WORKING PAPER

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Evaluating the potential role of a National Low-Carbon Fuel Standard to support sustainable aviation fuels

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Introduction

Multiple jurisdictions have introduced low-carbon fuel standards (LCFSs) over the past decade to incentivize the blending of alternative fuels to transition away from petroleum. An LCFS is a technology-neutral performance standard that implements a binding greenhouse gas (GHG) intensity mandate for transport fuels that strengthens over time. In LCFSs, fuels' emissions are assessed on a life-cycle basis, wherein fuels with GHG intensities above the GHG intensity mandate generate deficits, which must be offset with credits from the use of fuels with GHG intensities below the mandate, as shown in Figure 1. This policy structure has received support for several reasons, notably because it incentivizes alternative fuels in proportion to their GHG savings, incorporates market mechanisms to operate efficiently, and does not favor specific technologies for compliance.

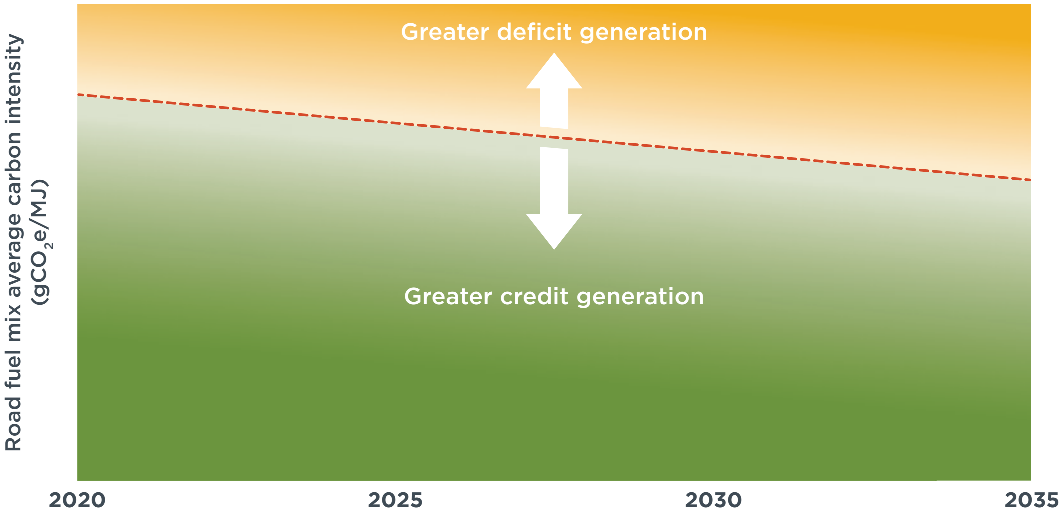

Figure 1. Illustrative example of a declining average transport fuel GHG intensity mandate implemented over time.

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California operates the longest-running LCFS program in the United States, and other state-level programs have recently been implemented in Oregon and Washington.[1] Similar programs also operate in British Columbia, Canada, and in Brazil.[2] Although these programs share a common structure, they differ in their GHG reduction targets, the value and size of their credit markets, and the methodology and scope of their life-cycle GHG accounting.

To date, LCFSs have primarily been adopted to promote the use of alternative fuels in the road sector. However, a 2019 amendment to the California LCFS allowed for the inclusion of sustainable aviation fuels (SAFs) on an opt-in basis, meaning that such fuels could qualify for LCFS credits based on their GHG reductions, but that the aviation sector would not generate deficits from the use of fossil aviation fuels.[3] Recently, California proposed to obligate the relatively small share of fuels consumed on intra-state flights. Some U.S. Members of Congress have proposed a national-level aviation LCFS, to be complemented with tax credits for certain qualifying SAFs.[4] The European Commission has also adopted revisions to the European Union (EU) Renewable Energy Directive (RED III), requiring that the carbon intensity of the transport fuel mix (including marine and aviation fuels) be reduced by 14.5% from the fossil fuel baseline by 2030.[5]

There are other policy incentives that could be used in place of, or as a complement to, an aviation LCFS. The 2021 "SAF Grand Challenge," announced by the Biden Administration, combines a national target of producing 3 billion gallons of SAF annually by 2030 with funding for additional research and development for the SAF industry.[6] The Renewable Fuel Standard (RFS), a federal biofuel volumetric mandate for the road sector, allows bio-based SAFs to qualify for Renewable Identification Numbers (RINs) used for compliance in the program on an opt-in basis. In theory, SAFs have similar compliance value to biofuels with comparable GHG savings under the program; depending on what RIN category it qualifies for, an SAF could generate approximately $1.50 to $4.5 per gallon of jet-equivalent based on 2023 RIN prices.[7] The 2022 Inflation Reduction Act (IRA) included a tax credit for SAF producers based on the fuel's life-cycle GHG savings relative to petroleum jet fuel. Fuels require a minimum 50% GHG reduction to qualify for a $1.25 per gallon tax credit and receive an additional $0.01 per gallon for every additional percentage of GHG savings up to $1.75, though the exact life-cycle methodology and eligibility criteria had not been announced at the time of publication.[8]

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1 Oregon Department of Environmental Quality, "Clean Fuels Program Overview," accessed December 8, 2023, https://www.oregon.gov/deq/ghgp/cfp/Pages/CFP-Overview.aspx; Washington State Department of Ecology, "Clean Fuel Standard," accessed December 18, 2023, https://ecology.wa.gov/air-climate/reducing-greenhouse-gas-emissions/clean-fuel-standard.

2 Government of British Columbia, Renewable and Low Carbon Fuel Requirements Regulation, B.C. Reg. 394/2008, December 9, 2008, as amended by B.C. Reg. 280/2022, December 31, 2022, https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/394_2008; Brazilian Chamber of Deputies, Dispõe sobre a Política Nacional de Biocombustíveis (RenovaBio) e dá outras providências, Lei Nº 13.576, December 26, 2017, https://www.gov.br/mme/pt-br/assuntos/secretarias/petroleo-gas-natural-e-biocombustiveis/renovabio-1/legislcao-e-documentos.

3 California Code of Regulations, Fuels Subject to Regulation, 17 CCR §95482.

4 U.S. Congress, Sustainable Aviation Fuel Act, H.R. 2747, 118th Cong., 1st sess., April 20, 2023, https://www.congress.gov/bill/118th-congress/house-bill/2747.

5 European Commission, Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, COM/2021/557 final, July 14, 2021, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-greendeal/delivering-european-green-deal_en.

6 U.S. Department of Energy (DOE), U.S. Department of Transportation, and U.S. Department of Agriculture, "Memorandum of Understanding: Sustainable Aviation Fuel Grand Challenge," 2021, https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf.

7 U.S. Environmental Protection Agency (EPA), "Public Data for the Renewable Fuel Standard," accessed December 18, 2023, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard.

8 U.S. Congress, Inflation Reduction Act of 2022, P.L. 117-169, §13203, https://www.congress.gov/bill/117th-congress/house-bill/5376/text. In its current form, the tax credit only extends through 2024. For 2025 through 2027, the tax credit for SAFs is based on a formula of $1.75 * (50 $kgCO_2e$/MMBtu – X)/(50 $kgCO_2e$/MMBtu), where X is that fuel's life-cycle GHG intensity in $kgCO_2e$/MMBtu of fuel.

It is generally acknowledged that policy intervention is necessary to drive the uptake of SAFs due to barriers to their adoption, namely the substantial cost gap between SAFs and conventional petroleum fuels, the lack of SAF production capacity, and the price sensitivity of possible SAF consumers.[9] These factors are exacerbated by the lack of meaningful carbon pricing for aviation in the United States, which lowers the incentive to reduce sectoral emissions. However, there remains substantial disagreement on the most effective form of policy support for SAFs and the role of SAFs in decarbonizing the aviation sector relative to other methods, such as modal shift, improved efficiency, and the use of zero-emission airplanes. The role of subsidies versus carbon pricing and the suitability of binding regulations to decarbonize the aviation sector are other topics of debate, as the aviation sector is both particularly expensive to decarbonize and disproportionately used by a smaller, wealthier subset of transportation consumers.[10]

This paper explores policy options for including aviation fuels in a hypothetical national LCFS policy. We expand on previous research on the potential impacts of a national LCFS in the road sector to model the inclusion of the aviation sector in a national LCFS scheme. We then explore the impact of different policy design options, including a GHG reduction target, sectoral obligation, and the use of supplementary tax credits on the mix of fuels supplied. Across these scenarios, we compare the total quantity of SAFs deployed, the share of second-generation SAFs, and the total climate impacts of the policy.

Methodology

For this analysis, we build upon modeling developed by Pavlenko, Searle, and Christensen for a possible road sector national LCFS.[11] For the road sector, which is modeled here in parallel to the aviation sector, we incorporate the existing baseline fuel consumption, fuel production cost, and life-cycle GHG impacts of fuel pathways from that study. For the baseline scenario, we incorporate a business-as-usual (BAU) projection of fuel consumption growth over time based on the Energy Information Administration (EIA)'s *Annual Energy Outlook*, but adjust projected gasoline consumption down to account for a projected increase in electric vehicle deployment, reaching a 70% sales share in 2035.[12] Using a fleet turnover model described by Lutsey, we estimate that electricity consumption for the light-duty vehicle (LDV) fleet will grow to 5.8 billion gasoline gallon-equivalents (GGE) by 2035, and adjust the EIA reference scenario to reduce gasoline consumption by an equivalent quantity, factoring in the efficiency difference between electric vehicles and gasoline LDVs.[13]

To model the impact of an LCFS on the aviation sector, we incorporate several additions to the road sector LCFS model. We include fossil jet fuel, as well as a selection of SAFs with different life-cycle GHG impacts and production costs. We also

9 International Civil Aviation Organization (ICAO), *Guidance on Potential Policies and Coordinated Approaches for the Deployment of Sustainable Aviation Fuels* (Montreal, Canada: ICAO, 2022), https://www.icao.int/environmental-protection/Documents/SAF/Guidance%20on%20SAF%20policies%20-%20Version%201.pdf.

10 Sola Zheng and Dan Rutherford, *Aviation Climate Finance Using a Global Frequent Flyer Levy* (Washington, DC: ICCT, 2022), https://theicct.org/publication/global-aviation-frequent-flying-levy-sep22/.

11 Nikita Pavlenko, Stephanie Searle, and Adam Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard* (Washington, DC: ICCT, 2022) https://theicct.org/wp-content/uploads/2022/03/risks-low-carbon-fuel-standard-mar22.pdf.

12 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*.

13 Nic Lutsey, *Global Climate Change Mitigation Potential from a Transition to Electric Vehicles* (Washington, DC: ICCT, 2015), https://theicct.org/wp-content/uploads/2021/06/ICCT_ghg-reduction-potential-evs_201512.pdf.

include baseline fuel consumption data and a projection of jet fuel demand through 2035. Lastly, we incorporate a demand-response curve to account for the impact of carbon pricing (mediated through an LCFS) on aviation consumer demand. In the subsequent sections, we briefly summarize the model structure and discuss each of these changes to the model in more detail.

Model structure

For our analysis, we use a partial equilibrium model of the U.S. transport fuel sector, wherein we evaluate the market response to several different LCFS policy scenarios relative to a counterfactual baseline case, as described in more detail in the appendix. Pavlenko, Searle, and Christensen provide a full description of the model design.[14] The model includes several different agents within the transportation fuel market that make cost-optimized decisions, including representative consumer agents purchasing vehicles, blender agents purchasing fuels, and supply agents for different fuel blendstocks.

Aviation sector reference data

To expand the model to include the aviation sector, we incorporate baseline aviation sector activity data on current fuel consumption, demand growth, and prices. We use 2019 aviation fuel consumption data from the EIA's *Annual Energy Outlook* for the initial 2020 baseline year rather than 2020 data due to the disruption of Covid-19 on the aviation sector.[15] We project that in the baseline scenario, fuel demand will grow 1.5% year-over-year, reflecting a 2.5% annual demand increase and a 1% year-over-year efficiency improvement.[16] For the baseline, fossil jet fuel prices are based on a five-year average wholesale price reported by the EIA.[17]

To assess the uptake of SAFs, we expand the scope of the analysis in Pavlenko, Searle, and Christensen to include a set of emission factors for SAFs, including both direct production emissions and indirect land-use change (ILUC) emissions.[18] Combined, these comprise the GHG intensity of fuels that informs the decisions of fuel blenders and the LCFS credit generation potential for fuel suppliers. We include a selection of existing, commercialized fuel pathways and second-generation SAFs expected to be available in the near to medium term, which each have their own specific GHG intensity and production cost. This study does not assess the impact of different ILUC assumptions on the analysis, instead assigning ILUC scores only to those feedstocks whose ILUC emissions have been previously assessed by U.S. Environmental Protection Agency for the RFS.[19] Direct emissions for pathways are taken from the default values developed by the International Civil Aviation Organization (ICAO) life-cycle assessment methodology.[20] We assume e-kerosene is produced from additional, renewable electricity and has a near-zero GHG intensity.[21] In this analysis, the GHG intensity

14 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard.*

15 EIA, *Annual Energy Outlook 2020* (Washington, DC: EIA, 2020), https://www.eia.gov/outlooks/archive/aeo20/.

16 Based on an extrapolation of trends from 2013 to 2019 from Brandon Graver, Dan Rutherford, and Sola Zheng, *CO2 Emissions from Commercial Aviation: 2013, 2018, and 2019* (Washington, DC: ICCT, 2020), https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf.

17 EIA, *Petroleum Marketing Monthly*, https://www.eia.gov/petroleum/marketing/monthly/.

18 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*.

19 EPA, *Renewable Fuel Standard: Final Regulatory Impact Analysis* (Washington, DC: EPA, 2010), https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1006DXP.txt.

20 ICAO, *CORSIA Supporting Document: CORSIA Eligible Fuels – Life Cycle Assessment Methodology* (2019), https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf.

21 Michael Wang et al., *Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model ® (2021 Excel)* (DOE Office of Energy Efficiency and Renewable Energy, 2021) https://doi.org/10.11578/GREET-EXCEL-2021/DC.20210902.1.

of fuels does not change over time or in response to the policy. Rather than drive improvement within a fuel pathway, this modeling framework is limited to switching between blendstocks to generate LCFS credits. The full set of GHG intensities used in the modeling is summarized in Table 1.

Because the SAF industry is in its early stages of development, this analysis uses techno-economic assessments of SAF production prices rather than real-world market data. Currently, the primary commercial SAF production pathway is the hydroprocessed esters and fatty acids (HEFA) pathway, using either used cooking oil (UCO) or inedible animal fats, which still retains a high production cost premium over conventional fossil jet fuel.[22] The production costs of other, next-generation SAFs are less certain and may vary based on economic assumptions (e.g., financing costs), technical assumptions (e.g., yield), as well as feedstock choice and conversion process.[23] Though the costs of these pathways vary considerably, overall the cost range for these technologies are uniformly more expensive than conventional, fossil jet fuel. We also include e-fuels (i.e., electrofuels or power-to-liquids) as a compliance option, though these fuels are currently not produced in commercial quantities. E-kerosene production prices are estimated based on future renewable electricity production costs and point source carbon capture from 2025 to 2050.[24] The full set of baseline fuel production costs used in the modeling is summarized in Table 1.

Table 1. Life-cycle assessment and cost data inputs for fuel compliance modeling

Fuel pathway	Direct emissions	Wholesale cost ($/JGE)
Fossil jet fuel	89.0	$1.73[a]
Corn, alcohol-to-jet (ATJ)	65.7	$7.79
Sugar Cane ATJ	24.1	$7.65
Agricultural residues, ATJ	29.3	$10.57
Energy crops, ATJ	43.4	$10.94
Municipal Solid Waste (MSW), Gasification Fischer-Tropsch (FT) (0% biogenic)	5.2	$6.21
Agricultural residues, gasification-FT	7.7	$8.25
Energy crop, gasification-FT	10.4	$8.67
Soy oil hydroprocessed esters and fatty acids (HEFA)	40.4	$5.05
Canola HEFA	47.4	$5.05
Used cooking oil HEFA	13.9	$4.08
Tallow HEFA	22.5	$4.08[b]
Corn Oil HEFA	17.2	$5.05[c]
e-Kerosene	0.4	$12.01[d]

Notes: Direct emission values are taken from ICAO *CORSIA Supporting Document: CORSIA Eligible Fuels – Life Cycle Assessment Methodology*, with the exception of e-kerosene, which is taken from Wang et al., *Greenhouse Gases, Regulated Emissions, and Energy Use*. Cost values are from Pavlenko, Searle, and Christensen, *The Cost of Supporting Alternative Jet Fuels in the European Union*, except where noted.

[a] Source: EIA, *Petroleum Marketing Monthly*, https://www.eia.gov/petroleum/marketing/monthly/.

[b] Assumed same as UCO HEFA.

[c] Adjusted UCO HEFA based on corn oil renewable diesel price versus UCO renewable diesel.

[d] Source: Searle and Christensen, *Decarbonization Potential for Electrofuels in the European Union*, using $2.50/liter policy support as a midrange value, adjusted for energy content of jet fuel.

22 Nikita Pavlenko, Stephanie Searle, and Adam Christensen, *The Cost of Supporting Alternative Jet Fuels in the European Union* (Washington, DC: ICCT, 2019), https://theicct.org/sites/default/files/publications/Alternative_jet_fuels_cost_EU_2020_06_v3.pdf.

23 Adam Brown et al., *Advanced Biofuels – Potential for Cost Reduction* (IEA Bioenergy, 2020), https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf.

24 This is consistent with the e-fuel price assumed in Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*. For another application, see Stephanie Searle and Adam Christensen, *Decarbonization Potential for Electrofuels in the European Union* (Washington, DC: ICCT, 2018), https://theicct.org/publication/decarbonization-potential-of-electrofuels-in-the-european-union/.

Aviation consumer demand

We estimated the demand response of air travel to hypothetical carbon prices based on price elasticities from the literature and global operations data in 2019. Specifically, we used pan-national level price elasticities, by region pair and by length of haul (short vs. long), from an InterVISTAS consultant report commissioned by the International Air Transport Association.[25] The average elasticities for North American routes are -0.6 (long-haul) and -0.66 (short-haul), with a range from -0.36 to -0.79.[26] While leisure travel is generally more elastic than business travel, we used average elasticities across trip types to match the granularity of fare and emissions data.

We purchased a dataset of average economy-class fares by route from market intelligence firm RDC Aviation that covered almost half of passenger operations in 2019, and extrapolated ticket prices for the remaining operations based on average rates per kilometer by flight distance and region. Flight fuel-burn data are from ICCT's Global Aviation Carbon Assessment (GACA) model, which includes all route-aircraft type combinations in 2019.[27] GHG emissions were estimated using an assumed emission factor of 3.16 tonnes of CO_2 emitted per tonne of aviation fuel, which only factors in tank-to-wake emissions.

The effect of complying with the LCFS can be modeled as an increase in fuel cost for the airlines. We used a fuel cost pass-through rate of 75%, representing the percentage of the increase in fuel costs that airlines pass on to consumers by increasing ticket prices. The literature suggests that the pass-through rate typically falls within the range of 50% to 100%.[28]

The change in demand for each route-aircraft type combination departing from the United States is calculated as follows:

$$\text{Price Increase [\$]} = \text{Fuel Burn [gal]} / \text{Passenger Count} \times \text{Carbon Price [\$/gal]} \times \text{Pass Through Rate [\%]}$$

$$\text{Percentage of Price Increase [\%]} = \text{Price Increase [\$]} / \text{Fare [\$]}$$

$$\text{Percentage of Demand Reduction [\%]} = \text{Price Elasticity} \times \text{Percentage of Price Increase [\%]}$$

Equation 1. Calculation of change in aviation demand based on price changes

The overall decrease in passenger counts for all U.S.-departing routes and carbon prices from $1 to $700 were used to derive a demand response curve, illustrated below in Figure 2. The magnitude of demand response would be smaller if fuel burn per passenger decreases or if base fare increases from the 2019 level. This corresponds to an elasticity of 0.6 for long-haul flights and 0.66 for short-haul flights in North America, as noted above.

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25 InterVISTAS Consulting Inc., *Estimating Air Travel Demand Elasticities: Final Report* (2007), https://www.iata.org/en/iata-repository/publications/economic-reports/estimating-air-travel-demand-elasticities---by-intervistas/.

26 Short-haul flights are defined as less than 1,500km in great circle distance, and all other flights are categorized as "long-haul" for the purpose of matching elasticities.

27 Graver, Rutherford, and Zheng, *CO2 Emissions from Commercial Aviation: 2013, 2018, and 2019*.

28 Carl Koopmans and Rogier Lieshout, "Airline cost changes: To what extent are they passed through to the passenger?" *Journal of Air Transport Management* 53 (2016): 1–11. https://doi.org/10.1016/j.jairtraman.2015.12.013; Bojun Wang et al., "Modelling the Pass-Through of Airline Operating Costs on Average Fares in the Global Aviation Market" (paper, 21st Air Transport Research Society World Conference, Antwerp, July 5-8, 2017), https://www.atslab.org/wp-content/uploads/2017/08/Wang_ATRS_248.pdf.

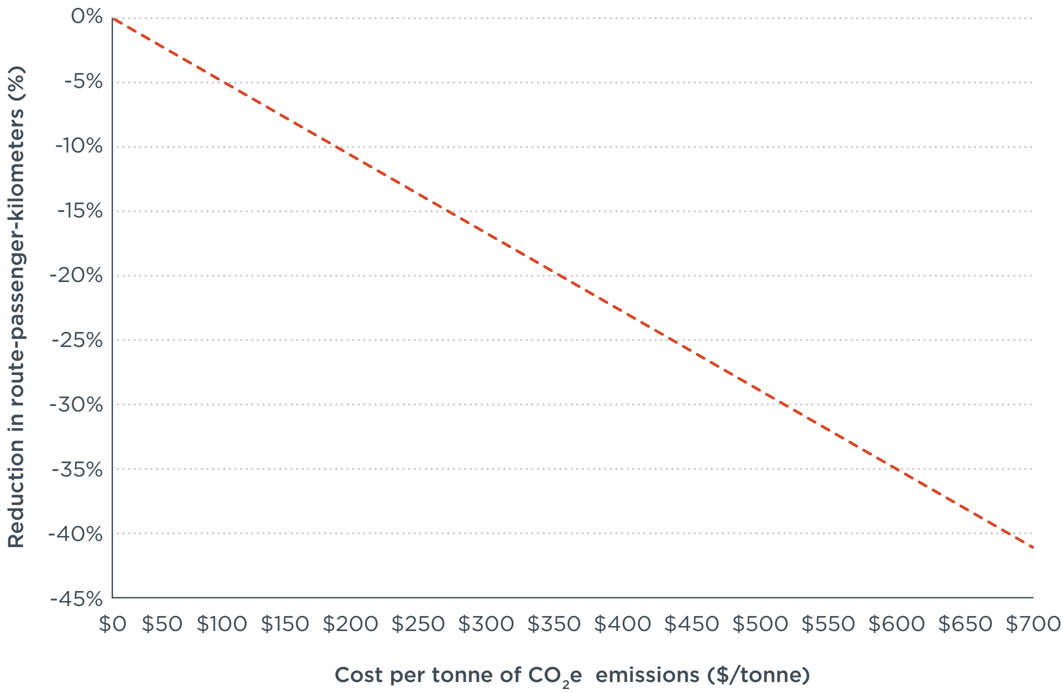

Figure 2. Elasticity of demand for aviation in response to carbon pricing.

Scenario design

In this study, we present eight different scenarios for possible LCFS implementation. Table 2 below specifies key design decisions for each scenario, indicating the 2035 GHG intensity reduction target for the fuel mix, the maximum credit price level in the scenario, which transportation sectors are obligated to comply with the policy, and whether there are any supplemental policies in place. For each scenario, the maximum credit price is set as an exogenous assumption and the model is run with the policy constraints for that scenario to identify the GHG reduction target necessary to reach that credit price. Therefore, the GHG reduction targets for each scenario reflect both the maximum price and the combination of eligibility requirements, supplemental policies, and obligated sectors in that scenario.

Table 2. Overview of aviation LCFS modeling scenarios and parameters

Scenario name	Sectoral obligation	Credit price	GHG reduction target	Supplemental policies
1 – Low ambition	Road and aviation	Low	13.0%	n/a
2 – Medium ambition	Road and aviation	Medium	21.0%	n/a
3 – High ambition	Road and aviation	High	29.0%	n/a
4 – High ambition, advanced fuel focused	Road and aviation	High	23.0%	Food-based and waste oil-based fuels capped at 2020 levels
5 – High ambition, supplementary SAF tax credit	Road and aviation	High	30.0%	Additional $1.25-$1.75/gal tax credit for qualifying SAFs
6 – High ambition, aviation-only LCFS	Aviation	High	2.3%	n/a
7 – High ambition, aviation-only, supplementary SAF tax credit	Aviation	High	4.3%	Additional $1.25-$1.75/gal tax credit for qualifying SAFs
8 – High ambition, aviation opt-in	Road	High	32.0%	n/a

The first five scenarios consider combined policies that obligate compliance from both the road and aviation sectors. This means that compliance can be cross-sectoral, depending on what is most cost-effective for a fuel blender (e.g., aviation sector deficits can be offset through credits generated in the road sector). The first three scenarios examine different GHG reduction target levels. To calculate the GHG reduction targets for each scenario, we work backwards from three assumed maximum credit prices of $250, $450, and $650 per tonne of CO_2e to simulate low, medium, and high ambition LCFS targets, respectively; the model then solves for the GHG intensity reduction that could be achieved when constrained by that credit price maximum.

Scenarios 4 and 5 consider the impact of supplemental policy decisions on the combined road and air LCFS. In these scenarios, we retain the maximum credit price of $650/tonne of CO_2e from the high ambition scenario. In Scenario 4, we cap the contribution of potentially risky feedstocks to the program, on an energy basis, to 2020 levels; this leaves more room in the policy for compliance with second-generation pathways. However, as these fuels are more expensive to produce, the scenario only allows a GHG intensity reduction target of 23% at the same credit price as before. In Scenario 5, we retain the credit price maximum from Scenario 3 but also incorporate a tax credit for SAFs that reduces their production cost; this gives some fuels an additional incentive and competitive advantage within the program. The value of the SAF incentive is based on the structure of the tax credit in the 2022 Inflation Reduction Act, wherein fuels with 50% to 100% GHG savings relative to fossil jet fuel receive a tax credit of between $1.25 and $1.75 per gallon, depending on their GHG savings. Unlike the IRA, which offers this credit through 2024, we assume it is in place through 2035. The supplemental incentive allows for a higher GHG reduction target of 32%.

Scenarios 6 and 7 consider the impact of an aviation-only LCFS that does not place any obligations on road sector fuel suppliers—all GHG reductions must come from blending SAFs. Keeping the credit price at the high ambition level, the GHG intensity reduction targets drop to 2.2% in Scenario 6 and 4.3% in Scenario 7. This implies that decarbonizing aviation specifically has a higher cost than reducing emissions in the road sector. However, the only deficits in the system are generated by fossil aviation fuel and compliance must come from within the aviation sector, thus creating a direct incentive for SAF blending.

Scenario 8 reflects a policy design similar to the present-day status quo in California, but at a nationwide level. In this scenario, only the road sector is obligated under the LCFS and, therefore, only road fuels generate deficits in the LCFS program. However, SAFs are still eligible to generate credits on an opt-in basis. This allows for slightly more cost-effective overall program compliance, as it gives fuel suppliers an additional source of LCFS credits. In practice, this allows fuel producers to generate value from the SAF that some renewable diesel technologies generate as a co-product.

Results

The figures below illustrate the impacts of the different hypothetical policy scenarios. Due to the wide range of potential pathways modeled, in conjunction with the small volumes of some individual pathways, we consolidate the fuels into three categories: waste oil-derived HEFA fuels, crop-based fuels, and second-generation fuels. The latter category includes all lignocellulosic biofuels, as well as e-kerosene. The secondary y-axis illustrates the blend of SAF as a share of all aviation fuels over time for each scenario. For scenarios in which the road sector is included, the road sector results are very similar to those in Pavlenko, Searle, and Christensen.[29] Therefore, we focus on the mix of fuels supplied to the aviation sector specifically.

Scenario 1, illustrated in Figure 3, represents the impact of a 13% GHG intensity reduction for the combined road and aviation fuel mix by 2035. In this scenario, it is clear that that the bulk of SAF production comes from waste oil-derived HEFA fuels as a co-product of renewable diesel produced for the overall LCFS policy. Total SAF use peaks at roughly 100 million jet gallon equivalent (JGE) by 2035, with minimal deployment of second-generation SAF pathways.

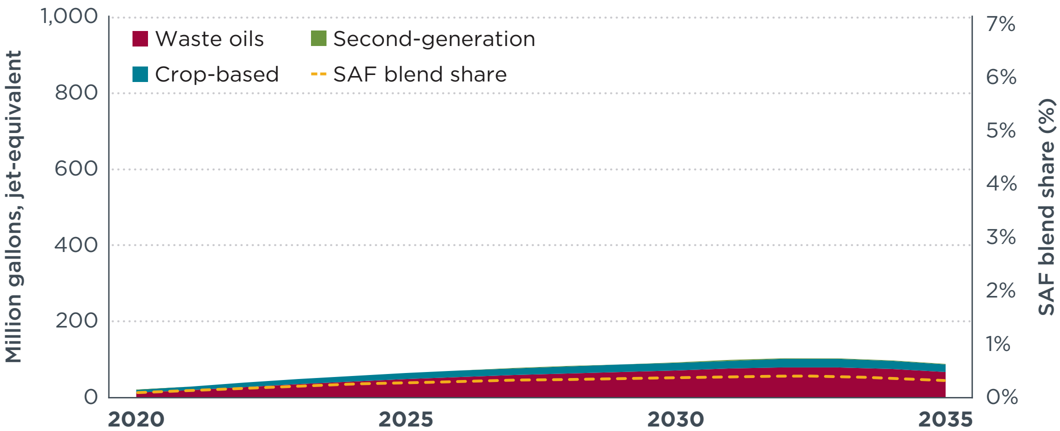

Figure 3. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 1 (road and aviation obligated, $250/tonne credit cap, and 13% reduction target).

Scenario 2, illustrated in Figure 4, is a medium ambition scenario that mandates a 21% GHG intensity reduction and has a $450/tonne maximum credit price. Total SAF production through 2035 is roughly double that of Scenario 1, growing to approximately 200 million JGE, with about two-thirds coming from waste oils. The deployment of second-generation SAF pathways increases to approximately 60 million JGE by 2035.

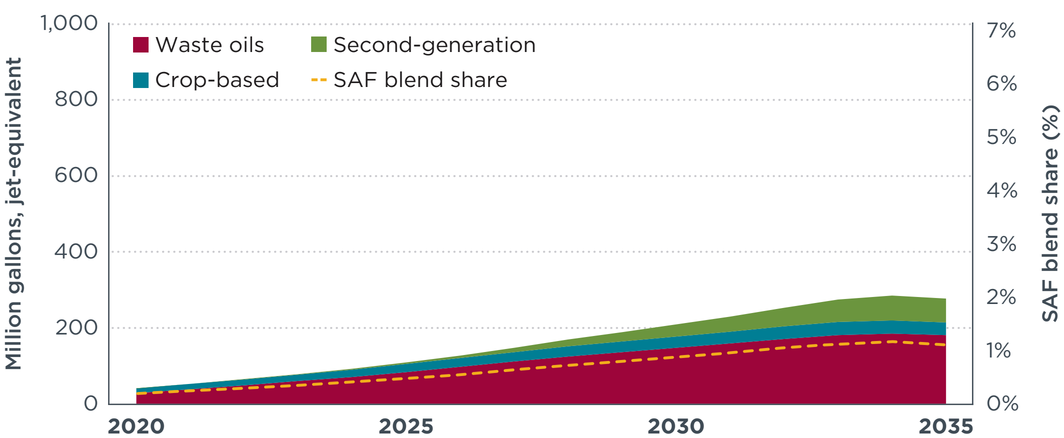

Figure 4. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 2 (road and aviation obligated, $450/tonne credit cap, 21% reduction target).

29 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*.

Scenario 3, illustrated in Figure 5, has the highest maximum credit price ($650/tonne) and a deeper GHG intensity reduction target (29%), resulting in the highest uptake of SAFs among the first three scenarios, reaching approximately 1 billion gallons by 2035. From 2020 through 2030, the majority of SAFs are HEFA fuels produced from UCO and soy oil. These pathways reach a maximum of approximately 400 million JGE in 2035. However, starting in 2025, the supply of second-generation SAFs begins to increase rapidly, reaching approximately 600 million JGE in 2035. We note that this growth is not linear with credit price, suggesting that higher volumes of SAFs are possible beyond the $450/tonne credit price, likely due to the expense of generating LCFS credits in the road sector relative to the aviation sector. The majority of this growth comes from the municipal solid waste (MSW) gasification – Fischer-Tropsch (FT) pathway, which is the cheapest of the lignocellulosic biofuel pathways; this is followed by the gasification – FT agricultural residues pathway. In this scenario, the high cost of e-kerosene restricts total production below 1 million JGE.

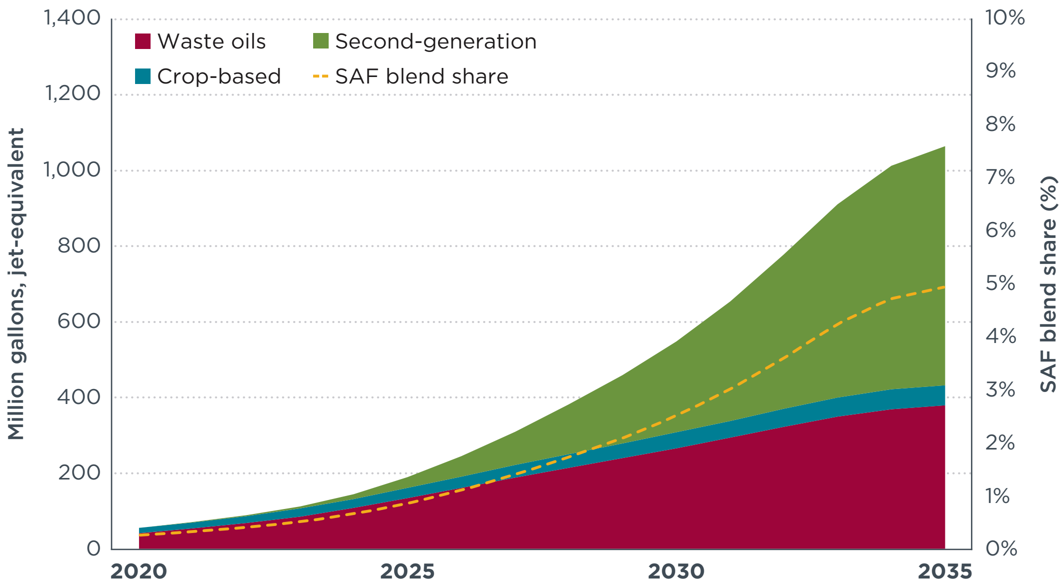

Figure 5. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 3 (road and aviation obligated, $650/tonne credit cap, 29% reduction target).

Scenario 4, illustrated in Figure 6, is a modified version of Scenario 3 that maintains the maximum credit price but caps the contribution of all fuels across transport sectors made from waste oils and crops to 2020 consumption levels. The total SAF consumption of approximately 1 billion JGE in 2035 is roughly similar to Scenario 3; however, the SAFs deployed differ significantly.[30] Here, second-generation SAFs contribute approximately 90% of SAF production, which reaches approximately 900 million JGE by 2035, with the remainder largely coming from soy HEFA. The bulk of the second-generation SAF comes from MSW, followed by agricultural residues.

30 SAF blending in this scenario peaks in 2033 due to a high penetration of EV charging in 2034-2035 in conjunction with the imperfect foresight of credit banking in the model. Specifically, after 2033, there are sufficient banked credits and EV credits to reduce SAF production.

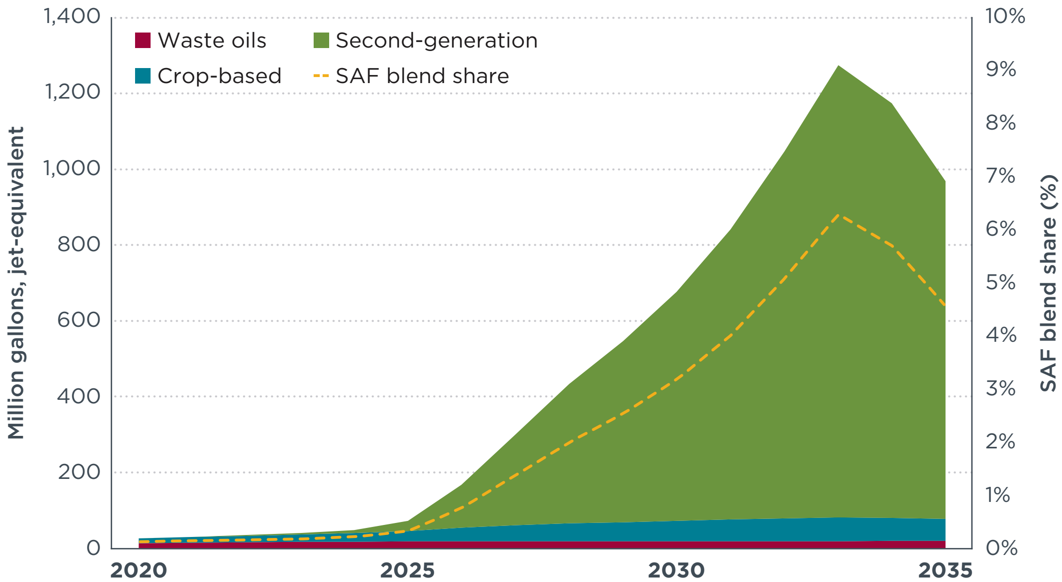

Figure 6. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 4 (road and aviation obligated, $650/tonne credit cap, 23% reduction target, crop-based and waste oil-derived biofuels capped at 2020 levels).

Scenario 5, illustrated in Figure 7, is a modified version of Scenario 3 that supplements the high maximum credit price with a supplemental tax credit for SAFs with greater than 50% GHG savings relative to fossil jet fuel. By 2035, SAF production is more than double that in Scenario 3, reaching approximately 2.7 billion JGE. The mix of SAFs supplied is predominantly waste oil HEFA through 2025, with a large growth in second-generation pathways starting after 2025. By 2035, the sector uses approximately 600 million JGE of waste oil HEFA and 2 billion JGE of second-generation SAFs, predominantly MSW. The blend level reaches nearly 14% of aviation fuels by 2035. Soy HEFA, which also benefits from the tax credit, increases to 150 million JGE. E-kerosene use doubles in this scenario relative to Scenario 3, though remains under 1 million JGE.

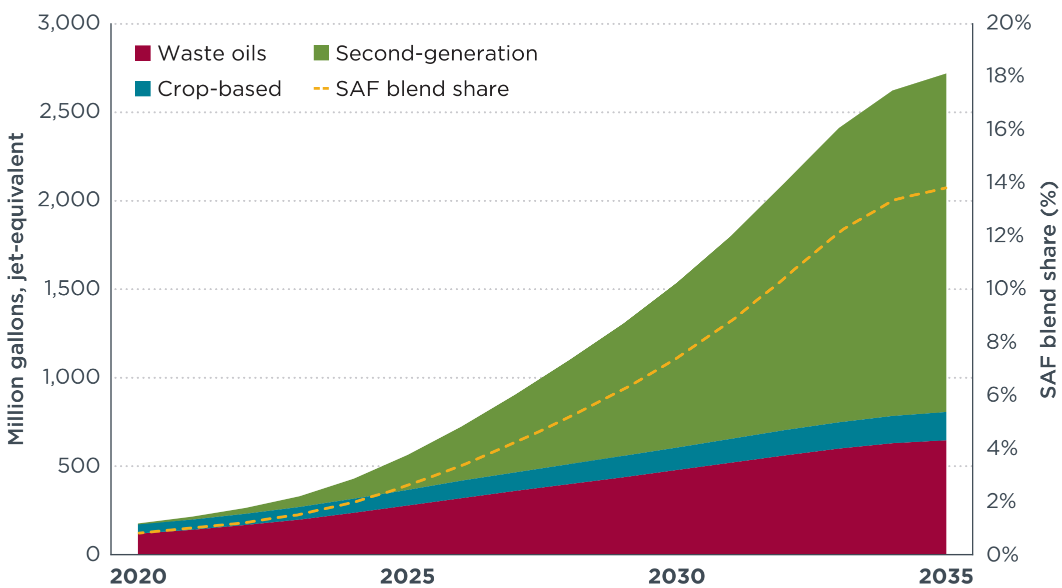

Figure 7. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 5 (road + aviation obligated, $650/tonne credit cap, 30% reduction target, supplemental tax credit for SAFs).

Scenario 6, illustrated in Figure 8, estimates the mix of SAFs deployed under an aviation-only LCFS. Though the GHG intensity reduction target is much lower than the combined road and aviation LCFS scenarios (Scenarios 1-3), the volume of SAFs supplied is between the medium and high target scenarios, reaching approximately 800 million JGE by 2035. In this scenario, the bulk of the SAF comes from waste oil HEFA fuels, which grow to approximately 500 million JGE. Second-generation SAFs grow to approximately 200 million JGE, though e-kerosene production stays below 1 million JGE.

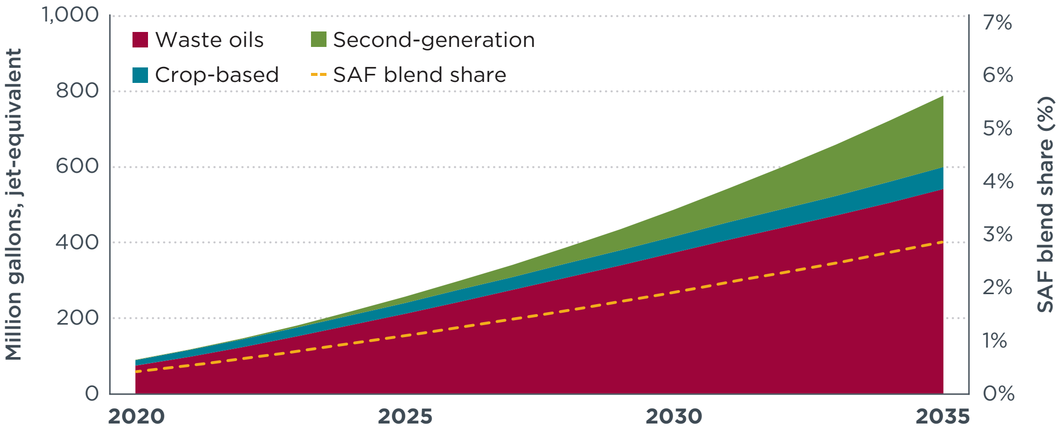

Figure 8. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 6 (aviation-only obligated, $650/tonne credit cap, 2.3% reduction target).

Scenario 7, illustrated in Figure 9, modifies Scenario 6 to supplement the aviation-only LCFS with a tax credit for SAFs. This facilitates more cost-effective compliance, and thus the target level increases to a 4.3% GHG intensity reduction by 2035 at the same maximum credit price as Scenario 6. The value of the tax credit improves the cost viability of second-generation biofuels, while also making soy HEFA and waste oil HEFA fuels cheaper; therefore, this scenario has high growth in all three categories. Second-generation biofuel consumption grows to approximately 500 million JGE, whereas crop-based HEFA and waste oil HEFA grow to approximately 150 million JGE and 800 million JGE, respectively.

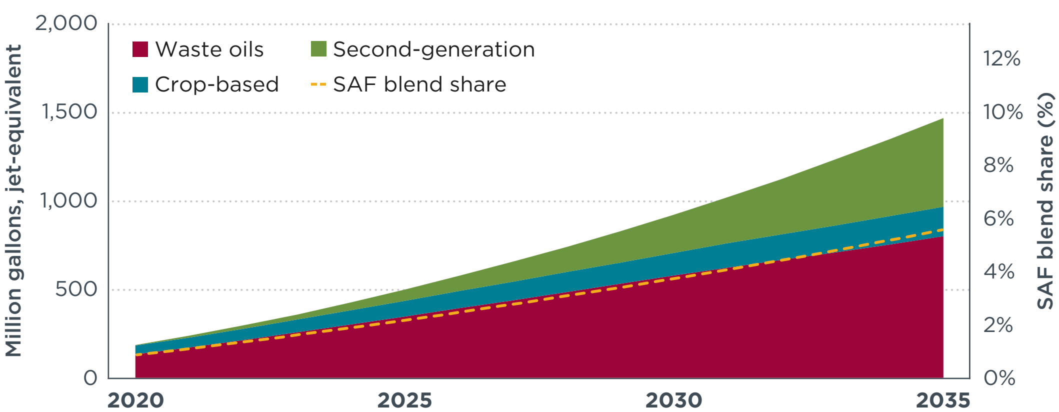

Figure 9. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 7 (aviation-only obligated, $650/tonne credit cap, 4.3% reduction target, supplemental tax credit for SAFs).

Scenario 8, shown in Figure 10, reflects an aviation opt-in LCFS policy, illustrating the mix of alternative fuels delivered to the aviation sector through 2035. In this scenario, there is no deficit generation for fossil aviation fuels, so SAFs generate credits on an opt-in basis for road sector compliance. Therefore, while the volumes of road sector biofuels supplied in this scenario are substantial, SAF usage only grows to approximately 200 million JGE. This underscores that aviation decarbonization is more expensive than road sector compliance; however, there is an incentive to use volumes of predominantly HEFA fuels generated as a co-product for renewable diesel production in the road sector. Due to this additional compliance flexibility, this scenario has a higher GHG intensity reduction target of 32%, compared to 29% for the combined aviation and road LCFS high ambition scenario (Scenario 3). As this scenario also results in a large uptake of second-generation fuels in the road sector, there is a modest increase in second-generation aviation fuels to approximately 50 million JGE, mostly from MSW.

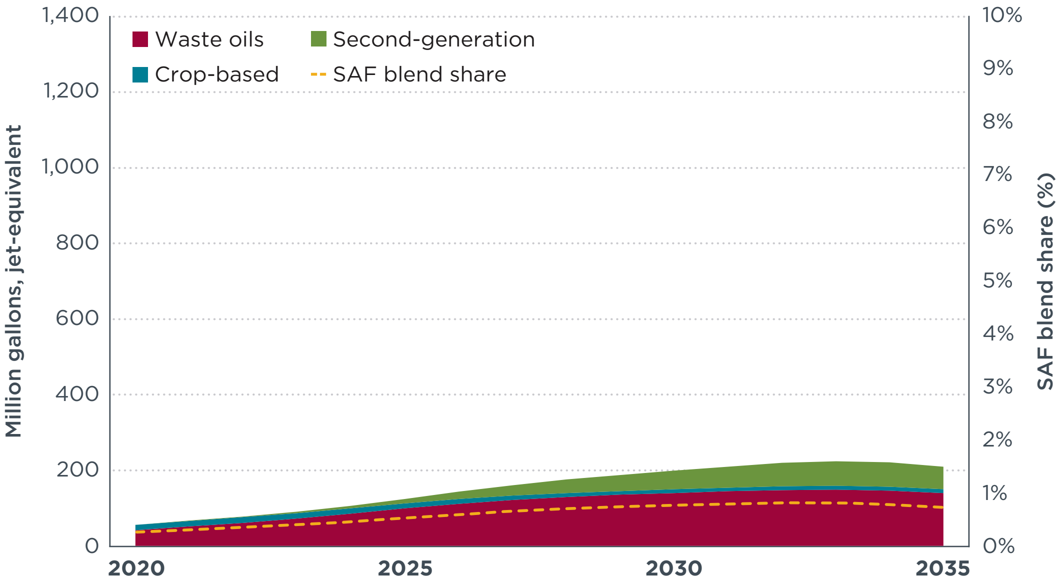

Figure 10. Mix of fuels supplied to the U.S. transport sector in 2020–2035 in Scenario 8 (road-only obligated, $650/tonne credit cap, 32% reduction target).

Discussion

We find that the ambition of an LCFS, the extent to which different transport sectors are included under the program, and the existence of supplemental incentives can greatly affect both the scale of SAF deployment and the types of SAFs that enter the market. In Figure 11, we illustrate the total supply of three categories of SAFs in 2035: waste oil-based SAFs, crop-based SAFs, and second-generation SAFs. For the first two categories, we also present the increase in consumption of those feedstocks relative to the 2035 BAU case as a percentage change. Across the scenarios, in absolute terms, a high maximum credit price generally results in higher SAF volumes; however, between the high ambition, high maximum credit price scenarios (Scenarios 3 through 8), there is substantial variation in the mix and quantity of SAFs supplied. In terms of absolute volume, the highest quantity of SAFs is supplied in Scenario 5, where there is a binding obligation on both the aviation and road sectors in conjunction with a subsidy.

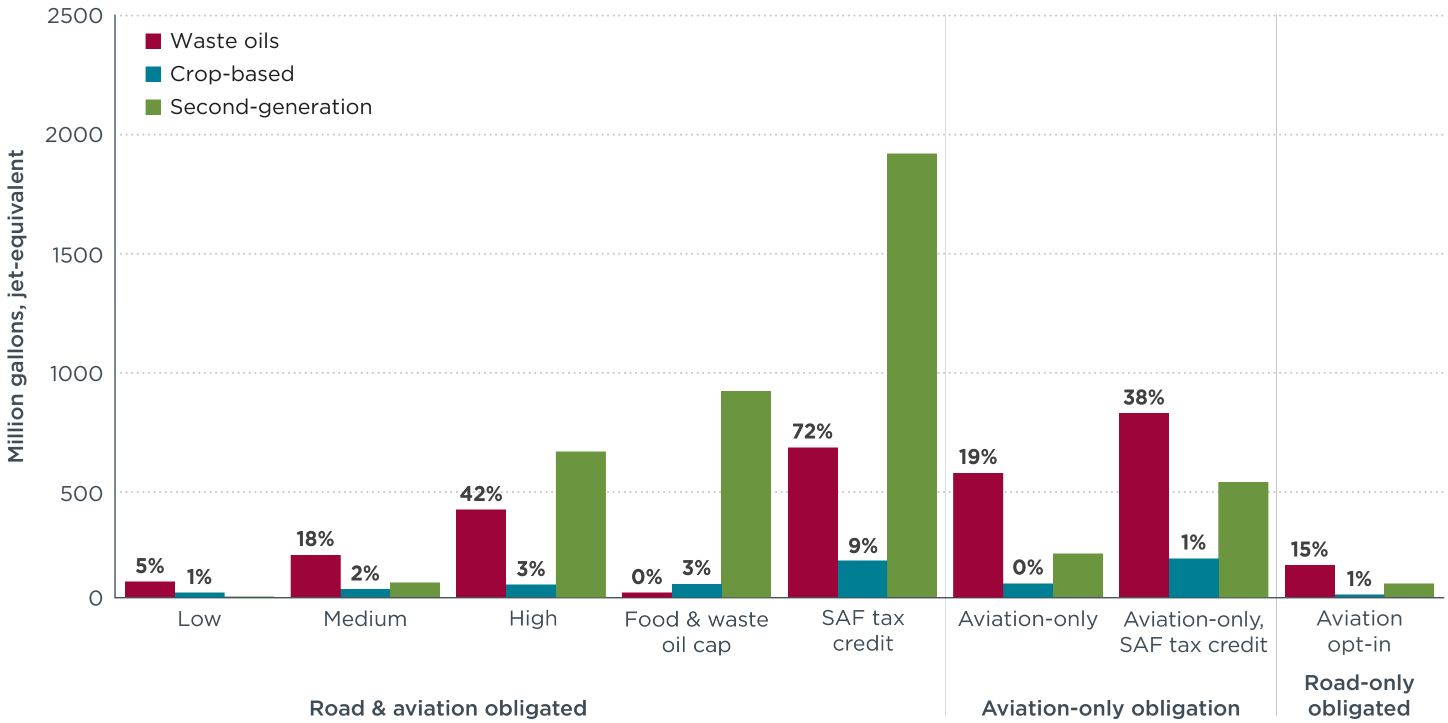

Figure 11. Projected 2035 volumes of crop-based, waste oil-based, and second-generation SAFs, across different aviation LCFS implementation scenarios. Percentages indicate the shares of aviation-induced increase in consumption of waste oils and vegetable oil-based biofuels versus the 2035 business-as-usual case.

Waste oil use increases from 5% to 72%, relative to 2020 consumption, in the scenarios where usage is uncapped in the program. This increase factors in only the waste oil increase attributable to aviation; due to over-compliance with the LCFS within the diesel sector, we estimate that waste oil usage increases significantly in the LCFS overall. For example, in Scenario 3, waste oil use in aviation alone causes a 42% spike in total waste oil consumption versus BAU; in that scenario, road sector waste oil usage grows negligibly. We find that the increase in waste oil demand is similar to the estimated growth in road-only LCFS scenarios modeled in Pavlenko, Searle, and Christensen.[31]

Though the use of waste oils has accelerated in the last five years, the domestic availability of these resources is limited. For example, 80% of retrievable UCO is estimated to already be collected in the United States.[32] There is some flexibility for additional collection of other fats, oils, and greases, but the overall potential falls far short of that necessary to provide the quantities suggested in these scenarios.[33] Comparing the aggregate increase in waste oil demand from road and aviation fuels against domestic potential plus an additional 1 billion GGE of potential waste oil supply in Asia when applying the standard collection rates discussed in Pavlenko, Searle, and

31 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard.*

32 Greenea, *The Year 2021: Which Investments Will See the Light in the Biofuel Industry?* (2021), https://www.greenea.com/wp-content/uploads/2021/01/Greenea-Horizon-2030-Which-investments-will-see-the-light-in-the-biofuel-industry-1.pdf.

33 Yuanrong Zhou, Chelsea Baldino, and Stephanie Searle, *Potential Biomass-Based Diesel Production in the United States by 2032* (Washington, DC: ICCT, 2020), https://theicct.org/publications/potential-biomass-based-diesel-production-united-states-2032.

Christensen, we find that demand exceeds supply in all but Scenario 4.[34] Scenarios 3, 5, and 7 also exceed a theoretical limit of 5 billion GGE of waste oils with higher, more optimistic collection rates. Greatly increasing the demand for waste oils to these levels exacerbates the risk of diversion from other non-transport sectors and of fraud, particularly from mislabeled virgin palm oil with potentially high deforestation impacts.

Overall, we find that the growth in crop-based biofuel in aviation is low across all scenarios. Virgin vegetable oil consumption attributable to aviation demand increases by up to 9% relative to the 2035 baseline consumption, depending on the scenario. One key barrier to the contribution of crop-based biofuel is the high GHG intensity of corn alcohol-to-jet SAF; though this fuel is relatively low cost and abundant, it generates GHG savings of less than 20% compared to fossil jet fuel and falls above the GHG intensity standard for some of the more ambitious scenarios in later years. Another contributing factor is the impact of cross-sector compliance; we find that soy use overall grows considerably in the road sector in every scenario barring Scenario 4, where the consumption of crop-based biofuels is capped at 2020 levels. Thus, we find that it is often cheaper to blend soy renewable diesel for compliance than soy HEFA; in scenarios with both the road and aviation sectors obligated under the LCFS, we find that diesel over-compliance is used to meet aviation sector compliance. This changes slightly in Scenario 5, where the SAF tax credit improves the relative value of soy HEFA and shifts some volumes of soy oil away from the road sector towards aviation.

We find that the SAF tax credit increases both the supply of SAF and the deployment of more expensive, second-generation pathways into the sector. For the two scenarios with a tax credit in place (Scenarios 5 and 7), we find that SAF volumes increase by approximately 2.5 to 2 times their quantities in corresponding non-tax credit scenarios (Scenarios 3 and 6, respectively). Though soy HEFA is eligible for the tax credit, the performance-based structure of the credit provides greater value for second-generation and waste oil pathways, thus driving greater growth from those fuels. However, we note that this analysis may overstate the impact of tax credits on motivating new production. The short duration and lack of policy certainty associated with the biodiesel producer tax credit in the United States may prompt investors in new projects to discount the value of the tax credit when assessing potential new projects.[35] A new SAF facility may take several years to construct and have an operating lifetime of at least a decade, whereas the SAF tax credit in the IRA currently lasts only through 2027. It is therefore possible that the tax credit may incentivize the near-term shuffling of existing renewable diesel production towards SAFs but lack the certainty to stimulate investment in projects with long-term payoffs.

Figure 12 illustrates the 2035 fuel mix GHG intensity reduction target and SAF blending rate of each scenario. We find that the aviation-only LCFS scenarios generally allow for more targeted and effective GHG reductions in the aviation sector. Though the policy-wide GHG reduction targets are lower in these scenarios, compliance is generated entirely within the aviation sector. Notably, these scenarios do not exhibit the large, policy-wide increases in soy and waste oil demand seen in the other scenarios—the increase in consumption of these feedstocks is solely attributable to the aviation sector and is overall more constrained. For example, despite a policy-wide 29% GHG reduction target in the high ambition scenario (Scenario 3), the SAF blending rate only

34 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard.*

35 Evan Markel, Charles Sims, and Burton C. English, "Policy Uncertainty and the Optimal Investment Decisions of Second-Generation Biofuel Producers," *Energy Economics* 76 (October 2018): 89–100, https://doi.org/10.1016/j.eneco.2018.09.017.

increases to 5%. Policies with dedicated SAF tax credits, such as Scenarios 5 and 7, have the highest SAF blending levels. In contrast, the opt-in SAF LCFS in Scenario 8 only generates SAF blend levels of 0.7% by 2035 and has a minimal impact on the GHG intensity of aviation fuels.

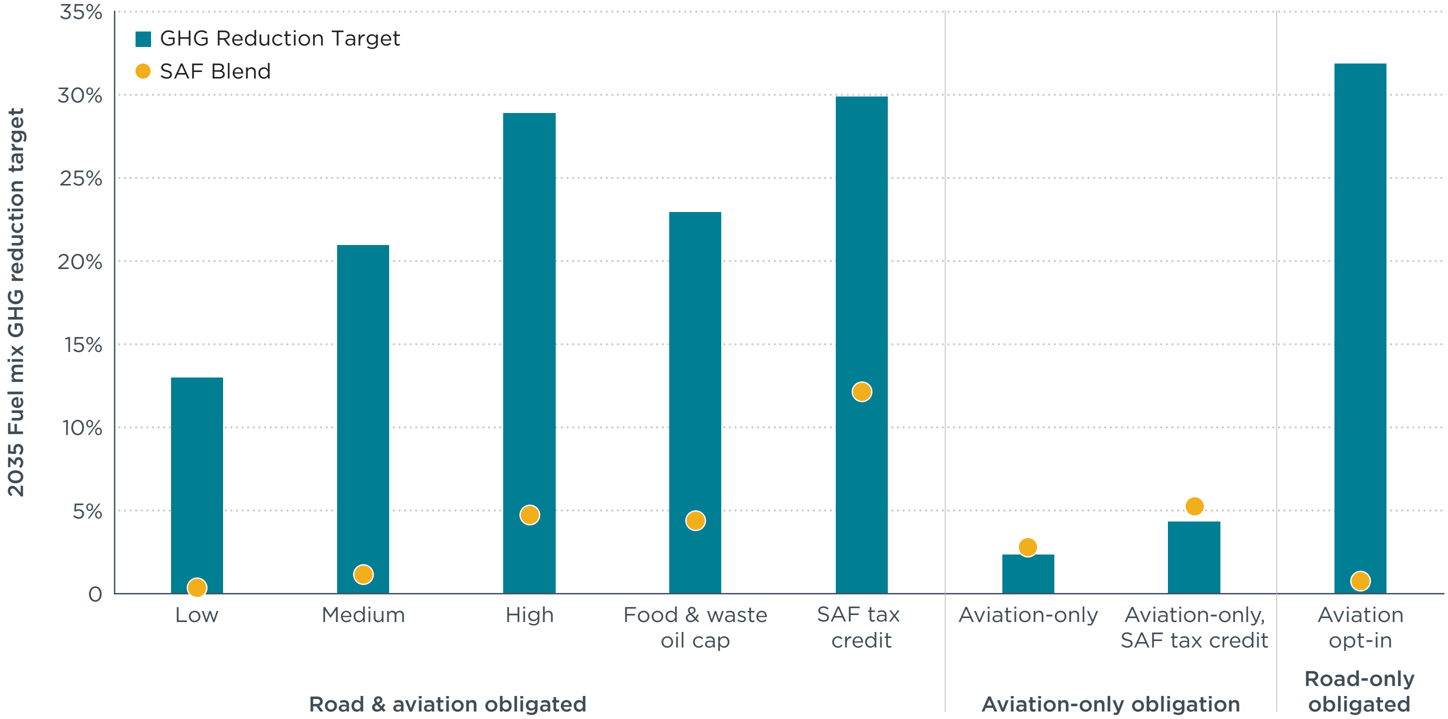

Figure 12. 2035 fuel mix carbon intensity reduction targets and SAF blending rates (represented by triangles), by scenario.

Together, these results suggest that an opt-in, all-incentive approach for motivating SAF use will have limited effects. Although tax credits can reduce the cost of SAF production and make pathways more cost-competitive for compliance by obligated parties, tax credits alone do not create a sizeable market for SAFs, particularly if those tax credits do not make SAFs cost-competitive with fossil fuels. Notably, the aviation opt-in scenario falls far short of the Biden Administration's 3 billion gallon SAF target, reaching only approximately 200 million gallons of SAFs by 2035. In contrast, the scenarios with the highest levels of SAF deployment (Scenarios 5 and 7) obligate the aviation sector and use subsidies to facilitate compliance.

As noted in Pavlenko, Searle, and Christensen, the assumed penetration of electric vehicles in the road sector and cross-sector credit trading may blunt some of the intended impact of an LCFS on liquid alternative fuel deployment.[36] For example, in scenarios that include the road sector, the volume of credits from electric vehicle charging provides nearly two-thirds of total program compliance by 2035, greatly exceeding the contribution from SAFs. Similarly, despite the deficit generation from gasoline being more than double that of diesel and aviation, the relatively low cost and minimal blend constraints of renewable diesel enables over-compliance in the diesel sector. This matches existing behavior noted in the California LCFS, wherein the ethanol blend wall of 10% has driven compliance towards drop-in renewable diesel,

36 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*.

reaching blending levels in excess of 50% in 2023.[37] For this reason, the actual GHG intensity reductions for aviation fuels consumed in 2035 fall short of the overall GHG intensity reduction target in most of the scenarios that include the road sector, as shown in Figure 12. Scenario 5 provides a partial exception to this case, as the tax credit improves the relative case for SAF blending and reduces over-compliance in the diesel sector.

We find that demand response can vary significantly depending on the scenario. Figure 13 illustrates the change in total aviation fuel demand (which is a proxy here for aviation demand) between the 2035 BAU case and the 2035 results for each scenario. Overall, we find that demand changes by approximately 0% in the lowest case, to a 23.6% reduction in the highest case. The highest demand reduction occurs in scenarios with high ambition and high credit prices where the road sector is also obligated alongside the aviation sector.

Interestingly, the aviation-only LCFS scenarios have lower demand reductions, ranging from 2.2% to 3.9% for Scenarios 6 and 7, respectively. Although this result appears counter-intuitive, it is primarily driven by two factors: the absolute impact of GHG intensity targets, and competition between sectors. Specifically, we find that the aviation-only LCFS scenarios have lower overall GHG reduction targets, and there is no competition with blenders for diesel blendstocks. This allows for the diversion of relatively small quantities of cheaper corn oil, tallow, and UCO from the road sector without increasing the cost of compliance with the LCFS (as the road sector is not obligated); thus, a large share of compliance can be generated prior to increasing the volumes of UCO imports and second-generation SAFs.

In contrast, Scenarios 2-5, which exhibit large demand reductions, have high policy compliance costs driven primarily through the blending of large quantities of renewable diesel in the road sector, which then passes a share of compliance cost onto the aviation sector. Though we find that an aviation-only LCFS creates the strongest signal for SAF deployment in the scenarios we assess here, this study does not take into account the existence of non-LCFS road sector biofuel policies. Imposing an aviation-only LCFS would necessarily make compliance with separate road sector policies more difficult, and increased competition could still drive up costs for feedstocks.

37 California Air Resources Board (CARB), “LCFS Data Dashboard,” accessed December 19, 2023, https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

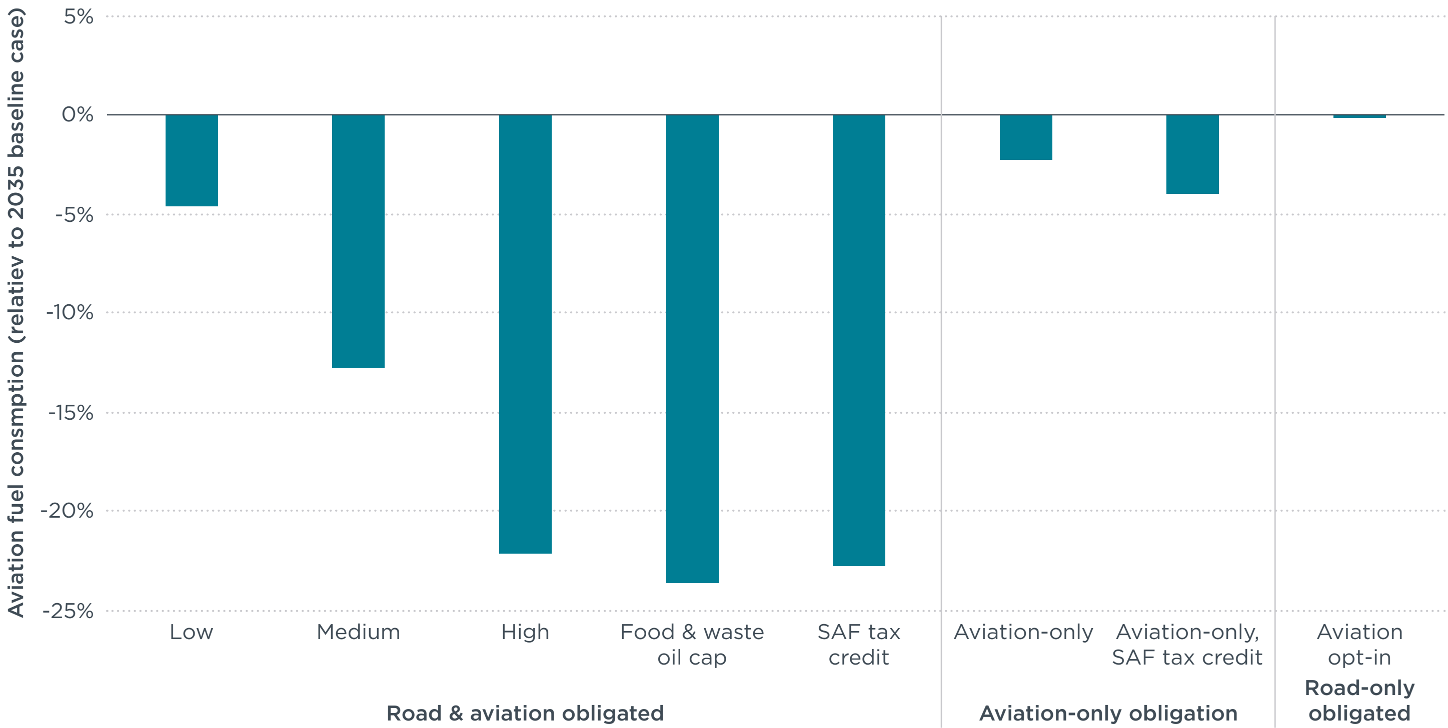

Figure 13. Change in aviation fuel demand by scenario, relative to 2035 business-as-usual case.

Although this modeling provides numerous insights into the impact of an LCFS on SAF deployment, we note several modeling limitations, data gaps, and opportunities for further work. A key limitation in the model structure is the fixed GHG intensity for each fuel pathway; the model can shift consumption across different fuels based on cost and GHG intensity but does not estimate the potential for GHG reductions within a given fuel pathway. The incentive for process improvement is a key component of the LCFS structure and has been a contributor to credit generation in the California LCFS.[38] For example, the opportunity to implement process improvements such as carbon capture and sequestration and renewable electricity use in corn ethanol refineries may allow corn ATJ fuel to play a larger role in an LCFS than projected here.[39]

We note that there are also large uncertainties with the future costs of second-generation biofuels that are currently produced in small volumes or are not yet commercialized. The cost curves used here assume a relationship between these fuels' modeled production costs and demand, but it may be possible for production costs to decline as economies of scale are reached.[40] In practice, this could reduce LCFS compliance costs and increase the relative quantities of second-generation pathways in the mix of fuels supplied to the transport sector. We note that the estimate of e-kerosene production cost here is more expensive than that estimated by Zhou, Searle, and Pavlenko, which factors in the potential for cost reduction year-over-year.[41] This effect, which was not able to be incorporated into the modeling

38 CARB, "LCFS Data Dashboard," accessed December 11, 2023.

39 Jim Spaeth, "Sustainable Aviation Fuels from Low-Carbon Ethanol Production," DOE, October 20, 2021, https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuels-low-carbon-ethanol-production.

40 Adam Brown et al., *Advanced Biofuels – Potential for Cost Reduction*.

41 Yuanrong Zhou, Stephanie Searle, and Nikita Pavlenko, *Current and Future Cost of E-Kerosene in the United States and Europe* (Washington, DC: ICCT, 2022), https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/.

framework here, could change the relative balance of second-generation fuels from lignocellulosic pathways towards e-kerosene, particularly in the 2030–2035 timeframe; however, it would still be more expensive than the higher volumes of waste oil HEFA fuels in most scenarios.

Emissions reduction from aviation attributable to demand reduction are not credited or included in the LCFS policy; the LCFS only regulates the emissions attributable to the fuel mix, regardless of the overall quantity of fuels consumed. The impacts of demand reduction on aggregate emissions are therefore unaccounted for and not credited within this policy, though they could comprise a sizeable share of overall sectoral emissions reduction.

The high contribution of electric vehicle charging to credit generation in most scenarios also distorts the credit market, as a large source of credits is generated outside of the liquid fuel pool, shifting the GHG intensity target for each scenario lower while simultaneously reducing the shifts in GHG intensity in the liquid fuel pools. If, for example, the LCFS credit generation from electric vehicles were to be phased out over time or limited to public charging, it would greatly change the GHG intensity target compliance strategy for the LCFS.

Conclusion

With many technical and economic barriers to deploying electric and hydrogen-fueled aircraft, particularly for long-haul flights, the aviation sector is likely to be reliant on liquid fuels through at least 2050. SAFs are produced in low quantities and most production pathways have high costs compared to conventional fossil jet fuel—this is particularly true for second-generation pathways made from abundant feedstocks with high GHG savings. Policy instruments like LCFSs can help to create an incentive to reduce emissions from aviation fuels, bridge the cost gap between SAFs and conventional fuels, and create a long-term market for SAFs. In this analysis, we model a selection of possible methods of including aviation fuels within a national-level LCFS policy. Across the scenarios, we find that an LCFS program can increase the quantity of SAFs deployed to the aviation sector. The exact quantity of fuels supplied and GHG emissions reductions within the aviation fuel mix depend strongly on several key policy design decisions.

An LCFS in which aviation opts in incentivizes much smaller quantities of SAFs compared to scenarios in which aviation is an obligated sector. Due to the high cost of SAF production and lack of carbon pricing on aviation, we estimate that SAF consumption only grows to 0.7% of aviation fuel demand by 2035 in an aviation opt-in LCFS scenario and falls far short of the U.S. SAF deployment targets. Of that total, the majority of aviation opt-in compliance is estimated to come from virgin vegetable oil and waste oils, primarily co-products of the bulk of LCFS compliance occurring in the road sector's diesel pool. We find that scenarios that obligate aviation, or are aviation-only, have a much greater impact on SAF deployment.

Cross-sector compliance can dilute the impact of a transport-wide LCFS on deploying SAFs. We find that in scenarios where the aviation sector is included in an LCFS alongside the road sector, it is still more cost-effective to blend drop-in, renewable diesel. While the inclusion of the aviation sector can increase volumes of SAFs significantly compared to the baseline case, reaching up to 14% of aviation fuel in 2035 in one scenario, it remains cheaper to over-comply in the road sector than to offset aviation deficits solely with SAFs. We find that this effect can be mitigated by supplementary outside incentives, such as an SAF tax credit; including such a credit in a combined road and aviation LCFS increased SAF volumes by more than 2 times compared to a similar scenario without the tax credit in place. We also find that a dedicated, aviation-only LCFS can have a much more direct impact on SAF deployment despite having a lower stated GHG reduction target, as the entire target would be met in-sector, without cross-sector credit trading.

A supplemental SAF tax credit can greatly improve the cost viability of SAF production within an LCFS. SAFs are more expensive to produce than road sector fuels even when using the same feedstock. We find that in scenarios with an SAF tax credit in place, the volume of SAF deployed increases by 2 to 2.5 times compared to similar scenarios without the tax credit. We find that in a scenario with both road and aviation sector obligation, the tax credit improves the cost viability of blending SAF in place of over-compliance in the diesel sector with cheaper renewable diesel. In the aviation-only LCFS scenario, we find that the tax credit enables a higher overall LCFS target and makes more SAF available at the same maximum credit price. The structure of the tax credit, which is proportionally adjusted based on the GHG intensity reduction, creates a greater incentive for shifting waste oil-derived and second-generation biofuels with higher GHG savings to the aviation sector. Though the current tax credit for SAF production in the IRA is set to expire after 2027, a stable tax credit over the duration of the LCFS could encourage investment and growth the SAF industry.

Feedstock-specific guardrails built into the LCFS structure could mitigate sustainability risks and create opportunities for second-generation alternative fuels. Although existing LCFS policies such as California's LCFS are fully technology-neutral, we find that this approach prioritizes blending larger volumes of cheaper, first-generation fuels, with potential sustainability concerns such as indirect land-use change emissions and waste oil fraud. Consequently, we find that in most of the scenarios, the inclusion of aviation fuels increases waste oil consumption, from 6% to 72% relative to 2020 consumption levels; combined with growth in road sector consumption, this likely pushes waste oil imports beyond global availability and greatly increases the risk of waste oil fraud. Despite having a theoretically higher per-gallon value under an LCFS, second-generation fuel pathways struggle to reach a large market share in several scenarios. We find that capping the contribution of first-generation crop-based and waste oil-based biofuels in the LCFS program on an energy basis can contain the risks associated with these feedstocks while still incentivizing process improvements for them and creating greater opportunities for second-generation SAF pathways necessary for long-term decarbonization.

Appendix

This appendix summarizes the equilibrium model structure used for this analysis. This analysis uses a GAMS-based partial equilibrium model of the U.S. transport fuel sector, in which we use a set of counterfactual policy scenarios to evaluate the market response to different LCFS policy scenarios versus a BAU projection based on the Energy Information Administration's *Annual Energy Outlook*. A full description of the model is provided in Pavlenko, Searle, and Christensen.[42] The model includes several agents within the transportation fuel market that make cost-optimized decisions, including representative consumer agents purchasing vehicles, blender agents purchasing fuels, and supply agents for different fuel blendstocks. The sections below provide an overview of these agents and the model structure.

Consumer agents

Consumer agents are modeled as cost minimizers that make vehicle purchase decisions based on the cost of vehicles and the cost of vehicle miles traveled (VMTs). Consumer agents can choose between different vehicles, factoring in vehicle purchase price, vehicle efficiency, and the cost of fueling. For aviation consumer agents, there is not an option to change between vehicle technologies, as we assume all aircraft relevant to the analysis will be reliant on liquid jet fuel. The aggregate VMT generated by each vehicle class is modeled by a constant elasticity of substitution (CES) style production function. The CES style production function allows for vehicle preferences to change between categories and is used to capture the aggregate preferences for all consumers; we use the calibrated share form of the CES function.[43] The consumer agent problem can be described mathematically as the following optimization problem (Equation A1).

Equation A1. Consumer agent optimization

$$\min_{VKT_v} \sum_{v,f} \left[\frac{P_f - P_f^{LCFS}}{Y_v} + Z_v^{opex} + Z_v^{capital} \right] VMT^v$$

$$\text{s.t.} \sum_{v,f} \left[\theta_v \left(\frac{VMT^v}{VMT^v} \right)^{\rho} \right]^{\frac{1}{\rho}} = D$$

Where:

$v \in V$	represents different vehicle technologies
$f \in F$	represents blended fuels that are used in each vehicle
P_f	represents the final price for the underlying blended fuel, with the consumer assumed to be a price taker from the blender agent
P_f^{LCFS}	represents the final value (cost or benefit) of the GHG credits associated with a finished (blended) fuel, with the consumer assumed to be a price taker from the blender agent
VMT_v	are decision variables that represent the number of miles driven by a vehicle *(billion miles/year)*
Y_v	is the fuel economy of the vehicle *(miles/Megajoule [MJ])*
ρ	is the substitution parameter (which is related to the elasticity of substitution)
θ_v	is the market value share for vehicle *v*

42 Pavlenko, Searle, and Christensen, *Opportunities and Risks for a National Low-Carbon Fuel Standard*.

43 T.F. Rutherford, "Lecture Notes on Constant Elasticity Functions" (notes for a lecture, University of Colorado, Boulder, CO, November 2002), https://windc.wisc.edu/downloads/summercourse_2021/thursday/ces.pdf.

Z^{opex}_{v} is the data that represent non-fuel vehicle operating costs *($/mile)*
$Z^{capital}_{v}$ is the data that represent vehicle capital costs *($/mile)*
D is the aggregate vehicle market value for an agent *(billion $)*

The final demand is described by an isoelastic function shown in Equation A2, and is a function of the aggregate price index (*PD*), which is exactly the dual variable of the CES production function in Equation A1. The aggregate price index is equal to 1 at the benchmark when using the calibrated share form of the CES production function.

Equation A2. Consumer agent final demand equation

$$D = \bar{d}\left(\frac{PD}{1}\right)^{-\epsilon}$$

Where:

D represents aggregate consumer demand
$\bar{d}$ is the baseline aggregate vehicle market value for an agent *(billion $)*
PD is the aggregate price index
ϵ is the agent's demand elasticity

Blender agent

The blender agent represents the obligated parties in the LCFS program; the model assumes that a single blender agent is responsible for blending all fuels and meeting the necessary policy requirements. Like consumer agents, the blender agent will minimize costs. The blender agent is assumed to purchase quantities of energy from fuel suppliers. The blender agent problem can be described mathematically as the base optimization problem shown in Equation A3.

The single blender model implies that the price of the LCFS credit is equivalent to the marginal price on the credit market clearing condition (i.e., with zero net credits). As the volumes of SAFs deployed in the 2020–2035 timeframe fall far short of the 50% blending limit for currently certified SAF pathways, we do not include a blender constraint on the aviation sector.[44] The model incorporates cross-fuel pool compliance to allow for compliance to be achieved outside of the sector that generates LCFS deficits; for example, if it is more cost effective to achieve compliance in the aviation sector with LCFS credits generated by light- or heavy-duty vehicles, then blender agents will attain all their credits in the LDV and HDV sector, and apply them against deficits generated in the aviation sector.

Equation A3. Optimization equation for blender agents

$$\min_{Q^{blend}_{bs,f}} \sum_{bs \in BS\,(bs,f)} \left[Q^{blend}_{bs,f}\, \rho_{bs} \right]$$

$$\text{s.t. } P_f = \sum_{bs} \frac{Q^{blend}_{bs,f}}{Q_f}\, \rho_{bs}$$

44 ASTM International, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," updated November 28, 2023, www.astm.org/Standards/D7566.htm.

$$Q_f = \sum_{bs} Q_{bs,f}^{blend}$$

$$Q_f = \sum_{v,a} \frac{VMT_{v,a}}{Y_v}$$

$$E_f = \frac{\sum_{bs,f} Q_{bs,f}^{blend}}{\sum_{bs,f} \frac{Q_{bs,f}^{blend}}{\rho_{bs}^{v}}}$$

$$\sum_{bs,bst,f} \frac{\frac{Q_{bs,f}^{blend}}{\rho_{bs}^{v}}}{\frac{Q_f}{E_f}} \leq BLEND_{bs,f}^{UP}$$

$$\sum_{bs,bst,f} \frac{\frac{Q_{bs,f}^{blend}}{\rho_{bs}^{v}}}{\frac{Q_f}{E_f}} \leq BLEND_{bs,f}^{LO}$$

$$\sum_{bs,bst,f} \frac{\frac{Q_{bs,f}^{blend}}{\rho_{bs}^{v}}}{\frac{Q_f}{E_f}} \leq BLEND_{bs,f}^{FX}$$

Where:

$bs \in BS$	represents different fuel blendstocks
$f \in F$	represents blended fuels that are used in each vehicle
$bst \in BST$	represents common categories of blendstock types (e.g., all ethanol, all FAME, or all SAF)
$\rho^{v}{}_{bs}$	is the energy density of a blendstock *(MJ/physical unit)*
P_f	is the final price for blended fuel *($/MJ)*
$Q_{bs,f}^{blend}$	are decision variables that represent the portion of energy from a blendstock used in a finished fuel *(billion MJ)*
Q_f	are decision variables that represent the total energy of a finished fuel *(billion MJ)*
E_f	are decision variables that represent the energy density of a blended fuel *(MJ/physical unit)*
$BLEND_{bst,f}^{LO,UP,FX}$	are technology-based limits on blending fuels (e.g., E10 blends)

Fuel supply is modeled via an isoelastic supply curve. The price of a given blendstock is a factor of its baseline cost, baseline consumption, and demand across all included transport sectors, with the change over the total quantity informed by the supply elasticity. This curve is represented by Equation A4.

Equation A4. Blender agent supply curve equation

$$\frac{P_{bs}}{\bar{p}_{bs}} = \left[\frac{Q_{bs}}{\bar{q}_{bs}}\right]^{\frac{1}{\eta_{bs}}}$$

Where:

P_{bs}	is the price at which a quantity of blendstock fuel can be supplied *($/MJ)*
Q_{bs}	is the quantity of blendstock that is demanded under a policy shock *($/MJ)*
$\bar{p}_{bs}$	is the baseline price at which the baseline quantity of blendstock is supplied *($/MJ)*
$\bar{q}_{bs}$	is the baseline quantity of blendstock fuel *($/MJ)*
η_{bs}	is the supply elasticity for a particular blendstock fuel