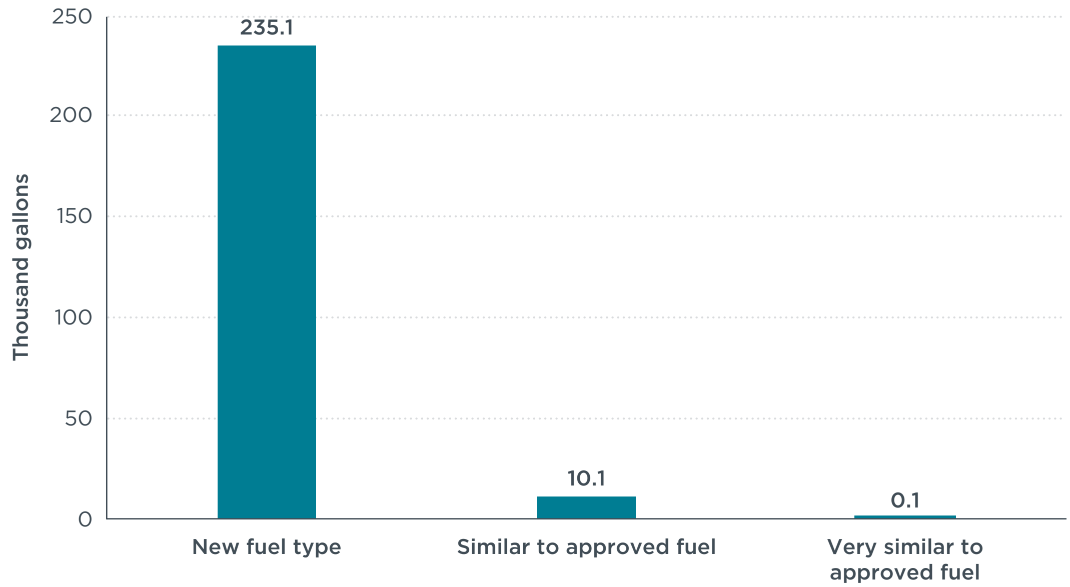

Figure 3. Maximum alternative fuel volumes required for ASTM certification for new fuel types and fuels that are similar to already certified fuels.[34]

Once fuel has been produced and certified, blending it and burning it in aircraft are relatively straightforward steps. Certified jet fuels can be blended in conventional jet fuel at levels up to 50%. The blended fuel is then distributed from the airport's fuel farm to all aircraft at the airport. When United Airlines first started using blended HEFA fuel from AltAir at Los Angeles International Airport, the company delivered the fuel directly to its aircraft via tanker truck at the request of other airlines. After a two-week demonstration period, these airlines accepted the supply of blended fuel from the airport's central fuel farm. In cases like this, the airline took initiative in supplying alternative fuel, but in others, airports have played the lead role. Seattle-Tacoma International Airport forged a partnership with 13 airlines operating at the airport in support of blending alternative fuel, while Geneva airport is contracting directly from an alternative fuel producer. The situation at each airport is different, and each case of alternative fuel supply will have kinks to work out. In the few examples witnessed to date, however, these challenges were easily solved.[35]

Table 1 summarizes the progress and challenges discussed above in producing and delivering low-carbon fuel to the aviation sector. While challenges exist at every step, the bottleneck is in the earlier stages of this process: from feedstock supply to upgrading. Cost, technology development, and logistical problems limit the current production of low-carbon advanced fuel. On the other hand, supplying and using this fuel in aircraft is relatively easy. The steps most in need of policy support are early in the process.

34 Data from Commercial Aviation Alternative Fuels Initiative. (2013). "ASTM D4054 Users' Guide." Retrieved from http://www.caafi.org/information/pdf/d4054_users_guide_v6_2.pdf

35 Anastasia Kharina, "Kinks in the pipeline: a survey of downstream alternative jet fuels challenges," ICCT blog, Oct. 31, 2018, https://www.theicct.org/blog/staff/kinks-pipeline-survey-downstream-alternative-jet-fuels-challenges

Table 1 Summary of progress and challenges in delivering and using advanced low-carbon fuel in the aviation sector, by step in process

Step in jet fuel decarbonization	Current status	Remaining challenges	Overall status
Feedstock supply	• Municipal solid waste already collected • Some crop residue supply available • No energy crops available • Additional renewable electricity for power-to-liquids possible	• Crop residue harvest logistics in challenging regions • Develop energy crop plantations and supply chains	• Very early commercial
Feedstock preparation	• Small amounts of cellulosic feedstock processed	• Contamination with rocks, etc. • High cost	• Very early commercial
Fuel conversion	• Technology demonstrated at small scale	• High cost • High perceived investment risk • Challenges specific to each technology	• Early commercial
Upgrading to drop-in jet fuel	• Technology demonstrated at small scale	• Added cost	• Early commercial
Fuel blending	• Successfully demonstrated	• Logistics to solve at each airport	• Commercially ready
Delivery and use in aircraft	• Successfully demonstrated	• Logistics to solve at each airport	• Commercially ready

TOWARD A LONG-TERM POLICY STRATEGY FOR ALTERNATIVE JET FUEL

While low-carbon jet fuel may be necessary in the long term to decarbonize a challenging sector, our assessment shows that the most promising near-term steps might be to support advanced fuel technologies primarily for the road sector. The most urgent priorities for developing sustainable low-carbon jet fuel are to develop feedstock supply chains and commercialize the advanced fuel industry. These challenges are common to both road and jet fuel. As long as there is still demand for liquid fuel in the road sector, the climate benefits of low-carbon fuel are the same whether that fuel is used in the road or aviation sectors. We find few barriers to upgrading and delivering low-carbon road fuel to aircraft, which means that low-carbon road fuel supply chains established now can easily be adapted to deliver to aircraft at a future time.

Prioritizing low-carbon fuel use in aviation in the near term might actually be counterproductive for long-term policy goals. For some technologies, such as Fischer-Tropsch synthesis, tilting the advanced fuel product slate toward jet fuel is costly and inefficient. Similarly, upgrading cellulosic ethanol to jet fuel significantly increases the cost of fuel production. Given that production cost is one of the most limiting factors, directing low-carbon fuel to the aviation sector could increase costs and slow commercialization of advanced technologies. It is most economical for advanced fuel producers to continue supplying the majority of their products to the road sector. Thus, policies that promote the use of low-carbon fuel regardless of end-use sector will be most effective at developing the advanced fuel industry, and in turn setting this industry on the path to decarbonize a greater share of jet fuel in the long term. If and when liquid fuel demand in the road sector is greatly reduced, shifting the product slate at existing biorefineries or upgrading cellulosic ethanol can increase the throughput of jet fuel at that time.

Based on the assessment above on prevailing barriers, Figure 4 illustrates an approach that recognizes the necessary near-term and long-term actions to decarbonize jet fuel. As illustrated, there are many developments needed and they span several sectors. As a primary step, the advanced fuel industry needs to massively ramp up. Concurrently, there needs to be a transition from using first-generation feedstocks to utilizing waste, sustainable cellulosic biomass, and renewable power-to-liquids for the fuel pathways that are more sustainable, have minimal land use effects, and demonstrably reduce lifecycle carbon intensity by at least 50%. In the medium term, advanced fuel industry growth will be maximized if fuel is supplied mainly to the road sector, with advanced jet fuel as a co-product. Changes in aircraft and vehicle technology are necessary to reduce liquid fuel demand growth in aviation and eliminate all liquid fuel demand in the road sector. In the longer term, as liquid fuel demand in road evaporates, existing biorefineries can adjust their processes to supply mostly or entirely jet fuel. Some conversion processes already do this, and it is possible that others could be adjusted to produce mostly jet fuel with future technological progress. Having enough sustainable biomass available to decarbonize future jet fuel supply also requires a phaseout of biomass in heat and power generation, transitioning those sectors to using only other renewables, such as wind, solar, and geothermal, and reserving the entire sustainable biomass resource for the transportation sector.[36] Such a drastic shift in the use of biomass, especially given strong political support for biomass heat and power in Europe, may not be easy, even in the 2050 time frame.

36 Stephanie Searle, "Decarbonizing aviation through low-carbon fuels will be beyond difficult," ICCT blog, Nov. 15, 2018, https://www.theicct.org/blog/staff/decarbonizing-aviation-through-low-carbon-fuels-will-be-beyond-difficult

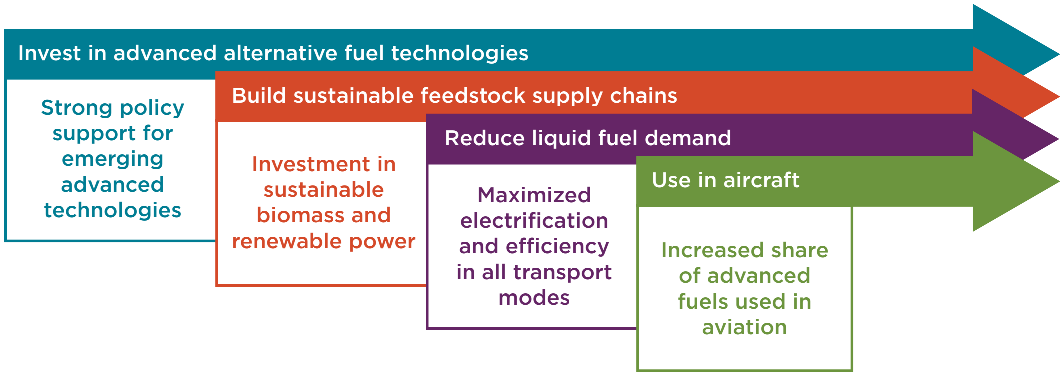

Figure 4. Timeline of developments necessary for decarbonization of aviation fuel

None of these changes will be easy to make, and all of them require time. In the road sector, the IEA argues that a rapid increase in electric vehicle sales beyond current rates is needed to achieve a scenario with mostly electric and hybrid new sales by 2050.[37] The advanced fuel industry has ramped up much more slowly than electric vehicles: At the current annual growth rate, cellulosic biofuel would still supply less than 0.1% of total U.S. transport energy demand in 2050.[38] Growth of this industry is constrained by practical limits, as production and ramp-up of first-of-a-kind plants can take nearly 10 years.[39] Companies typically wait to realize gains on a pioneer plant before commissioning a second; if a new company starts a project in 2020, it may be 2035 or 2040 before its second facility is operating at full capacity. The pace of new project announcements is not nearly fast enough to put us on a path to decarbonizing a significant fraction of jet fuel demand by 2050. Deep decarbonization of the transport sector in the 2050 time frame requires major changes to policy in the near term, in particular to more strongly support the commercialization of advanced low-carbon fuel technologies for use in any sector.

NEAR-TERM POLICY OPPORTUNITIES

EFFECTIVE POLICY DESIGN FOR PROMOTING LOW-CARBON JET FUEL

Strong policy support for advanced fuel technologies is needed to enable a significant shift from petroleum-based fuels to sustainable, low-carbon alternatives in the mid-century time frame. These types of policies can include mandates, fiscal incentives, and grant programs, and will be most effective if they are offered to all fuel types.

Direct fuel mandates for the aviation sector have been discussed. While such mandates seem an intuitive solution, they would actually be counterproductive. Near-term

37 John Dulac, *Global transport outlook to 2050: Targets and scenarios for a low-carbon transport sector*, (IEA: 2013). https://www.iea.org/media/workshops/2013/egrdmobility/DULAC_23052013.pdf

38 Calculated as a linear regression from annual cellulosic biofuel volumes used for RFS compliance in 2016 and 2017 from "Public Data for the Renewable Fuel Standard," U.S. Environmental Protection Agency, accessed Sept 27, 2018, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard; Forecasted 2050 U.S. transport energy demand from U.S. Energy Information Administration, "Annual Energy Outlook 2018 with projections to 2050" (2018). https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

39 Nik Pavlenko, "Failure to Launch: Why Advanced Biorefineries Are So Slow to Ramp Up Production," ICCT blog, Nov. 13, 2018, https://www.theicct.org/blog/staff/failure-to-launch-biorefineries-slow-ramp-up

alternative aviation fuel mandates would very likely be met using the most commercially ready jet fuel technology—HEFA—and the further growth of this technology cannot be supported using low-carbon feedstocks. Experiences with alternative fuel policies in the European Union and United States, such as the Renewable Energy Directive and the Renewable Fuel Standard (RFS), respectively, have demonstrated the tension between achieving high alternative fuel volumes and sustainability goals. These policies have overwhelmingly been met with inexpensive, readily available food-based biofuels linked to land use change. Long-term high penetration of sustainable, low-carbon jet fuel requires immediate and strong policy support specifically for advanced technologies that can process sustainable feedstocks.

There are a wide variety of regulatory and financial support policies that can support advanced biofuels, but not all are effective. Very strong policy support (equivalent to up to $5 per gasoline-equivalent gallon in recent years) has been available for cellulosic ethanol in the United States, but industry development has still been excruciatingly slow. The same kinds of policy mechanisms that have successfully grown a first-generation biofuels industry (blending mandates, short-term tax credits) are ineffective for supporting advanced technologies. Because advanced fuel facilities have high upfront capital expenses, much greater policy certainty is needed to reduce investment risk. Our research has found that government capital grants, which provide high certainty in the amount of policy support delivered, are more effective at supporting cellulosic biofuel projects per dollar spent compared with per gallon subsidies.[40] Government grant programs also appear to have been more effective at supporting successful cellulosic biofuel facilities in the United States than the cellulosic biofuel mandate in the RFS.[41] The most important policy elements to support investor certainty are dedicated incentives for advanced fuels with a clear, predictable value to producers.[42] One policy proposal that would provide high investor certainty is a contract for difference (CFD) program that would set a guaranteed price floor for advanced fuel producers. When conventional fuel prices or the value of existing government incentives (e.g., the value of RFS support) changes, the government subsidy adjusts to maintain the same profit margin for advanced fuel producers. A reverse auction can be used to establish the lowest tolerable price floor for more efficient advanced fuel producers, minimizing government spending.

Although we do not recommend near-term mandates for aviation biofuels specifically, support for fuels used in both the road and aviation sectors is important for supporting advanced technology commercialization. This will ensure that advanced fuel producers generating a product slate can receive full support for all products they supply. California Air Resources Board has only recently proposed allowing alternative jet fuels to participate in the Low Carbon Fuel Standard (LCFS), and most European Union member states do not include any support for alternative jet fuels. For producers using Fischer-Tropsch or hydroprocessing technologies, generation of jet fuel, as well as other co-products such as propane, is unavoidable. Policies that only promote gasoline

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40 Nikita Pavlenko, Stephanie Searle, Brett Nelson, *A comparison of contracts for difference versus traditional financing schemes to support ultralow-carbon fuel production in California* (ICCT: Washington DC, 2017). https://www.theicct.org/sites/default/files/publications/CfD-Cost-Benefit-Report_ICCT_Working-Paper_vF_23012017.pdf

41 Chelsea Petrenko, "Is the Renewable Fuel Standard enough to spur progress in advanced biofuels? Probably not.," ICCT blog, Oct. 18, 2018, https://www.theicct.org/blog/staff/renewable-fuel-standard-enough-spur-progress-advanced-biofuels-probably-not

42 Kristine Bitnere, Stephanie Searle, *Effective policy design for promoting investment in advanced alternative fuels* (ICCT: Washington DC, 2017). https://www.theicct.org/sites/default/files/publications/Advanced-alternative-fuels_ICCT-white-paper_21092017_vF.pdf

and diesel substitutes do not support these producers' full product slates. Designing advanced fuel policies to include jet fuel as well as lighter products such as propane is important to effectively support newer technologies.

Policies that do promote jet fuel generally do so by allowing these fuels to "opt in" to road fuel mandates. Road fuel suppliers are obligated to blend certain amounts of renewable or low-carbon fuel and to submit a certain number of credits each year to demonstrate compliance with that obligation. Jet fuel suppliers, on the other hand, carry no obligation, and any low-carbon fuel they choose to blend in the aviation sector generates credits that can be sold to road fuel suppliers. This design arguably constitutes a wealth transfer from road users to aviation users, as road fuel suppliers are paying jet fuel suppliers for their use of low-carbon fuel. In the near-term, any distortion on overall transport costs caused by opt-in provisions is unlikely to be felt by consumers because the volumes of alternative jet fuel supported will be low compared with the amount of road fuel that is mandated. In the longer term, as a greater share of low-carbon fuel is used in the aviation sector, obligating aviation fuel suppliers would more evenly distribute the costs of complying with mandates. For policies other than mandates, such as government grants or CFD programs, low-carbon jet fuel should simply be eligible alongside road fuel.

In the near to medium term, it will also be important for governments to directly support sustainable feedstock supply chains. Similar to investors in advanced fuel facilities, farmers need certainty to make upfront investments in establishing energy crop plantations. Programs such as long-term government procurement contracts can help bridge that uncertainty gap until strong feedstock demand is clearly established by the cellulosic biofuel industry.

Beyond the next five years, more aggressive policy changes will be necessary to accelerate the advanced low-carbon fuels industry. The opportunities listed above represent important first steps in growing this industry. Because it will likely take a long time to fully ramp up the advanced fuels industry to displace a high share of liquid fuel demand, stronger incentives than those under consideration by progressive countries now will be needed in the 10 to 15 year time frame.

REGIONS TO FOCUS ON IN THE NEXT FIVE YEARS

Based on our understanding of the issues and opportunities above, and our understanding of applicable policy venues to accelerate the decarbonization of jet fuels, we see at least six key venues to focus on for policy developments in the next five years. These are jurisdictions that have or are developing policy frameworks that specifically support advanced low-carbon fuel conversion technologies using non-food feedstocks. These include key regional, national, and subnational governments where there is clear ability to overcome many of the barriers identified above and capitalize on the policy and technology developments already in motion there.

Global: The International Civil Aviation Organization is introducing support for alternative fuels by including them as an eligible pathway in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). However, this policy is unlikely to be an effective incentive for alternative fuels, since it will be much less expensive for airlines to comply with CORSIA using carbon offsets.[43] Robust policy support for

43 Nikita Pavlenko, "ICAO's CORSIA scheme provides a weak nudge for in-sector carbon reductions," ICCT blog, Aug. 6, 2018, https://www.theicct.org/blog/staff/corsia-carbon-offsets-and-alternative-fuel

low-carbon jet fuel is more likely to come from the national level than a global forum. In the remainder of this section, we present recommendations on policy opportunities for supporting long-term jet fuel decarbonization in some of the most progressive countries in terms of fuel policies.

United States: Increase federal grant spending on advanced fuel projects through the Department of Energy (DOE) and the U.S. Department of Agriculture. DOE grants in particular have been instrumental in supporting many active cellulosic biofuel projects in the United States.[44] The RFS has not been a very effective driver for investment in cellulosic biofuels due to political and policy uncertainty. There are no major opportunities for improving support of the RFS program for advanced fuels unless very progressive options are considered in a revision bill by Congress.

California: Implement opt-in provision for jet fuels in the LCFS and introduce direct fiscal support for advanced low-carbon fuels. The LCFS has not promoted significant volumes of cellulosic or other advanced fuels because the mandate can be met using less risky first-generation technologies. California is considering introducing a CFD program for dairy biogas, a very low-carbon first generation pathway.[45] This model could be applied to advanced fuel projects.

United Kingdom: Support strong implementation of the Renewable Transport Fuel Obligation (RTFO). The United Kingdom recently introduced an opt-in provision for jet fuel in the RTFO and a development fuels target for drop-in jet or road fuels made from wastes and residues. The UK Department for Transport set a high cost cap for development fuels of 1.60 pounds per liter (around $7.90 per gallon). This means that oil companies can choose to pay the government 1.60 pounds for every liter of development fuels they do not supply. This will provide a strong price signal to investors, because oil companies have a strong incentive to purchase any development fuels available at a price lower than 1.60 pounds per liter.[46]

Progressive EU countries: Strengthen policy support for advanced fuels and allow jet fuel to opt in. Denmark, Germany, Italy, Netherlands, and Sweden have all made recent policy updates to more strongly support advanced low-carbon fuels. Denmark, Italy, and Netherlands in particular all have fairly strong sub-targets for advanced biofuels for the 2020 to 2022 time frame within their national mandates. Of these five countries, only Netherlands allows jet fuel to opt-in. All EU countries are required to implement an ambitious 2030 target for advanced alternative fuels in the recast Renewable Energy Directive (RED II) by mid-2020. In addition, the RED II includes a 1.2x multiplier for renewable fuels used in aviation, sending a strong signal that jet fuel should be included in national policies. Denmark, Germany, Italy, Netherlands, and Sweden are the most likely to introduce robust policy measures. Although a continuation of current biofuel mandates is likely, these countries may consider measures to support a clear value signal (such as a high cost cap) and additional direct fiscal incentives.

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44 Chelsea Petrenko, "Is the Renewable Fuel Standard enough to spur progress in advanced biofuels? Probably not.," ICCT blog, Oct. 18, 2018, https://www.theicct.org/blog/staff/renewable-fuel-standard-enough-spur-progress-advanced-biofuels-probably-not

45 An act to add Sections 39730.5, 39730.6, 39730.7, and 39730.8 to the Health and Safety Code, and to add Chapter 13.1 (commencing with Section 42652) to Part 3 of Division 30 of the Public Resources Code, relating to methane emissions, California Senate Bill No. 1383, Chapter 395, Sept. 19, 2016, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383

46 Recent policy developments in the UK and EU countries are reviewed in Jacopo Giuntoli, *Advanced biofuel policies in select EU member states: 2018 update* (ICCT: Washington DC, in press).

India: Introduce strong fiscal incentives and other measures to support sustainable feedstocks and advanced technologies, and allow jet fuel to opt in. India recently proposed a new national biofuels policy with ambitious blending targets and fairly progressive, although vague, sustainability safeguards targeting the use of wastes and energy crops. India must implement the national biofuels policy with specific measures to incentivize fuel production. The government is considering a grants program for cellulosic ethanol facilities utilizing crop residues.[47]

A timeline for policy opportunities in these progressive jurisdictions is shown in Figure 5. This figure lists specific opportunities for policy developments that could strengthen support for advanced low-carbon fuels in general in the near term, which in turn will support the production of low-carbon jet fuels in the longer term. Arrows indicate the approximate duration of longer windows during which continued policy actions can have an effect.

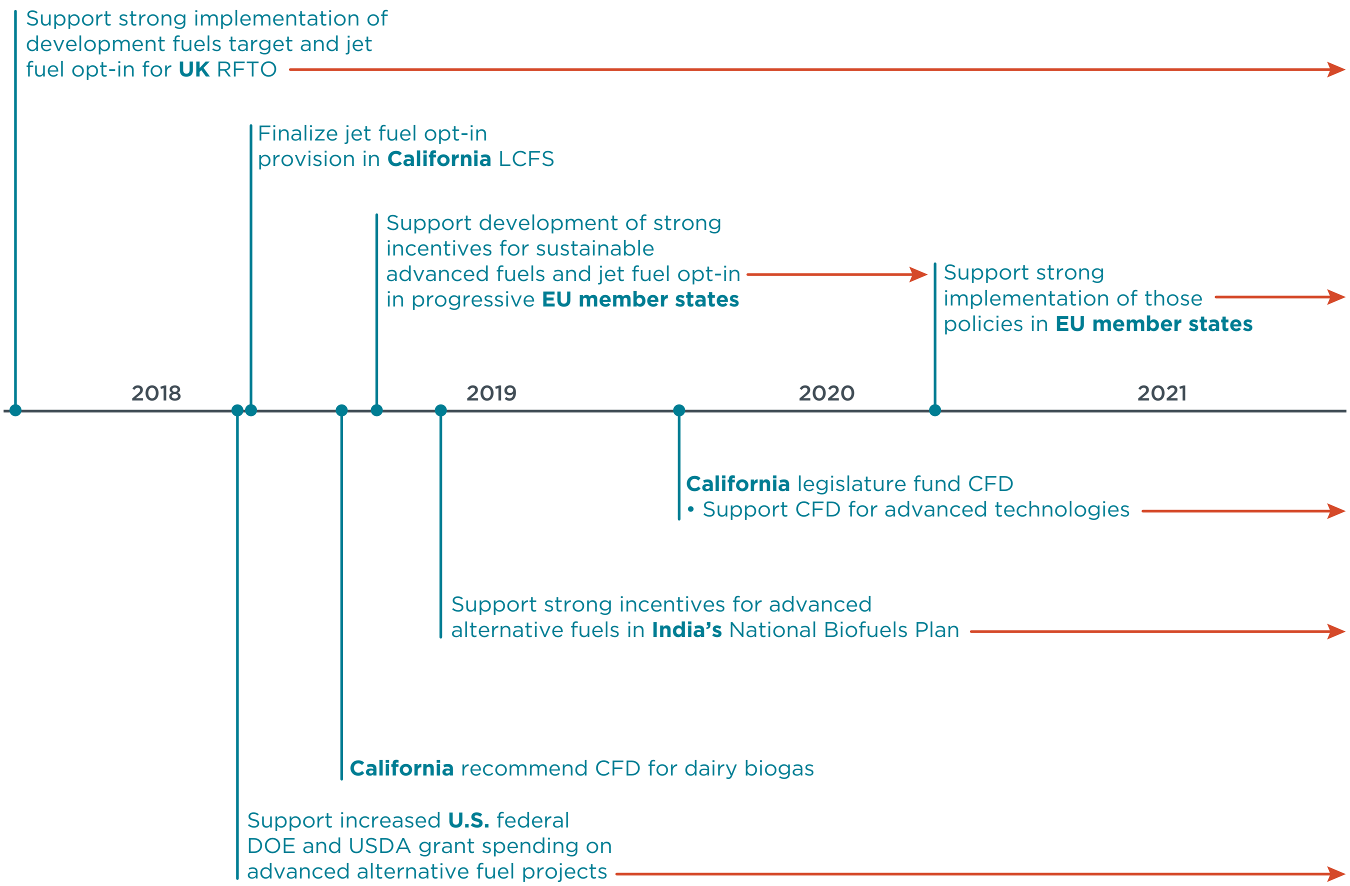

Figure 5. Timeline of near-term policy opportunities to support long-term jet fuel decarbonization

47 National Policy on Biofuels, Government of India, Ministry of New & Renewable Energy, n.d., https://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf; Bilal Abdi, "India proposes new bio-ethanol policy to spur Rs 5,000 crore investments," *Energyworld*, Nov. 23, 2017, https://energy.economictimes.indiatimes.com/news/oil-and-gas/india-proposes-new-bio-ethanol-policy-to-spur-rs-5000-crore-investments/61755856

Other major economies: The list above includes some of the largest economies in the world, but we do not expect all large countries to contribute significantly to this vision. While **China** has pushed the forefront on other clean technologies, such as the production of wind turbines and solar panels, it has been notably absent on the renewable fuels stage. As a densely populated country, China is concerned with the impact biofuel production could have on its domestic food supply. Starting in 2010, the government phased out policy support for grain-based ethanol because of increasing grain prices. Limited land availability also constrains potential cellulosic energy crop production.[48] **Indonesia** and **Brazil** have given substantial government support for biofuels, but their policies lack sustainability safeguards or GHG mitigation requirements. Indonesia in particular largely supports the use of palm oil in biodiesel, and this crop is strongly associated with deforestation, peat drainage, and very high GHG emissions from land use change.[49]

Although the progressive countries listed above represent a small share of global jet fuel consumption, they could be instrumental in accelerating the advanced fuels industry. Technological learning in one country can be easily exported to others. In the distant future, we expect the majority of advanced fuel production to take place in locations with the highest feedstock availability, for example countries with high potential for growing cellulosic energy crops or abundant wind and solar power for producing power-to-liquids. Development of a nascent advanced fuels industry does not necessarily need to begin in those locations, however. Any policy opportunity for supporting the emerging advanced fuel industry is valuable in these early stages.

48 Guangling Zhao, "Assessment of potential biomass energy production in China towards 2030 and 2050" (2016) *Int. J. Sust. Energy* 37(1), doi: 10.1080/14786451.2016.1231677

49 Chelsea Petrenko, Julia Paltseva, Stephanie Searle, *Ecological impacts of palm oil expansion in Indonesia* (ICCT: Washington DC, 2016) https://www.theicct.org/publications/ecological-impacts-palm-oil-expansion-indonesia