Policy Interactions and the Cost of Decarbonizing Aviation*

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Abstract

U.S. federal and state biofuel policies interact in complex ways, but existing models insufficiently capture these relationships, limiting analyses and the effective design of new policies. We develop a detailed partial equilibrium model of road and air transportation fuel markets to compare policy options to incentivize the deployment of sustainable aviation fuel (SAF). We find several federal policy options result in similar emissions reductions and costs but different incidence across jurisdictions, fuel users, and taxpayers. Our lowest cost policy scenario entails replacing current biofuels policies with a modest carbon tax on fossil transportation fuels and a SAF tax credit.

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Transportation is the highest emitting sector in the United States, representing 28% of total greenhouse gas (GHG) emissions in 2022 (EPA 2024). Electrification of road transport has gained momentum in recent years, but decarbonization of aviation, which represents 9% of transportation emissions, remains a challenge. Globally, air transportation passenger trips are expected to increase by 3.8% annually over the next 20 years (IATA 2024). Although short-haul flights can potentially be electrified, and hydrogen fuel might be an option decades from now, for the foreseeable future the path towards decarbonizing long-haul jets relies on sustainable aviation fuel (SAF). SAFs are liquid aviation fuels derived from feedstocks such as waste oils and fats, crops such as corn, soy, and sugarcane, cellulosic biomass, municipal solid waste, or captured CO_2. Because they generally have lower estimated GHG emissions than petroleum jet fuels, can be blended at high ratios with petroleum fuels, and can be used with existing aviation infrastructure, SAFs are the most likely technologies for near-term reductions in aviation emissions outside of reducing air travel demand (Bergero et al. 2023).

SAFs are, however, far more expensive than petroleum jet fuel and are expected to remain so (Braun, Grimme, and Oesingmann 2024; Watson et al. 2024). The highly competitive nature of the airline industry makes it unlikely that voluntary firm-level commitments will provide a durable basis for widespread adoption. Thus, under current cost projections, SAFs will not be widely adopted without long-term policy support.

In 2011, the U.S. Federal Aviation Administration set a goal for U.S. airlines to use one billion gallons (Bgal) of SAF annually by 2018 (FAA 2011). Actual SAF production fell far short of this target: in 2018 only 1.8 million gallons were produced (GAO 2023). In 2021, the Department of Energy launched the SAF Grand Challenge, which set annual domestic production targets of 3 Bgal by 2030 and 35 Bgal by 2050 (White House 2021).[1] At the beginning of 2024, U.S. annual production capacity for SAF was approximately 30.66 million gallons, representing just 1% of the 2030 target level and roughly 0.1% of the current U.S. jet fuel supply of 25 Bgal (EIA 2024). Company announcements and trade press suggest that capacity has since increased dramatically, reaching approximately 460 million gallons per year by mid-2025, although this capacity could instead be used to produce renewable diesel for surface transportation (EIA 2025b).

Because currently available SAFs are predominantly biofuels, SAF policy will interact with policies that promote the production and use of biofuels for surface transportation. In the United States, these policies include the Renewable Fuel Standard (RFS), which mandates blending biofuels into the surface transportation fuel supply, federal tax credits, state-level Low Carbon Fuel Standards (LCFS), and state tax credits. These policies provide subsidies for producers and consumers of biofuels and, depending on the policy, the cost of these subsidies falls on drivers, surface freight shippers, or taxpayers. Together these policies create a subsidy stack that varies by feedstock, type of fuel, carbon intensity, and the location of production and/or consumption. The interactions between policies are central to determining economic and environmental outcomes; therefore, any

1. The SAF Grand Challenge has since been renamed the Sustainable Aviation Fuel Initiative; as of September 2026 it remains active and is listed on the Department of Energy website.

proposed SAF policy must be developed and assessed in the context of existing biofuel policies. The mix of policies in place helps determine the total quantity, as well as the composition by technology and feedstock, of biofuel produced and consumed in the United States for surface and aviation fuel.

In this paper, we build a partial equilibrium model of road and air transportation fuel markets that incorporates existing and potential biofuel policies. We use the model to examine policy options for meeting a 3 Bgal annual SAF target by 2030, which would result in SAF comprising about 12% of U.S. jet fuel consumption in that year. This goal, whether formally adopted or not, represents a useful near-term benchmark along a meaningful path toward decarbonizing aviation and appears to be feasible from a technological perspective.

The model represents 12 biofuel-feedstock combinations ("pathways") including pathways that integrate carbon capture and storage (CCS) to reduce fuel emissions intensity. Total production costs for each pathway are calibrated using residual feedstock supply elasticities and process production cost data drawn from rack-level data and the techno-economic literature. We solve for the prices of tradable allowances, such as RFS Renewable Identification Numbers (RINs), so that all the policy mandates hold (either binding or slack). We evaluate six alternative policy scenarios designed to achieve the 3 Bgal SAF target and discuss the estimated emissions reductions, cost effectiveness, fuel-feedstock mix, and cost incidence of each policy.

We have five main findings. First, we find that current policies alone are insufficient to achieve the SAF production target of 3 Bgal by 2030. Specifically, under the current policy scenario and absent any voluntary SAF demand, 75 million gallons of SAF are produced in 2030. A large amount of biodiesel feedstock that could be used for SAF is converted instead to less-expensive renewable diesel, which replaces petroleum diesel in California to satisfy the California LCFS. That is, the current U.S. policy mix incentivizes the use of biofuels for surface transportation over aviation. To reach the 3 Bgal target, additional or alternative policies are needed. We explore several possible policy tools that could be used to reach this goal.

Second, we find that several of these policy options, including (1) a regulatory change to the RFS that creates a SAF requirement separate from biomass-based diesel, (2) the introduction of a SAF tax credit in addition to current policy, and (3) the introduction of a clean aviation standard in addition to current policy, would all result in similar overall economic costs and total emissions, but would yield different cost incidence. Relative to the current policy mix, these three policy tools would result in higher economic costs and lower total emissions.

Third, we find that replacing all current federal and state biofuel policies with a $15/metric ton carbon tax on fossil transportation fuels and a SAF tax credit could reduce emissions, reach the 3 Bgal target, and substantially reduce total policy costs, all relative to the current policy mix.

Fourth, additional policy costs of reaching the 3 Bgal target are disproportionately borne by California. This occurs because increased demand for SAF outside of California, encouraged by state-level tax incentives, increases competition for feedstocks otherwise used to produce biomass-based diesel for compliance with California's LCFS.

Fifth, it follows from the first two findings that achieving the 3 Bgal SAF target through the

enactment of additional policy is more costly than maintaining current policy, at least in a static sense and as long as biofuel policy continues to maintain a mandated level of total biofuel use. The costs reported in this paper, however, do not account for any technological innovation induced by a durable SAF policy that would spur investment; costs arguably could be driven down further by extensive federal R&D support for advanced low-carbon SAFs, a mechanism we do not model.

This paper contributes to the growing literature on interactions among overlapping climate and energy policies by providing a detailed, sector-specific analysis of how SAF policies interact with existing state and federal incentives for biofuel use in road-transportation (Holland, Hughes, and Knittel 2009; Goulder and Stavins 2011; Scott 2024; Perino, Ritz, and Benthem 2025). Relative to the existing policy literature, this paper is the first to situate SAF policies in the context of a detailed model of existing U.S. and state biofuels policies, the first to solve endogenously for the full subsidy stack, the first to incorporate the important influence of the California LCFS, and the first to allow for some policy requirements to be binding while others are nonbinding. This paper also adds to a small but growing literature on the techno-economic feasibility of decarbonizing aviation under various SAF pathways (Delbecq et al. 2023; Bardon, Massol, and Thomas 2025) and to literature on U.S. policy options for stimulating SAF production (Winchester et al. 2015; Jiang and Yang 2021; Zheng, Wang, and Jiang 2024).

The remainder of this paper is organized as follows: Section I provides background on the fuel technologies and policies under consideration. Section II describes the model, data, and scenarios used. Section III describes the results and Section IV concludes and provides policy implications.

I. Background

A. Fuel Pathways

Sustainable aviation fuels (SAFs) are hydrocarbon fuels made from non-petroleum feedstocks that result in lower GHG emissions than conventional jet fuel. Two SAF production technologies are currently operational in the US: (i) hydroprocessed esters and fatty acids (HEFA), which uses vegetable oils and waste fats, and (ii) alcohol-to-jet (ATJ), which typically uses ethanol or isobutanol from sources like corn and sugarcane.[2] Others, including Fischer-Tropsch and power-to-liquid, are still under development and beyond the scope of this study; a full list of development-stage pathways is provided in Supplemental Appendix Section H.

A biofuel pathway is defined as a combination of a feedstock, a production process, and a fuel type. The life-cycle carbon intensity of each pathway accounts for emissions across the full supply chain, including direct emissions from feedstock production, processing, transportation, and fuel use, and indirect emissions from induced land-use change, shifts in non-feedstock crop production (e.g., methane emissions from rice paddies) and changes in livestock production (Lark et al. 2022).

2. Although ASTM has certified ATJ pathways, ATJ remains at the pilot stage, and LanzaJet's Soperton, Georgia, is currently the only operating plant. We provide a detailed summary of current ATJ-SAF plants in Supplemental Appendix Section H. We assume ATJ projects will reach final investment decisions and begin construction soon after policies take effect; however, this is highly optimistic.

To evaluate pathway emissions under each policy scenario, we rely on the CA-GREET model, which is used by the California Air Resources Board for LCFS implementation. Importantly, these estimates depend on model assumptions and are characterized by a high degree of uncertainty, in part because supply chains are often complex, and especially because there is disagreement about the appropriate way to model indirect land-use change (ILUC) emissions. These emissions arise when increased demand for feedstocks leads to additional land conversion and the subsequent release of carbon previously stored in vegetation and soils, and they can be particularly large when biofuel production results in tropical deforestation in, for example, Brazil to grow soybeans or Indonesia to grow oil palm. Model-based estimates of ILUC vary, and there is a robust academic debate about the true emissions of crop-based biofuels and indeed whether they are significantly lower than fossil fuels (Lark et al. 2022; Searchinger et al. 2018; Berry, Searchinger, and Yang 2024).

The 12 biofuel production pathways we model in this study are listed in Table 1. The three most common biofuels are ethanol, biodiesel, and renewable diesel. Ethanol is almost entirely produced from corn or sugarcane, although a small amount is made from cellulosic feedstock. Biodiesel and renewable diesel are made from crop-based vegetable oil (e.g., soybean oil, canola), tallow, or used cooking oil. Biodiesel use is somewhat limited by its lower energy density compared to petroleum diesel, its greater sensitivity to cold, and its potential to clog fuel lines and corrode storage tanks, all of which result in a technical blending limit of 20% for use in most diesel engines. Additional non-technical constraints such as labeling requirements have limited biodiesel blending rates in California to approximately 7.5%. Unlike biodiesel, renewable diesel is chemically indistinguishable from petroleum diesel and can be used in diesel engines without restriction.

The HEFA process, which is currently the most common way to produce SAF, is also used to produce renewable diesel. It is similar to the process used to desulfurize petroleum diesel, so existing petroleum refineries can be, and have been, converted to produce renewable diesel and SAF; indeed, HEFA production facilities are increasingly being designed to co-produce both fuels. We therefore model HEFA producers as capable of producing both fuels with choice variables over both the quantity of production and the ratio of SAF to RD. However, even under a configuration designed to maximize SAF output, it can only comprise about 55% of total liquid product; we therefore include a 55% SAF yield constraint (Baldwin, Nimlos, and Zhang 2022).[3] In addition to HEFA SAF, we also model SAF produced through ATJ and ATJ with carbon capture and storage (CCS).[4] SAF is currently approved to be mixed with conventional jet fuel at levels of up to 50%, is compatible with existing aircraft, and requires no modifications to current fueling infrastructure.

Table 1 shows the estimated CI of a representative set of fuels under each pathway. As illustrated in the last three columns of this table, CI values vary substantially between models used by the

3. SAF typically only makes up about 15% of the total liquid product from these facilities (vs. 75% for RD), with the remainder consisting of "light ends." Industry sources suggest that the maximum SAF yield may reach 75–80% of volumetric liquid fuel output under more aggressive process optimization, with renewable diesel reduced to roughly 5–10%. We conduct a robustness check on this yield structure assumption in Supplemental Appendix Section G.4.

4. ATJ+CCS is viable mainly because ethanol fermentation creates a CO_2-rich off-gas stream that is easy to capture. HEFA does not produce a similarly concentrated CO_2 stream; it could be paired with direct air capture, but this remains expensive and is therefore not treated as a viable option in our modeling.

TABLE 1: Biofuel pathways and estimated carbon intensities

Fuel	Production Process	Feedstock	Carbon Intensity (gCO_2e/MJ) EPA LCA (RFS)	CA-GREET	45ZCF-GREET (CA Fuels, no ILUC)
SAF Pathways					
Sustainable Aviation Fuel	HEFA	Crop-based vegetable oils	35.77	47.37	25.84
		Tallow & waste oils	13.04	33.60	17.46
	ATJ	Corn	61.96*	61.96*	55.68
		Sugarcane	49.21*	49.21*	33.99
	ATJ w/CCS	Corn	31.96**	31.96**	25.68
		Sugarcane	19.21**	19.21**	3.99
Road Transport Fuel Pathways					
Biodiesel	Average	Crop-based vegetable oils	40.72	47.53	21.64
		Tallow & waste oils	13.04	23.34	17.96
Renewable Diesel	Average	Crop-based vegetable oils	34.78	49.97	24.61
		Tallow & waste oils	13.04	33.89	16.69
Ethanol	Average	Corn	73.21	69.40***	40.17
		Sugarcane	36.10	52.04	23.24

Notes: This table shows the 12 modeled biofuel pathways and the estimated carbon intensity (CI) of a representative set of fuels within each under EPA RFS, CA-GREET (LCFS), and 45ZCF-GREET (only CA fuels). For EPA RFS, we include CIs of the most common technology for each feedstock-fuel combination. For CA-GREET, we calculate average CIs from currently approved pathways under LCFS. For 45ZCF-GREET, we calculate CIs based on sample inputs for California production and exclude indirect land-use change in line with recent policy amendments and to provide a consistent comparison between models. When CI estimates are not available in CA-GREET or EPA LCA (indicated by *), we include 45ZCF-GREET CI values (with ILUC) calculated for fuels produced in California. We assume CCS can lower the CI of ATJ by $30gCO_2e/MJ$ (indicated by **), based on estimates from Xu, Lee, and Wang (2022). The average estimated CI for corn ethanol under CA-GREET is $69.68gCO_2e/MJ$; we force it to be 69.40, which is the 2030 CARB gasoline standard (indicated by ***). Corn ethanol is unlikely to generate CARB deficits, and its CI has declined in recent years. Details about assumptions and data sources used to construct this table are provided in Supplemental Appendix Section B.1.

California Air Resources Board (CARB) for LCFS implementation (CA-GREET model) and those used by the federal government for 45Z tax credit implementation (45ZCF-GREET) and for the calculation of lifecycle greenhouse gas emissions under the RFS program.

Most of the differences between carbon intensity estimates shown in Table 1 stem from differences in LCA modeling methodology.[5] For example, recent amendments to 45Z excluded ILUC from emissions accounting (U.S. Congress 2025), resulting in significantly lower estimated carbon intensity values. Our modeling assigns models to particular policies to match how eligibility and incentive values are actually determined in practice (e.g., 45ZCF-GREET, excluding ILUC emissions, is used for 45Z; CA-GREET is used for California's LCFS). We use 45ZCF-GREET (including ILUC emissions) to determine eligibility for both state tax and hypothetical federal SAF tax credits. As noted earlier, while we estimate the emissions impact of hypothetical policies using CA-GREET, assumptions made under all models have been subject to ongoing scrutiny and may not fully represent the true carbon intensity of biofuel production and use.

5. Some of the variation shown in the table may stem from differences in fuels credited under these programs or pathway assumptions we made when estimating these values. For additional discussion, see Appendix Section B.1.

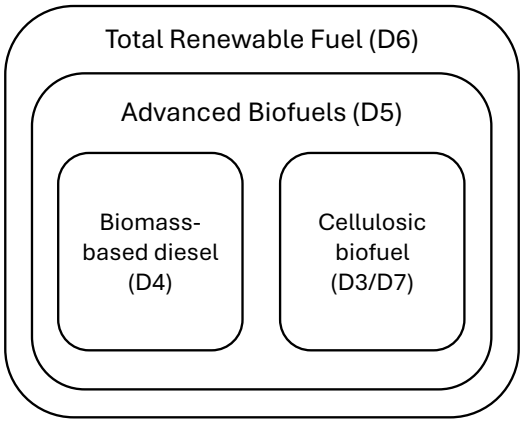
B. Policy Context

Policy efforts to incentivize the development and deployment of biofuels in the United States have largely targeted road transportation in the form of volumetric mandates, tax incentives, and emissions intensity standards. We describe each of the major policies below.

1. Renewable Fuel Standard

Under the federal Renewable Fuel Standard (RFS), the Environmental Protection Agency (EPA) sets volumetric mandates for the use of several classes of road transportation biofuels, with each class corresponding to a required carbon emissions reduction relative to petroleum alternatives. It has a nested structure, as depicted in Figure 1.[6] First, it requires a total quantity of renewable fuel (D6). Second, a specified portion of this renewable fuel must be advanced biofuels (D5). Corn ethanol is the only widely used biofuel that qualifies for the total mandate but not the advanced mandate. Third, specified portions of advanced biofuels must be cellulosic biofuels (D3/D7), which are made from the inedible parts of plants, and biomass-based diesel (D4) fuels. Imported biofuels are able to generate RFS credits, provided they certify their production process with an eligible carbon intensity following EPA data requirements.

FIGURE 1: Nested structure of RFS compliance and RIN D-codes



Alt text: Diagram of four nested boxes where Total Renewable Fuel contains Advanced Biofuels, which in turn contains two side-by-side boxes for biomass-based diesel and cellulosic biofuel.
Notes: This figure shows the nested structure of the Renewable Fuel Standard and RIN D-codes that are associated with each required fuel type.

To implement the RFS, EPA divides the annual volumetric RFS mandates by the amount of gasoline and diesel expected to be used that year to generate a percentage obligation for producers. Importers and refiners of gasoline and diesel must demonstrate that the amount of renewable fuel used meets or exceeds this percentage. Compliance is demonstrated through a system of tradeable

6. D6, D5/D4 and D3/D7 fuels are required to achieve a 20%, 50%, and 60% reduction relative to petroleum alternatives, respectively. The carbon intensity of these alternatives in shown in Table A1. In 2024, 21.54 Bgal of renewable fuel (D6) was required. 6.54 Bgal of this was required to be met by advanced biofuel (D5), 3.04 and 1.09 Bgal of this was required to be met by Biomass-based diesel (D4) and cellulosic biofuel (D5/D7), respectively.

credits, or renewable identification numbers (RINs). When a firm produces a gallon of biofuel it generates a unique RIN corresponding to a specific class of biofuel (see Figure 1). This RIN may be surrendered to EPA directly or sold to another obligated party that needs to demonstrate compliance. SAF is currently eligible to generate RINs under the RFS (typically either D4 or D6 RINs). However, there is no volumetric requirement for SAF and petroleum-based jet fuel suppliers face no compliance obligation.

The RFS effectively imposes a tax on petroleum fuels and subsidy for biofuels based on the market value of RINs. RIN prices typically reflect the difference between production cost of the biofuel and the energy adjusted cost of the petroleum fuel they replace (Irwin, McCormack, and Stock 2020). Empirical evidence indicates that the cost of RIN compliance credits is passed through to fuel prices by fossil fuel suppliers (Knittel, Meiselman, and Stock 2017; Li and Stock 2019; Mazzone, Smith, and Witcover 2022).

2. Tax Credits

The Inflation Reduction Act of 2022 created the Clean Fuel Production Credit (45Z), under which domestically produced biofuel with a CI at or below 47.4 gCO_2e/MJ is eligible to claim a tax credit equal to \$1 per gallon multiplied by an emissions factor, which is calculated by comparing the fuel's CI to a baseline of 47.4 gCO_2e/MJ. SAF received a higher credit value in the original statute, but recent amendments reduced this level to be the same as for road-transportation biofuel.[7]

Select states have also implemented their own tax credits to encourage the in-state production and use of SAF. Specifically, Hawaii, Illinois, Iowa, Minnesota, Nebraska, and Washington State have broad SAF tax credits in place (see Table 2). Together, these states produce 11.5 billion gallons of biofuels annually, with nearly 60% of total U.S. ethanol production capacity and 15% of biomass-based diesel production capacity (USDA 2024). Arkansas also has a tax credit for SAF; however, it only applies to SAF produced from woody biomass feedstocks, a process not yet commercially viable, and is therefore excluded from this analysis.

3. Low Carbon Fuel Standard

A low carbon fuel standard (LCFS) is a tradable performance standard that regulates the emissions intensity of the road transportation fuel supply. Fuel suppliers whose emissions intensity is lower than the standard generate credits that they can sell to suppliers whose emissions intensity is above the standard. In this way, an LCFS acts as an implicit tax on fuels with an emissions intensity above the standard and a subsidy on fuels with an emissions intensity below the standard. Like the RFS, there is a compliance credit market; however, LCFS credits reflect metric tons of CO_2e rather than gallons of fuel. Imported fuels may also generate LCFS credits but must certify their carbon

7. Tax incentives for carbon capture and storage (CCS) technology (45Q) are also available, but they cannot be used in combination with other federal tax credits to provide additional support for the production of biofuels. Therefore, we assume that biofuel producers that employ CCS will choose the maximum tax credit available to them. For more details, see Supplemental Appendix Section A.2.

TABLE 2: State-level tax credits for sustainable aviation fuel

State	Avg Subsidy ($/gal)	Value ($/gal)	In-State Eligibility Defined by	Recipient
IL	1.50	1.5	Use	Purchaser
MN*	1.50	1.5	Production & use	Producer/blender
WA	1.38	1 + 0.02 per % <50%	Production/ blending or use	Purchaser or producer/blender
NE*	0.78	0.75 + 0.01 per % <50%	Production	Producer
HI*	0.36	$0.20 per 76,000 Btu	Production & sale	Producer
IA*	0.25	0.25	Production	Producer

Notes: In-state use means consumed at an airport within the state for in-flight combustion. States with maximum payouts (indicated by *) include Minnesota, which limits the total credit to $7.4M and $2.1M in 2025 and 2026-2027, respectively (unused funds roll over), Nebraska, which limits the total credit to $500K per year, Hawaii, which limits the total credit to $20M per year and $3.5M per year for individual recipients, and Iowa, which limits the total credit to $10M (allocated across renewable chemical & SAF programs) and $1M per year for individual recipients.

intensity, including emissions from fuel transportation, under California's LCA model CA-GREET (see Table A2).

California was the first state to implement an LCFS in 2011, and Oregon (2016), Washington (2017), and New Mexico (2026) have followed suit. Essentially all of the renewable diesel consumed in the U.S. is used in California because it earns LCFS compliance credits in addition to RFS and federal tax incentives. California's LCFS does not include a compliance obligation for petroleum jet fuel, despite recent consideration of policy amendments to do so (CARB 2024b). The LCFS does allow SAF suppliers to "opt-in" to generate compliance credits for producing fuel below the benchmark emissions intensity, making California the first choice destination market for SAF. However, the new state-level tax incentives shown in Table 2 may induce SAF use outside California.[8]

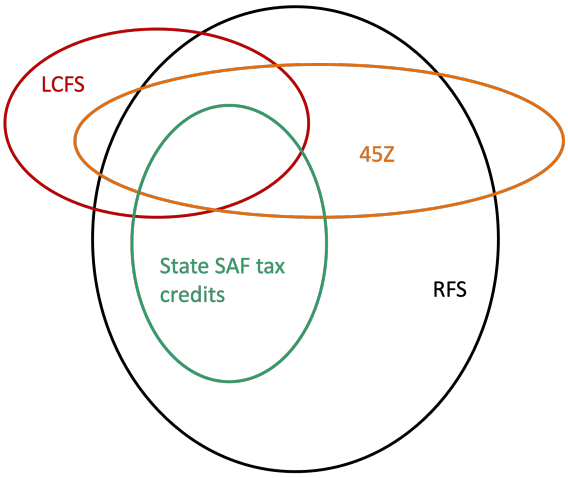
C. Policy Interactions

The use of multiple policies to incentivize the deployment of renewable fuels results in a complex landscape of overlapping incentives (see Figure 2) that leads to important interaction dynamics and may at times undermine policy objectives (Scott 2024). This is a particular challenge when both federal and state-level policies are implemented to achieve similar outcomes (Goulder and Stavins 2011). For instance, if California's LCFS were to incentivize more biofuel than mandated under the RFS, then the RFS would not be binding for that category and the compliance burden would fall on the LCFS. RIN prices would decrease and LCFS prices would increase (Whistance, Thompson, and Meyer 2017). However, if California's LCFS were to incentivize less biofuel than mandated under the RFS, then the RFS would be binding for the quantity of that biofuel and the LCFS would incentivize the consumption of that fuel in California instead of another state.

The effect of any policy implemented to reach the SAF target depends on how it interacts with existing biofuel policies. Consider a new SAF tax credit layered on a binding volumetric

8. Without state-level SAF tax incentives, no SAF is produced. Analysis details are provided in Section G.2.

FIGURE 2: Overlapping policies



Alt text: Venn diagram of four overlapping ellipses where the Renewable Fuel Standard spans most of the area, the Low Carbon Fuel Standard overlaps its upper left, the 45Z credit crosses both horizontally, and state tax credits sit inside the Renewable Fuel Standard.

Notes: This figure illustrates the mix of federal and state policies in the U.S. that incentivize the use of biofuels for road and air transportation.

requirement like the RFS. The credit induces SAF production, but that SAF also generates RINs that count toward the volumetric requirement. Because the mandated volume is fixed, this SAF displaces biomass-based diesel that would otherwise have been produced to fulfill the volumetric standard (Irwin, McCormack, and Stock 2020). This mechanism is analogous to the *waterbed effect* documented for overlapping policies under an emissions cap (Rosendahl 2019).[9] The change in total emissions depends on the difference in carbon intensity between SAF and the displaced BBD, multiplied by the displaced quantity. Because both fuels draw on similar feedstocks and have similar carbon intensities, this difference in emissions may be small, while total fuel costs rise. Consequently, layering SAF incentives on the volumetric mandate may deliver small changes in emissions at a high cost. In practice, interactions are further complicated by LCFS, 45Z, and state-level tax incentives.

Policies that provide greater incentives for fuels with lower carbon intensity (e.g., California's LCFS, 45Z tax credits) may also alter the mix and composition of fuel pathways used to meet a volumetric standard, even if volumes are unchanged. Likewise, differences in program eligibility shape the resulting fuel mix. Since 45Z and state-level tax credits are restricted to domestic production, imports can only access RFS and LCFS credit components of the stack, resulting in a domestic-import subsidy wedge that structurally favors domestic production. Therefore, representing the complex mix of policies in place including their specific design and emissions accounting procedures is necessary to assess potential policy outcomes.

9. Appendix Section A4 Figure A1 provides a graphical illustration.

II. Model

To assess the cost, emissions, and fuel-feedstock mix that result from alternative policy scenarios, we develop a partial equilibrium structural model of the road and aviation transportation fuel sectors in 2030. The model employs calibrated supply curves for the production of biofuels across 12 main production pathways and feedstocks. Because the Section 45Z Clean Fuel Production Credit and many state-level incentives apply only to domestically produced fuel, we model 2030 biofuel supply as domestic, with Brazilian sugarcane ethanol as the sole imported feedstock.[10] Total demand for transportation is set exogenously from forecasts in the *Annual Energy Outlook 2025* (AEO 2025; EIA 2025a) and is modelled as responsive to policy-induced price changes assuming a constant elasticity of demand.

Given supply and demand curves, state and federal tax credits, RFS volumetric mandates, LCFS intensity standards, and world petroleum fuel prices, the model solves for biofuel prices and quantities, RIN prices, and LCFS credit prices. To evaluate each policy alternative, we introduce the policy into the subsidy stack and compute the price of the compliance certificate for quantity or intensity policies.

The model represents two regions: California (CA) and the rest of the United States (ROUS) to account for the additional policy incentives in California (CA LCFS) which make it the first-choice destination for many biofuels (see Section I.B.3).

A. Fuel Supply

We assume that the supply of fossil fuels is perfectly elastic at the wholesale rack level price of $P^j_{\mathcal{F}0}$ for fossil fuel $\mathcal{F}$ (gasoline, diesel, jet) in region j. Depending on the policy scenario, petroleum fuel producers face policy costs ($\text{PolicyCost}^j_{\mathcal{F}0}$) from the RFS, California's LCFS, the carbon tax, and the aviation intensity standards (fossil jet only). Empirical evidence demonstrates that policy costs are passed through to consumers (Knittel, Meiselman, and Stock 2017), therefore fossil fuel prices equal the price of world fossil fuel ($\overline{PC_{\mathcal{F}0}}$) plus policy costs

$$\forall \mathcal{F}: \quad P^j_{\mathcal{F}0} = \overline{PC_{\mathcal{F}0}} + \text{PolicyCost}^j_{\mathcal{F}0}. \tag{1}$$

We exogenously set the 2030 world fossil fuel price based on AEO 2025. The price is set at \$2.07 for gasoline, \$2.41 for diesel, and \$2.36 for fossil jet fuel in 2024 dollars. $\text{PolicyCost}^j_{\mathcal{F}0}$ represents the per unit compliance obligation that a petroleum fuel $\mathcal{F}0$ needs to pay under the active policy constraints, described in Section II.D.

10. Imported renewable diesel historically represented 20–40% of total U.S. consumption, but the Section 45Z Clean Fuel Production Credit enacted in January 2025 is restricted to domestic production. In 2025, U.S. imports of renewable diesel and biodiesel fell by more than 70% to their lowest levels since 2012 (EIA 2026b), and EIA forecasts net imports to remain near zero or negative through 2027 (EIA 2026a).

TABLE 3: Marginal production costs (2024$)

Biofuel type	**Technical pathway**	**Feedstock (s)**	**Fixed cost** ($\overline{FC}_{f,s}$)	**Conversion rate** ($\theta_{f,s}$) lbs/gal
SAF	HEFA	Crop-based vegetable oils	1.63	9.00
		Tallow and waste oils	1.63	9.00
	ATJ	Corn	4.80	22.27**
		Sugarcane	6.07*	174.36
	ATJ+CCS	Corn	4.99	22.27**
		Sugarcane	6.26*	174.36
Biodiesel	HEFA	Crop-based vegetable oils	1.19	7.55
		Tallow and waste oils	1.19	7.55
Renewable diesel	HEFA	Crop-based vegetable oils	1.55	8.50
		Tallow and waste oils	1.55	8.50
Ethanol		Corn	0.83	13.10**
		Sugarcane	1.58*	102.56

Notes: * On July 30, 2025, the White House announced the imposition of an additional *ad valorem* duty rate of 40 percent on certain goods from Brazil (White House 2025). This presidential action includes sugarcane ethanol. The figures presented in Table 3 do not account for this new measure and are based on the assumption of a 12.5% tariff on imported Brazilian sugarcane. For the corn ethanol pathway, the conversion rate is adjusted to two-thirds of the actual volume needed to produce biofuel (as indicated by **) to reflect the revenue from DDGS. However, when determining feedstock demand, we use the full volume required for production.

Representative biofuel producers for each pathway maximize profit, based on the equation:

$$\text{Profit}(Q) = \sum_{j} \sum_{f,s} [P_f^j Q_{f,s}^j - C_{f,s}^j Q_{f,s}^j - \text{PolicyCost}_{f,s}^j \cdot Q_{f,s}^j], \tag{2}$$

where P_f^j represents the price of biofuel f (e.g., biodiesel, renewable diesel, sustainable aviation fuel or ethanol) in region j, $Q_{f,s}^j$ represents the quantity of fuel produced with feedstock s, and $C_{f,s}^j$ represents the marginal cost of production (detailed in equation (3)). $\text{PolicyCost}_{f,s}^j$ represents the negative of the per-unit subsidy stack available to a biofuel producer, described in Section II.D.

Biofuel facilities are typically modular and can be replicated or expanded over a several-year horizon. We therefore model marginal costs as depending on quantity only through the price of the feedstock. Accordingly, the marginal cost of biofuel production is:

$$C_{f,s}^j = \left(\overline{FC}_{f,s} + \theta_{f,s} P_s\right) \tag{3}$$

The constant component ($\overline{FC}_{f,s}$) includes amortized capital expenditure (CAPEX) and operating expenditure (OPEX) of producing one unit of fuel f from feedstock s. Transportation costs are not included in our analysis. Table 3 displays the values we use for the fixed cost of producing one gallon of biofuel f from feedstock-technical pathways $\{f, s\}$, expressed in 2024 dollars and the feedstock conversion rate. For pathways that use sugarcane imported from Brazil, the marginal cost includes the tariff currently imposed by the U.S. government on the product. See Supplemental Appendix Section B.2 for more details.

TABLE 4: Feedstock total supply elasticities

Feedstock Type	Total Supply Elasticity	Sources
Soybean oil*	0.189	Santeramo and Searle (2019)
Tallow and waste oils	2	
Corn	0.264 (0.14 to 0.50)	Goyal, Adjemian, and Secor (2022), Kim and Moschini (2018), and Hendricks, Smith, and Sumner (2014)
Sugarcane**	0.1 (0 to 0.2)	Elobeid and Tokgoz (2008), Babcock, Barr, and Carriquiry (2010), and Drabik et al. (2015)

Notes: * We use the supply elasticity of soybean oil as a proxy for all crop-based vegetable oil. ** Sugarcane shipped from Brazil represents the net supply to the U.S. market, and we treat this supply as relatively inelastic because of U.S. quotas and tariffs.

B. Feedstock supply

In the production of biomass-based fuels, feedstocks represent a significant portion of total costs, accounting for anywhere between 16% and 66% (Karimi, Simsek, and Kheiralipour 2024). As such, accurately estimating feedstock prices is crucial for determining the overall cost of biofuel production. In this model, log-log supply curves are employed for each biofuel feedstock s (e.g., crop-based vegetable oil, tallow and waste oils, corn, and Brazilian sugarcane). The supply elasticity is specified as the residual price elasticity relevant to biofuel production.

The supply curves for feedstocks dedicated to biofuel production take the following form:

$$\forall s: \quad Q_s^{Biofuel} = \alpha_s P_s^{\beta_s^{Biofuel}} \tag{4}$$

where the residual supply elasticity ($\beta_s^{Biofuel}$) is determined by subtracting the weighted average demand elasticities of non-biofuel uses (β_s^{OtherD}) — such as food and animal feed in the case of soybean oil and corn—from the total supply elasticity (β_s^{All}).

$$\beta_s^{Biofuel} = \frac{Q_s^{All}}{Q_s^{Biofuel}}\beta_s^{All} - \frac{Q_s^{Other}}{Q_s^{Biofuel}}\beta_s^{OtherD} \tag{5}$$

The total supply elasticity for each feedstock type is provided in Table 4. Due to the limited size of the market, we were unable to find published estimates of supply elasticities for U.S. tallow and waste oils; therefore, we assume a value of 2 for this analysis. Soybean oil currently dominates the U.S. crop-based vegetable oil market. Based on this fact and data constraints, we use the supply elasticity of soybean oil as a proxy for the supply elasticity of all crop-based vegetable oils (see Appendix B.3 for discussion of limitations of this assumption). For non-biofuel demand elasticities, we assume a value of -0.2 for soybean oil, consistent with recent estimates of global vegetable oil demand elasticities of -0.15 (Chen, Sexton, and Smith 2025), and for corn, consistent with the corn

TABLE 5: Fuel demand elasticities

Fuel Type	Demand Elasticity	Sources	World Fossil Fuel Price $\overline{PC_{\mathcal{F}0}}$ (2024$)
Gasoline	-0.37	Coglianese et al. (2017) and Knittel and Tanaka (2021)	2.07
Diesel	-0.07 (-0.36 to 0)	Dahl (2012) and Winebrake et al. (2015)	2.41
Jet Fuel	-0.26 (-0.35 to -0.16)	Fukui and Miyoshi (2017)	2.36

Notes: This table shows the assumed fuel demand elasticities, associated sources, and world fossil fuel price in 2024 dollars for each fuel type.

feed demand elasticity of -0.215 (McPhail and Babcock 2012) and long-run corn demand elasticity estimates of -0.36 (Adjemian and Smith 2012). We assume a value of 0 for tallow, waste oils, and imported Brazilian sugarcane ethanol because these feedstocks are modeled as used exclusively for biofuel production with no competing non-biofuel demand. Details on calculating the average residual elasticity and supply curve parameters are provided in Supplemental Appendix Section B.3.

C. Fuel demand

Demand for transportation fuel is responsive to price based on a constant elasticity of demand function:

$$\forall\{\mathcal{F}, j\}: \quad Q_{\mathcal{F},j} = \alpha^{D}_{\mathcal{F},j} P^{\beta^{D}_{\mathcal{F}}}_{\mathcal{F},j} \tag{6}$$

where $Q_{\mathcal{F},j}$ is the quantity demanded for fuel type $\mathcal{F}$ (e.g., diesel and substitutes, gasoline and substitutes, or jet fuel and substitutes in energy-adjusted gallons of fossil fuel equivalent) in region j (e.g., California or ROUS) as a function of the blended fuel price ($P_{\mathcal{F},j}$). The demand elasticity for each fuel type is represented by $\beta^{D}_{\mathcal{F}}$ with values displayed in Table 5.

We calibrate the demand curve parameters $\alpha^{D}_{\mathcal{F},j}$ starting with projections of 2030 travel demand in vehicle-miles travelled (VMT) from the EIA's 2025 Annual Energy Outlook and apply projections of fuel economy and fleet composition to translate VMT into energy-equivalent liquid fuel demand. Projections of total VMT for light-duty, medium-duty, and heavy-duty vehicle classes are taken from the reference case of the AEO 2025 (with alternative high and low travel demand scenarios examined in Appendix section G.13). We then adjust for projected changes in fuel economy and adoption of electric and hydrogen vehicles to obtain baseline projected liquid fuel consumption. For aviation, we source total revenue passenger miles (RPM) for passenger airlines and revenue ton miles (RTM) for cargo-only airlines from AEO 2025.[11] We adjust for projected fuel economy

11. Passenger airlines encompass both domestic and international flights departing from U.S. airports, while cargo-only airlines cover only U.S. domestic freight operations. Jet fuel demand for general aviation and military use is not

changes to obtain baseline jet fuel consumption. Further information on calibrating the regressions and projecting alternative travel demand scenarios based on various average GDP growth rates can be found in Supplemental Appendix Section B.4.

Ongoing improvements in fuel economy are anticipated to lower the amount of fuel needed to meet the projected VMT. We estimate average fuel efficiency for light-duty, medium-duty, and heavy-duty ICE vehicles in 2030 based on historical fuel economy trends, and assume aviation fuel economy improves by 1.5% per year (Graver 2022). Detailed fuel efficiency projections by vehicle type are provided in Appendix B.4.1.

We assume on-road and aviation travel demand in California is a fixed proportion of total U.S. travel demand.[12] Electricity is projected to supply an increasing portion of passenger transportation demand. Because incentives for biofuel adoption are not expected to significantly affect nationwide vehicle electrification rates (Bushnell et al. 2021), we assume a fixed share of total on-road travel demand will be met by electricity in 2030,[13] with California having notably higher EV penetration rates than the rest of the US (ROUS). Details on California's regional travel demand shares and fleet composition by vehicle and fuel type are provided in Appendix B.5. We assume that average light-duty electric vehicles will be driven the same number of miles as average internal combustion engine (ICE) vehicles.

We assume the fuel market is perfectly competitive, such that fuel blenders choose the lowest cost fuel mix capable of meeting demand for each type of transportation (light-duty, heavy-duty, air) subject to policy and fuel blending constraints. We also assume that biofuel and petroleum fuels are perfect substitutes on an energy-adjusted basis[14] so long as they remain under technical blend constraints and biofuel subsidies accrue to producers (Knittel, Meiselman, and Stock 2017). Because petroleum fuel supply is assumed to be perfectly elastic, demand for biofuels is determined by the quantity of biofuels that can be produced at a price less than or equal to that of their petroleum alternative, after accounting for policy incentives and subject to blending constraints.

The model includes blend constraints to reflect the maximum shares of biofuel that can be safely blended into the fossil fuel supply with existing infrastructure and technologies. Specifically, the maximum blend rate for ethanol is set at 15%,[15] biodiesel at 7.5% for California[16] and 20% for ROUS (Alleman et al. 2016), and SAF at 50% (IATA 2023). Notably, renewable diesel faces no blend constraint, which has resulted in it being the marginal compliance fuel under the LCFS in recent years (Lade 2023).

Ethanol may be blended with gasoline up to an approximately 10% blend limit and used in

included in our analysis.

12. This assumption is consistent with evidence that biofuel policies do not significantly affect the geographic distribution of travel demand (Bushnell, Peterman, and Wolfram 2008).

13. Sensitivity to this assumption is examined in Appendix G.12.

14. Gasoline or diesel gallon equivalence based on energy content is downloaded from Alternative Fuels Data Center, available at: https://afdc.energy.gov/fuels/properties.

15. E85 can only be used in flexible fuel vehicles, which are equipped with internal combustion engines specifically modified to operate on this blend.

16. Biodiesel blends accounted for approximately 7.5% of the market in California from 2020 to 2023, and less than 5% from 2018 to 2019.

traditional combustion engines (E10), sold as E15 where available, or sold in higher blends up to 85% which require specialized flex-fuel vehicles and infrastructure (E85). Up to the 10% blend limit, ethanol can substitute for gasoline, so the value of ethanol relative to fossil gasoline price ($\theta P_{\mathcal{G}0}$) would be its relative energy density ($\theta = 0.67$). However, ethanol has value as an octane enhancer so should not be valued only for its energy content (Babcock, Barr, and Carriquiry 2010; Irwin and Good 2017). Based on observed rack prices for ethanol and gasoline,[17] from May 2020 through November 2021 and after accounting for the volumetric ethanol excise tax credit we found there was price parity between gasoline and ethanol on a volumetric basis. However, the blending ratio remained at E10 levels, and refiners did not reduce ethanol usage or substitute it with aromatics. Therefore, we set θ equal to 1.

After exceeding the blend wall, the value of ethanol is lower because of limitations on widespread use. To account for this, we employ an inverse demand curve for ethanol of the form:

$$\forall j, \quad P^j_{E100} = \theta P^j_{\mathcal{G}0}\left[1 - \mathbb{1}\left(\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s} + Q^j_{\mathcal{G}0}} \geq 0.1\right)\left(e^{\left(\frac{\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s}+Q^j_{\mathcal{G}0}} - 0.1}{0.02} \ln 2\right)} - 1\right)\right] \tag{7}$$

where P^j_{E100} is the price of ethanol in region j and $Q^j_{E100,s}$ is the amount of ethanol consumed in region j using feedstock s (e.g., corn or sugarcane). The 0.1 indicator represents the 10% ethanol blend wall. The 0.02 scaling parameter and $\ln 2$ term calibrate the rate at which the ethanol price declines above the blend wall.

In principle, a source of demand for SAF is voluntary demand by airlines, perhaps representing preferences of passengers and/or shareholders. Because air travel is a highly competitive industry, we assume that voluntary demand for SAF is zero.

D. Policy constraints

As discussed in Section I.B, multiple policy instruments incentivize the deployment of biofuels, including a volumetric standard (e.g., RFS), an intensity standard (e.g., LCFS), and direct subsidies (e.g., tax credits). We assume full pass through of policy costs for all biofuel types.

1. RFS constraint

Under the RFS, each gallon of obligated petroleum fuel (gasoline or diesel) must retire a bundle of RINs for each "D" category set out in the regulation. The volume of D3 and D5 RINS traded is negligible,[18] so we exclude D3 and D5 RINs from the model. The percentage standards for the two RIN categories are:

$$\phi_{D4} = \frac{1.6 RFV_{D4}}{\text{TotalFF}}, \qquad \phi_{D6} = \frac{RFV_{D6}}{\text{TotalFF}} \tag{8}$$

17. Monthly rack level price data for fuel ethanol and gasoline is obtained from Economic Research Service of U.S. Department of Agriculture, available at https://www.ers.usda.gov/data-products/us-bioenergy-statistics.

18. From 2022 to 2024, D3 RINs traded are around 3% of total RINS traded and D5 RINs traded are less than 1% of total RINs traded volume.

where RFV_i is the annual volume required for each RIN category expressed in gallons, and TotalFF is projected petroleum gasoline and diesel consumption. The scale factor 1.6 arises because biomass-based diesel and SAF have about 60% higher energy density than ethanol and the units of all RINs are ethanol-equivalent gallons.

The per-gallon cost of the bundled RINs retired to comply with the obligation for petroleum gasoline and diesel is:

$$\text{PolicyCost}_{FF}^{RFS} = \phi_{D4} P_{D4} + (\phi_{D6} - \phi_{D4}) P_{D6} \tag{9}$$

Subsidies provided to each biofuel type through the RFS take the form of a negative policy cost:

$$\text{PolicyCost}_{Ethanol}^{RFS} = -P_{D6} \tag{10}$$

$$\text{PolicyCost}_{Biodiesel}^{RFS} = -1.5 P_{D4} \tag{11}$$

$$\text{PolicyCost}_{Renewablediesel}^{RFS} = -1.7 P_{D4} \tag{12}$$

$$\text{PolicyCost}_{SAF}^{RFS} = -1.6 P_{D4} \tag{13}$$

The scale factors 1.5, 1.7, and 1.6 reflect the energy densities of biodiesel, renewable diesel, and SAF relative to ethanol and convert wet gallons into "RIN gallons."[19] We assume that ethanol generates D6 RINs, while biodiesel, renewable diesel, and SAF produce D4 RINs. However, the eligible RIN category ultimately depends on the CI values presented in Table 1. ATJ-SAF produced without CCS technology is only eligible to generate D6 RINs. Because volumetric obligations can be met by nested D-codes (D4 RINs could be used to meet the D6 requirement), the D6 RIN price will never exceed the D4 RIN price (Irwin, McCormack, and Stock 2020). Therefore, RIN prices are subject to the constraint $P_{D6} \leq P_{D4}$.

2. Tax incentives

Petroleum fuel producers do not receive any tax incentives.

$$\text{PolicyCost}_{FF}^{TaxIncentive} = 0 \tag{14}$$

The available tax incentives for biofuel producers take the form of a subsidy per gallon of biofuel production. Similar to the subsidies provided under the RFS, these take the form of a negative policy cost:

$$\text{PolicyCost}_{f,s}^{TaxIncentive} = -TC_{f,s}^{45Z} - TC_{f,s}^{45Q} - TC_{f,s,j}^{State}, \tag{15}$$

where $TC_{f,j}$ is the tax credit biofuel type f produced in region j can get. It is a sum of 45Z or 45Q and the state level tax credit.

State level tax incentives vary by state in terms of the value, eligibility, and recipient, as

19. In EPA's June 2025 proposed renewable volume obligation (RVO) rule, the RD equivalency factor is reduced to 1.6. We test the robustness of our results by adjusting "RIN gallons" in Supplemental Appendix Section G.6.

described in Table 2. The state tax credit value function ($TC^{State}_{SAF,s,ROUS}$) takes the form:[20]

$$\text{TC}_{state} = \begin{cases} 2.28, & \text{if } \sum Q^{ROUS}_{SAF,s} \leq 0.0006 Bgal \\ 1.75, & \text{if } 0.0006 Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.0406 Bgal \\ 1.50, & \text{if } 0.0406 Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.5803 Bgal \\ 1.38, & \text{if } 0.5803 Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.9826 Bgal \\ 0.36, & \text{if } 0.9826 Bgal < \sum Q^{ROUS}_{SAF,s} \leq 1.0389 Bgal \\ 0, & \text{if } 1.0389 Bgal < \sum Q^{ROUS}_{SAF,s} \end{cases} \tag{16}$$

We assume the marginal cost of public funds equals one, meaning we do not adjust for the opportunity cost of the public revenue raised to pay subsidies out of the federal or state budget.

3. LCFS constraint

The California LCFS acts as a constraint on the emissions intensity of the regulated fuel supply in aggregate. LCFS allowance prices are determined endogenously so that the overall intensity constraint is met (i.e., total credits from low-carbon fuels are greater than or equal to total deficits from petroleum gasoline and diesel). The formula for deficits is

$$Deficits = \sum_{f} (CI_f - CI^*_{\mathcal{F}}) Q_f \overline{ED}_f \times 10^{-6} \tag{17}$$

where CI_f is the carbon intensity of petroleum fuel $f \in \{gasoline, diesel\}$ shown in Table A1, $CI^*_{\mathcal{F}}$ is the carbon intensity target, Q_f is fuel quantity in gallons, $\overline{ED}_f$ is energy density (to convert gallons to grams), and 10^{-6} is a scale factor to convert grams to tons.

The formula for credits is

$$\begin{aligned} Credits = & \sum_{f,s} (CI^*_{\mathcal{F}} - CI_{f,s}) Q_{f,s} \overline{ED_{f,s}} \times 10^{-6} \\ & + \left(CI^*_{\mathcal{G}} - \frac{CI_{Elec}}{EER_{Elec,G}} \right) Q_{Elec,LDV} \overline{EER_{Elec,G}} \times \overline{ED_{Elec}} \times 10^{-6} \\ & + \sum_{Elec,MDV/LDV} \left(CI^*_{\mathcal{D}} - \frac{CI_{Elec}}{EER_{Elec,D}} \right) Q_{Elec,MDV/HDV} \times \overline{EER_{Elec,D}} \times \overline{ED_{Elec}} \times 10^{-6} \\ & + \left(CI^*_{\mathcal{D}} - \frac{CI_{Hydro}}{EER_{Hydro,D}} \right) Q_{Hydro,HDV} \overline{EER_{Hydro,D}} \times \overline{ED_{Hydro}} \times 10^{-6} \\ & + \overline{Methane} + \overline{Other} + \overline{Infrastructure} + \overline{Bank} \end{aligned} \tag{18}$$

20. Supplemental Appendix Section C.2 provides details on calculating tax credit eligible quantities. This functional form assumes that the value of LCFS credits available to SAF consumers does not exceed the state-level tax credit of $1.5 in Illinois. Supplemental Appendix Section C.3 discusses cases where the LCFS available to SAF consumers exceeds state-level tax incentives. These alternative scenarios are considered during the analysis but are excluded from the final results as they lead to inconsistencies.

where we sum over the 12 fuels and pathways in Table 1. Several other pathways are included here that can also generate LCFS credits. *Elec* represents credits generated from light-, medium-, heavy-duty electric vehicles, and *Hydro* represents credits generated from heavy-duty hydrogen vehicles. Credits generated from these on-road transportation sources are calculated using the same equation as for biofuels, with adjustments for the energy economy ratio (EER), which represents the relative energy efficiency of alternative fuel vehicles compared to conventional vehicles. $\overline{Methane}$ represents credits generated from dairy and landfill biomethane production. $\overline{Infrastructure}$ denotes credits awarded for Hydrogen Refueling Infrastructure (HRI) and DC Fast Charging Infrastructure (FCI). $\overline{Other}$ represents credits generated from forklifts, light rail, other off-road electricity categories, innovative crude, and refinery investment credits.

We exogenously define credit levels generated from methane, infrastructure and other projects. We assume credits generated from methane will reach 10 million metric tons by 2030.[21] Infrastructure project credits are assumed to remain at the 2024 level (0.29 million metric tons per year in total). Similarly, credits from other projects are held constant at their 2024 value, amounting to 2.30 million metric tons annually. We also assume annual banked credits, $\overline{Bank}$, of 2.33 million metric tons. The total credit bank in 2024 was 37.34 million metric tons, which we distribute evenly over the period from 2025 to 2040. Alternative levels of credit generation are further tested and results shown in Supplemental Appendix Section G.7.

As described in Section I.B.3, an LCFS acts as an implicit tax on fossil fuels that have carbon intensity above the emission intensity standards and a subsidy for biofuels with carbon intensity lower than the emission intensity standards. The policy cost under the LCFS system can therefore be expressed as:

$$\text{PolicyCost}_{f,s}^{LCFS} = P_{LCFS}(CI_{f,s} - CI_{\mathcal{F}}^{*})\overline{ED_{f,s}}10^{-6} \tag{19}$$

where the P_{LCFS} represents the price of LCFS compliance credits, $CI_{f,s}$ represents the carbon intensity of biofuel or fossil fuel f, and $CI_{\mathcal{F}}^{*}$ represents the emissions intensity standard for fuel type $\mathcal{F}$. Only diesel and gasoline are obligated fuels under the California LCFS, but SAF can opt-in to generate credits based on an aviation benchmark aligned with the diesel standard. The LCFS credit price is constrained by a price ceiling of \$250 per metric ton ($P_{LCFS} \leq 250$). If the credits generated from biofuel and other pathways specified in equation (18) are insufficient to cover the deficits from obligated fuels, we assume CARB will issue credit allowances at the capped ceiling price.

E. Scenarios

We examine the cost, emissions impact, fuel mix, and feedstock input requirements of several alternative policy scenarios that achieve the 2030 3 Bgal domestic SAF production target. Table 6 summarizes the policies under each scenario.

21. Methane credits totaled 4.35 million in 2022, 5.33 million in 2023, and 7.6 million in 2024. Given this upward trend, we project that methane credits will reach approximately 10 million metric tons by 2030.

TABLE 6: Policy scenarios

Scenario	Current RFS	D2 RIN	IRA + OBBBA	State Subsidies	CA LCFS	SAF Credit	Carbon Tax	Aviation Std
0 No policy								
1 Current policy	X		X	X	X			
2 SAF credit	X		X	X	X	X		
3 Modified RFS	X	X	X	X	X			
4 Carbon tax + SAF credit						X	X	
5 Aviation intensity standard	X		X	X	X			X

Notes: This table shows the policies included in each policy scenario. The modified RFS scenario includes three possible modifications that are described in more detail in the text: (a) Nested D2, (b) D2 with Aviation Obligation, and (c) Nested D2 + Stricter RFS.

0. **No policy**: No policies are in place to support biofuel deployment. This scenario provides a baseline emissions and cost level for comparing alternatives.

1. **Current policy**: Current policy includes existing RFS, LCFS, state-level tax incentives, and the Clean Fuel Production Credit. We assume that percentage standards for biomass-based diesel (BBD) and total renewable fuel in 2030 remain consistent with 2025 RFS levels—3.15% for BBD and 13.13% for renewable fuel. The LCFS is expected to meet the 2030 carbon intensity benchmarks (CARB 2024a). We also assume state-level tax incentives remain in effect in 2030 and that the 45Z tax credit is extended through the end of 2030.

2. **SAF credit:** A taxpayer-funded subsidy is provided to reach 3 Bgal of SAF. Current policies remain in place, and SAF generates compliance credits under the RFS and LCFS. SAF credit eligibility is determined in the same way as the 45Z tax credit (using a 47.39 gCO_2e/MJ CI threshold and with domestic production requirements). Unlike 45Z, however, a fixed credit value per gallon is offered to all fuel produced at a carbon intensity below this threshold and ILUC is included in CI values when determining eligibility. SAF is eligible to receive both the 45Z tax credit and the SAF credit.

3. **RFS modifications**: An additional RFS category (D2) is created to reach the 3 Bgal target. As noted in Section I.B.1, the RFS essentially subsidizes biofuels through the generation and sale of RINs, which petroleum sellers need for compliance. Eligibility to generate D2 RINs is restricted to domestically produced SAF with an emissions intensity (based on the EPA lifecycle greenhouse gas emission model in Table 1) below 50% of its petroleum alternative, which corresponds to 44.50 gCO_2e/MJ (i.e. excluding ATJ pathways from corn and sugarcane without CCS). The U.S. EPA has the authority to introduce new RIN-earning pathways such as D2 for SAF, but a statutory amendment would be required to make petroleum jet fuel an obligated fuel. Therefore, we explore several ways the RFS could be modified:[22]

22. Details on percentage standards and volumetric requirements for each policy scenario are provided in Supplemental Appendix Section C.1, which also contains updated equations used to calculate compliance obligations for each scenario.

(a) **Nested D2**: An additional D2 RIN category requiring 3 Bgal of SAF is nested within D4. The required volumes for biomass-based diesel and total renewable fuel remain unchanged.[23] There is no compliance obligation for petroleum jet fuel.

(b) **D2 with aviation obligation**: An additional D2 RIN category requires 3 Bgal of SAF. The D2 RIN is nested within D6, but parallel with D4. This means SAF can be used to meet either D2 or D6 obligations, while D4 requirements must be fulfilled exclusively by on-road biomass-based diesel. Fossil jet fuel becomes a compliance fuel facing a compliance cost parallel to the one described in equation (9).

(c) **Nested D2 + stricter RFS**: An additional D2 RIN category requires 3 Bgal of SAF, with volumetric requirements for biomass-based diesel and total renewable fuel increasing by 3 Bgal. There is no compliance obligation for petroleum jet fuel.

4. **Carbon tax + SAF credit:** All existing policies are replaced with a carbon tax of $15 per metric ton applied to fossil transportation fuels and an additional taxpayer-funded subsidy is provided to reach 3 Bgal of SAF. Eligibility for the SAF incentive is the same as the SAF credit scenario, but the credit value, which is determined to ensure that the 3 Bgal of SAF is reached, is higher in this case ($4.41 per gallon versus $2.11 per gallon).

5. **Aviation intensity standard:** An emissions intensity standard is implemented exclusively on aviation fuels at the national level, set to achieve 3 Bgal of SAF. Carbon intensity values for credit generation are based on CA-GREET. Current policy remains in place, including 45Z and the eligibility of SAF to generate compliance credits under the RFS and LCFS.

F. Model Summary

Not counting hypothetical policies, the model has 108 exogenous parameters (e.g., global fossil fuel prices, LCFS intensity standard), 40 endogenous quantities (including biofuel, fossil fuel, and blended fuel quantities, as well as feedstock quantities), 27 endogenous prices (including RIN and LCFS prices, biofuel, fossil fuel, and blended fuel prices, as well as feedstock prices), and 34 Lagrangian multipliers, totaling 101 equations and 77 inequalities. The inequalities include non-negativity constraints on pathway quantities, nesting constraints on RIN prices, technical blending constraints, HEFA pathway production blending limits, and dual feasibility conditions for the Lagrangian multipliers. The system of equations consists of linear, log-linear, and more complex nonlinear components. The presence of non-differentiable stepwise functions and complementarity constraints gives rise to a non-convex optimization problem, which we solve using mixed-integer programming and the Gurobi optimizer. The complete set of equations and inequalities is presented in Supplemental Appendix Section D, and further details on the numerical solver are provided in Supplemental Appendix Section E.

23. In this case, the D2 requirement substitutes for other surface transportation in both the biomass-based diesel and total renewable fuel pools.

III. Results

We find that current policies are insufficient to achieve the SAF production target of 3 Bgal in 2030. Specifically, our model predicts reaching only 74.7 million gallons of SAF production in 2030 (see Figure 3). This occurs because biomass-based diesel remains the least expensive fuel to produce with fats and oils, preventing the profitable expansion of SAF in 2030 even with the combined incentives provided under the federal RFS, Clean Fuel Production Credit, state-level tax incentives, and California's LCFS. In our current policy scenario, all SAF is produced via ATJ, and CCS is essential for making ATJ-SAF viable by rendering these pathways eligible for policy support.[24]

When CCS is also available for surface transportation fuels, in this case ethanol, approximately 409.4 million gallons of HEFA-SAF and 112.7 million gallons of ATJ-SAF are produced. This increase reflects higher demand for corn ethanol, which becomes eligible for the Clean Fuel Production Credit when CCS is an option. Supplemental Appendix Section G.1 provides further details on associated policy cost shares and volume changes.

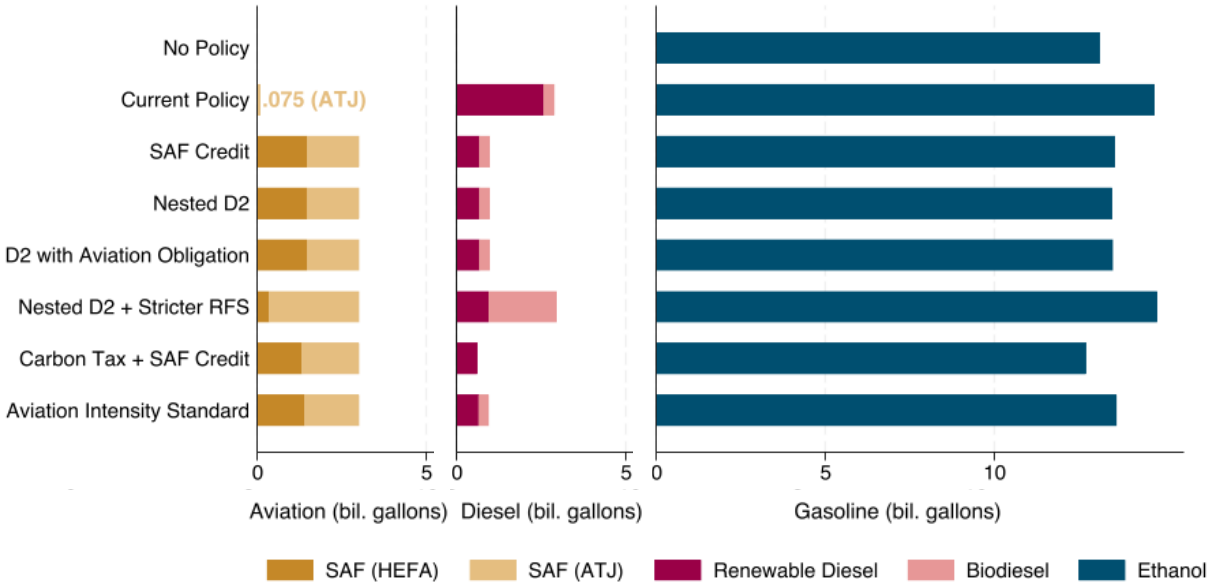


FIGURE 3: Biofuel production by policy scenario

Alt text: Three horizontal bar charts of biofuel volumes in billions of gallons for aviation, diesel and gasoline, where bars are segmented by HEFA SAF, alcohol-to-jet SAF, renewable diesel, biodiesel and ethanol across eight policy scenarios.

Notes: This figure shows the volume of biofuels, by type, produced under each policy scenario. Total volumes of aviation fuel, diesel, and gasoline (including both biofuels and fossil-based fuels) varied by less than 5% between scenarios; this variation is not illustrated here.

SAF production primarily competes with renewable diesel as both fuels can use similar feed-

24. Without applicable CCS, essentially no ATJ-SAF is produced, and SAF supply is limited to modest HEFA volumes (76.7 million gallons) under current policy. Detailed results, including volumes and policy cost shares, are reported in Supplemental Appendix Section G.1.

stocks and production processes. However, SAF suffers from four disadvantages. First, SAF requires greater feedstock inputs, resulting in higher per gallon production costs than renewable diesel (Rosales Calderon et al. 2024). Second, the market price for fossil jet fuel is lower than that for diesel, so SAF requires a greater subsidy than renewable diesel to be cost competitive with its fossil alternative. Third, HEFA upgrading to SAF is slightly more expensive than to renewable diesel. Fourth, current policy incentives tend to favor renewable diesel production. For instance, Figure 4 illustrates simulated production cost and maximized marginal incentives for RD and SAF under the current policy scenario. In this scenario, RD continues to act as the marginal compliance fuel under the RFS and LCFS and out-competes SAF (of all types). Under current policy, ATJ-SAF out-competes HEFA SAF; a modest quantity of ATJ-SAF produced from corn and utilizing CCS technology is profitable when sold in Illinois or Minnesota, where it qualifies for a state-level tax credit of $1.5 per gallon. However, it is noteworthy that HEFA-SAF is close to cost competitive with ATJ+CCS outside of California, which is why both pathways are adopted across scenarios reaching the 3 Bgal target.[25]

In reality, the current policy mix has resulted in some SAF production growth in recent years despite its high cost. Some airlines have been willing to voluntarily pay a premium for SAF in the short-term (Azarova, Singh, and Shams 2024), but in the long run consumers will likely not favor taking on additional costs (Xu et al. 2022).

The policy approach employed can have significant impacts on emissions and cost-effectiveness, distribution of costs, and feedstock mix. The following sub-sections examine these effects in turn.

A. Emissions and Cost-effectiveness

The policies we examine affect fuel prices and the types and quantities of fuels produced. We compute policy costs as the additional cost of purchasing the no-policy fuel quantities at the policy prices plus additional government spending and minus additional carbon tax revenue. The average abatement cost equals the policy cost divided by the emissions reduction relative to the no-policy scenario. We stress that this cost does not incorporate any benefit from induced technical improvements or learning by doing, which could reduce future costs (Gillingham and Stock 2018); (Hahn et al. 2024). Total emissions are calculated based on carbon intensity values from the CA-GREET model. Alternative CI values are tested and results are shown in Supplemental Appendix Section G.5. When ILUC values increase, average abatement costs rise, while the percentage reduction in transportation emissions falls.

The current policy mix represents costly emissions reductions at $461 per metric ton. Alternative policy scenarios that achieve the 3 Bgal target are also costly in terms of average abatement

25. Under alternative conversion rate values tested for HEFA-SAF feedstocks (using 8.5 lbs per gallon rather than 9), HEFA SAF is produced under the current policy scenario instead of ATJ+CCS. In this case, approximately 87.8 million gallons of HEFA SAF are produced and no ATJ SAF is produced. Results for the other policy scenarios are largely unchanged. Further details on biofuel volumes are provided in Supplemental Appendix Section G.3.1. Similarly, under highly elastic tallow supply, current policy shifts entirely to HEFA SAF. For mandate scenarios, the HEFA share ranges from 46% under inelastic tallow supply to 72% under elastic tallow supply (Appendix Section G.9).

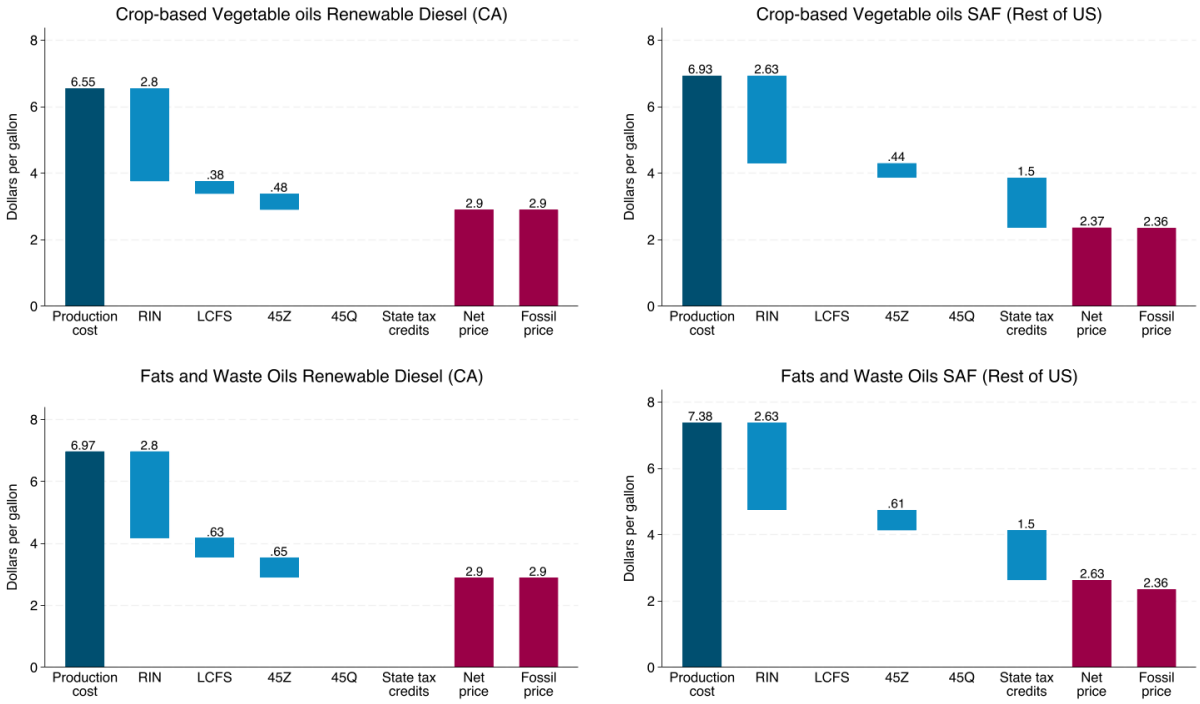


FIGURE 4: Costs and incentives in 2030 for SAF and Renewable Diesel under current policy

Alt text: Four waterfall charts of dollars per gallon where production cost is reduced in turn by RIN value, LCFS credit, 45Z, 45Q and state tax credits to reach a net price shown beside the competing fossil price, for two fuels in two regions.

Notes: This figure shows, for the year 2030, the production costs, incentives, and resulting net prices of California renewable diesel and sustainable aviation fuel outside of California under current policy.

costs but contribute additional emissions reductions. Figure 5 shows that, for scenarios that append additional SAF policies to the current policy mix, average abatement costs to achieve the target are similar or (in the case of the SAF Credit) higher than the current policy scenario. The modest increase in average abatement costs for most of these policies (relative to current policy) is due to an induced shift of biofuels from biomass-based diesel towards the relatively more expensive SAF technology. To put these abatement costs in perspective, Figure 5 includes a carbon-tax-only scenario set at \$27.7 per metric ton of CO_2, which achieves the same emissions reduction as the Nested D2 + Stricter RFS scenario. The resulting average abatement cost is \$25/ton.[26] This is approximately 17 times lower than the equivalent SAF mandate, reflecting the high feedstock and production costs that make SAF an expensive decarbonization pathway relative to demand-side carbon pricing. All of these policies also result in an increase in emissions reductions relative to the current policy, so *total* abatement costs increase.

The additional emissions reductions associated with reaching the 3 Bgal target range from 0.4 to 2% of transportation emissions (22 to 108% of the emissions reduction achieved by current

26. The average abatement cost is slightly lower than the carbon tax rate because ethanol production provides octane-enhancing co-benefits.

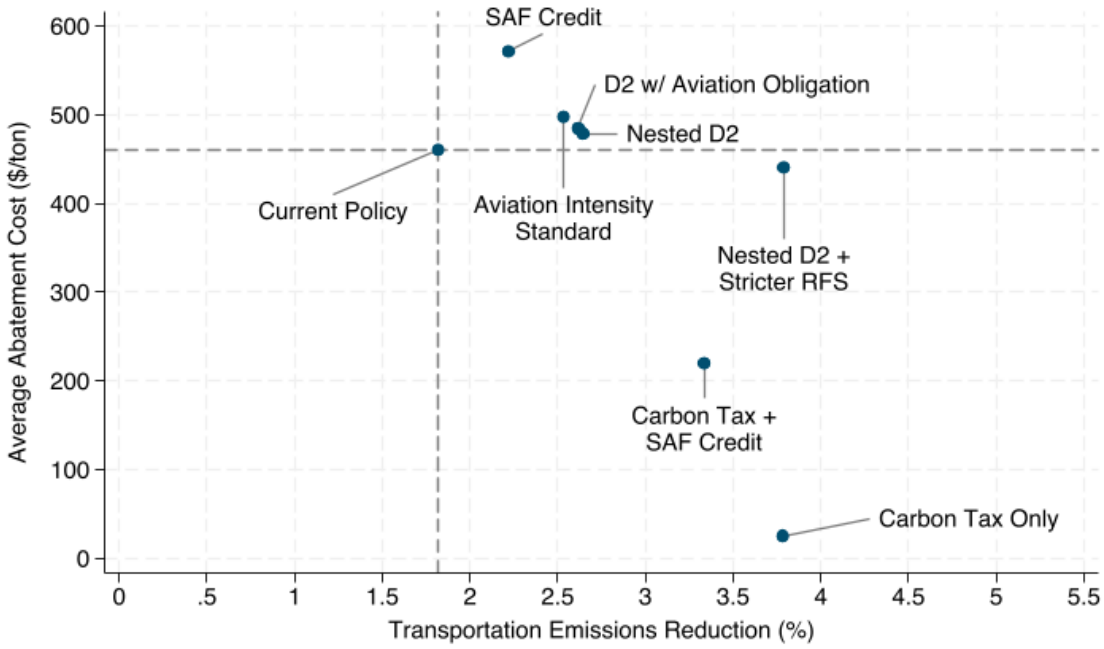


FIGURE 5: Emissions reduction and average abatement costs across policy scenarios

Alt text: Scatter plot of emissions reduction in percent against average abatement cost in dollars per ton, where each scenario is a labeled point and dashed lines mark the current policy values of 1.8 percent and 460 dollars per ton.

Notes: This figure shows, for each policy scenario, the percent decrease in transportation emissions (relative to no policy) and the average abatement cost of these emissions reductions, in dollars per ton. The carbon-tax-only scenario, which does not result in any SAF production, is designed to achieve emission reductions in line with the Nested D2 + Stricter RFS scenario.

policy). In most cases in which SAF policies are added to existing policies, emissions reductions are limited by the interaction between overlapping policies. Because additional SAF production generates credits that can be used to comply with volumetric requirements under the RFS and the intensity target of the LCFS, policies that achieve the 3 Bgal target displace biomass-based diesel consumption that would have occurred otherwise. The policy scenario that results in the largest emissions reduction involves increasing the stringency of the RFS; this approach nearly doubles emission reductions at an average abatement cost lower than the current policy scenario. This results from the more stringent RFS increasing the price of fossil fuels which elicit a demand response reducing total demand for transportation fuels, representing relatively low-cost abatement. Note, however, that the emissions reductions from the Carbon tax + SAF credit scenario are achieved at a substantially lower average abatement cost by further exploiting the demand reduction channel.

On-road light-duty vehicles account for 38–58% of total abatement, with the largest share under the carbon tax + SAF credit scenario. With a 3 billion-gallon SAF target, aviation contributes more than 30% of total abatement (except under Nested D2 + Stricter RFS, where higher RFS volumes shift additional biodiesel to the rest of the United States). Although California represents only about 10% of total U.S. travel demand, it provides roughly 70% of total emission reductions in

TABLE 7: Policy incentive values across policy scenarios

Scenario	State Credit ($/gal)	SAF Tax Credit ($/gal)	D2 RIN ($/RIN)	D4 RIN ($/RIN)	D6 RIN ($/RIN)	LCFS Credit ($/ton)	Av. Std. Credit ($/ton)	Carbon Tax ($/ton)
Current Policy	1.50	-	-	1.64	1.34	120.92	-	-
SAF Credit	1.38	2.10	-	0.47	0.47	250.00	-	-
Nested D2	1.38	-	1.77	0.43	0.43	250.00	-	-
D2 with aviation obligation	1.38	-	1.72	0.44	0.44	250.00	-	-
Nested D2 + stricter RFS	1.38	-	2.59	1.96	1.96	74.58	-	-
Carbon Tax + SAF credit	-	4.40	-	-	-	-	-	15.00
Aviation Intensity Std	1.38	-	-	0.51	0.51	250.00	283.84	-
Carbon Tax Only	-	-	-	-	-	-	-	27.70

Notes: This table shows the policy incentive value available for the marginal unit of biofuel production each policy under each scenario. RFS RIN prices are quoted in dollars per RIN. Ethanol is assigned an equivalence value of 1.0, while biodiesel has a value of 1.5, renewable diesel is set at 1.7, and sustainable aviation fuel (SAF) has an equivalence value of 1.6. The Carbon Tax only scenario sets the carbon tax at $27.7 per metric ton of CO_2, a level chosen to achieve the same transportation emissions reduction as the Nested D2 + Stricter RFS scenario.

most scenarios, reflecting the role of the LCFS in penalizing petroleum fuels and encouraging biofuel use. Further details on sectoral abatement are provided in Supplemental Appendix Section F.1.

The credit prices under each scenario are presented in Table 7. Under all scenarios that mandate 3 Bgal of SAF, except with a stricter RFS, California's LCFS credit market reaches the price ceiling of $250 per metric ton and the target emissions intensity reduction of 30% below 2011 levels is not reached. This occurs because the additional incentives for SAF outside of California from state-level tax incentives increase competition for feedstocks and raise prices, increasing compliance costs for biomass-based diesel fuels under the LCFS. In contrast, when the stringency of the RFS is increased, greater federal support for biomass-based diesel fuels helps reduce the cost of reaching the California target. However, it is important to acknowledge that reaching the LCFS target will depend on developments outside the scope of this model including vehicle electrification rates, hydrogen technology development, and the dairy biogas sector. Different levels of exogenous LCFS credit generation are analyzed in Section G.7. When we assume 3.9 million metric tons of additional exogenous credits, the LCFS credit price no longer reaches the ceiling.

We also examine alternative scenarios using a carbon tax alone, but obtained zero SAF production under such a policy. A carbon tax results in emissions reductions at lowest cost, but almost all reductions are a result of reduced demand for fuels, rather than a substitution toward lower-carbon biomass-based fuels. However, under one contrived policy scenario — a $15 per ton carbon tax with a SAF tax credit of $4.40 per gallon — greater emissions reductions as well as the SAF production target could be achieved at a 52% lower average abatement cost than the current policy scenario ($220 per ton vs. $461 per ton). Under this scenario, biomass-based diesel use in road transportation falls by about 79% relative to the current policy. Once again, emissions reductions in this scenario are driven more by lower transportation demand than by substitution toward lower-carbon fuels. Comparing this scenario with others that achieve the SAF production target, and with the carbon tax alone, highlights the finding that cost effectiveness is in many cases at odds with biofuel production targets.

Long-run costs may be lower than the static costs in our model because of the benefits from learning-by-doing innovation (Gillingham and Stock 2018). To encourage early learning in the development and distribution of sustainable aviation fuel, it may be desirable to incentivize the development of SAF even if it does not achieve low cost emissions reductions.

Our simulations capture a range of important interactions across overlapping federal and state policies. However, several state-level policies are not explicitly represented. For example, Washington, Oregon, and New Mexico have also adopted low carbon fuel standards. Because these states account for a small share of total fuel consumption, explicit representation of their LCFS programs is not expected to substantially alter national-level results. Nevertheless, market dynamics in these states would likely resemble the interaction patterns observed with California's LCFS.

Another state-level policy with potentially more significant implications is California's cap-and-trade (CAT) program. Previous research shows that interactions between the LCFS and CAT can shift compliance strategies in ways that alter total emissions outcomes (Scott 2024). Although neither fossil jet fuel nor SAF currently faces a compliance obligation under the cap, indirect interactions are possible. Specifically, if SAF consumption in California displaces biofuel (e.g., renewable diesel) that otherwise would be used in meeting LCFS compliance, consumption of fossil transportation fuel (e.g., diesel) may increase to satisfy transportation demand. This dynamic would raise allowance demand under the emissions cap, which, if binding, could induce additional emissions reductions in other sectors covered by the emissions cap. We label this effect reverse leakage: conventional emissions leakage describes how emissions reductions in a regulated sector or jurisdiction are partially offset by emissions increases elsewhere; here, the effect is reversed, with an increase in California transport-sector emissions inducing compensating reductions in other capped sectors via the binding cap. While uncertain, this reverse leakage mechanism could reduce cumulative emissions by an estimated 16-21 million metric tons and lower average abatement costs by 15%–20% in scenarios that achieve the SAF target with both the LCFS and CAT in place (see Supplemental Appendix Section F.2). This effect depends importantly on the assumption that California's cap-and-trade program imposes a binding constraint on emissions, rather than emissions allowances being sold at the price floor or ceiling.

B. Distribution of Costs

The distribution of policy costs across drivers, air passengers, and taxpayers both within and outside of California depends on the policy approach employed for achieving the SAF target (see Figure 6).[27] The relative costs imposed on drivers, airline passengers, or taxpayers depend on whether revenue used to support SAF production is generated from compliance obligations under the RFS and LCFS, whether fossil jet fuel faces a compliance obligation, and/or whether subsidies are provided through general tax revenue.

27. Policy costs shown here are defined in the same way as in Figure 5. Specifically, additional fuel costs are the extra costs incurred when purchasing the no-policy fuel quantities at the prices prevailing under each policy scenario. Government spending is the total value of tax credits at the state and federal level. Total policy cost is given by additional fuel costs plus government tax subsidies, net of carbon tax revenue.

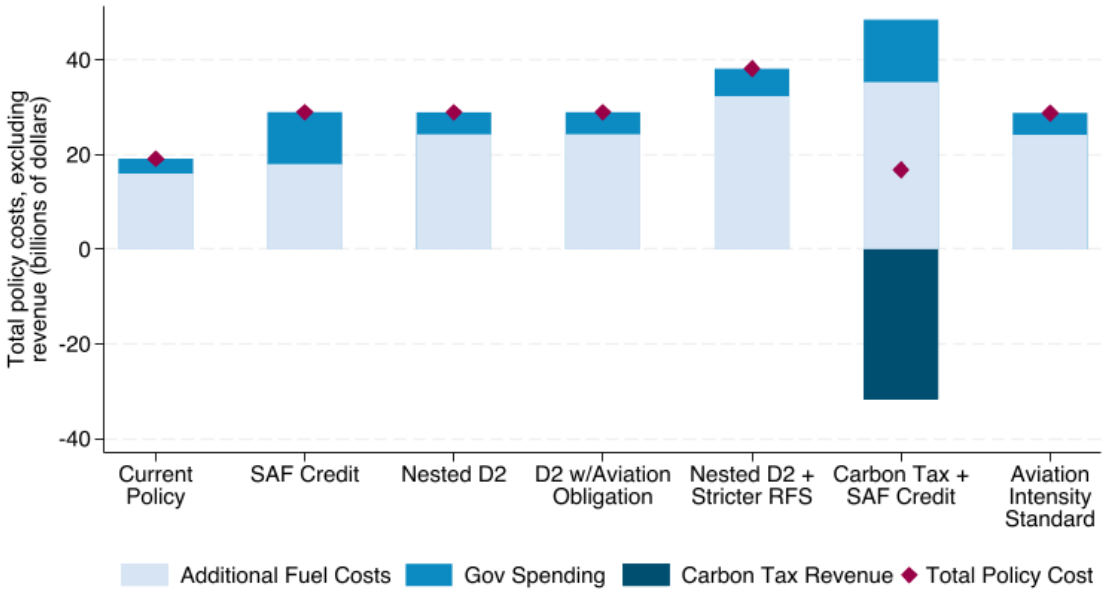


FIGURE 6: Policy cost breakdown across policy scenarios

Alt text: Stacked bar chart of policy cost in billions of dollars where each bar divides into additional fuel costs, government spending and carbon tax revenue, with revenue extending below zero and a diamond marking the total.

Notes: This figure shows how the three components of policy cost–additional fuel costs, government spending, and carbon tax revenue–vary by policy scenario. Diamond markers indicate total policy costs.

Figure 7 shows the incidence of direct policy costs across travel modes and regions. We define direct policy costs as the sum of policy obligations.[28] The two scenarios that achieve the SAF target with government-funded subsidies (SAF credit and carbon tax + SAF credit) impose the highest total cost on taxpayers. Airline passengers contribute nothing under three policy scenarios; the burden of the SAF tax credit falls on taxpayers, and nested D2 policies don't impose a compliance obligation on petroleum jet fuel, placing the burden of these policy changes on consumers of gasoline and diesel. For all scenarios that meet the 3 Bgal target, except "nested D2 + stricter RFS" and "carbon tax + SAF credit", California drivers contribute between 47% and 58% of the portion of the policy cost that is borne by gasoline and diesel consumers, even though they use only about 10% of the nation's gasoline and diesel. This finding is robust to the choice of diesel demand elasticity (Winebrake et al. 2015; Gillingham and Munk-Nielsen 2019). California's driver share of the on-road consumer burden falls by at most 2 percentage points across the reported elasticity bounds, confirming this is a structural feature of the LCFS rather than an artifact of the elasticity assumption (Appendix Section G.8). By comparison, California drivers bear approximately 21% of the on-road cost burden in the current policy scenario. This extra burden is caused by additional incentives for SAF outside of California increasing competition for SAF and biomass-based diesel

28. Policy costs are calculated using the realized quantities under each policy scenario, rather than the no-policy fuel quantities used in Figures 5 and 6.

feedstocks, resulting in higher LCFS credit prices.

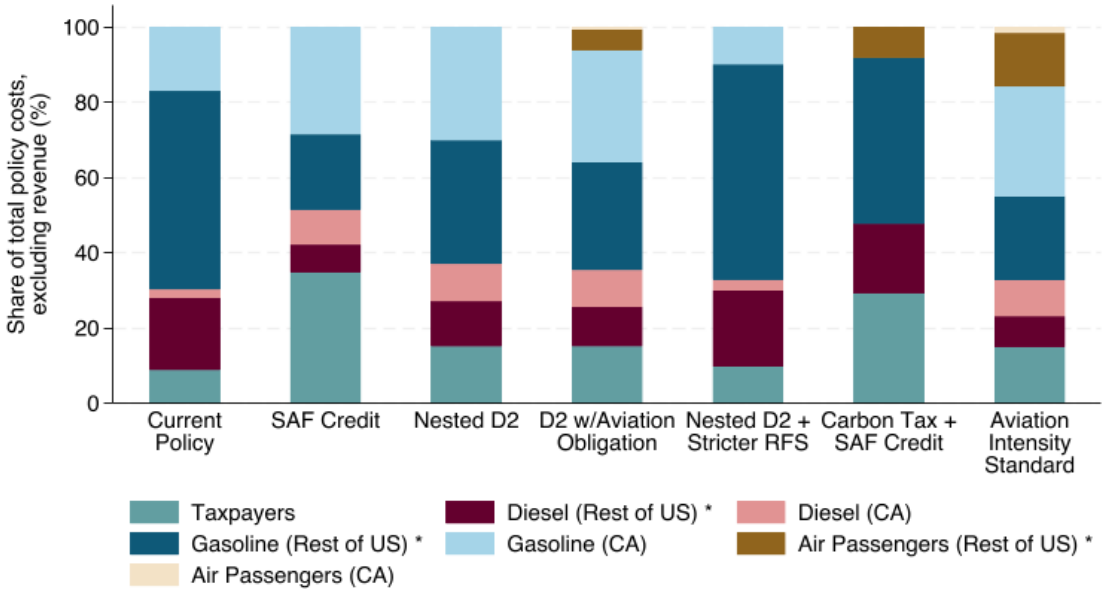


FIGURE 7: Actual policy cost distribution shares across policy scenarios (excluding tax revenue)
Alt text: Stacked bar chart of cost shares summing to 100 percent where each bar divides among taxpayers and consumers of diesel, gasoline and air travel, separately for California and the rest of the United States.

Notes: This figure shows how actual policy costs (excluding carbon tax revenue) are distributed across policy scenarios. Actual policy cost is defined as the sum of total obligations under the LCFS, RFS, carbon tax, and aviation intensity standard, plus government tax expenditures. The cost is distributed between taxpayers (who fund tax credits), and consumers of diesel, gasoline, and air travel (who experience price changes). The Carbon Tax + SAF Credit scenario does not include the CA LCFS program; in this scenario "Rest of the US" should be interpreted to include California.

The political feasibility of any policy change may depend on the impacts of fuel prices (see Figure 8). Notably, several policies used to reach the 3Bgal target result in substantial increases in blended diesel prices in California (e.g., SAF credit, Nested D2, D2 with aviation obligation, and aviation intensity standard) alongside slight reductions in blended diesel prices for the rest of the U.S. relative to current policy.[29] This result is due to the incentive created by state-level tax credits to produce and consume SAF outside of California. This incentive creates competition for feedstocks and higher prices for biomass-based diesel that make it more costly to meet the California LCFS standard. As SAF is used to satisfy RFS standards, RIN prices are expected to fall, and blended diesel prices in the rest of the United States become lower than under the current policy scenario. When RFS stringency is increased, additional biodiesel must be produced in the rest of the United States to meet the biomass-based diesel and total renewable fuel standards. Higher RIN prices then shift part of the compliance burden away from California's LCFS, leading to large increases in diesel prices in the rest of the United States.

29. The ranking of blended diesel price impacts is preserved under the same elasticity bounds, with blended diesel prices in California changing by at most 5.5% at the bounds of the reported range (Appendix Section G.8).

Including a compliance obligation for fossil jet fuel is expected to reduce the costs borne by on-road diesel fuel (e.g., under the D2 with aviation obligation and aviation intensity standard). This may also be where the most cost effective policy in terms of emissions reductions – the carbon tax and SAF tax credit – likely runs into political feasibility barriers, by increasing diesel prices by $0.20 per gallon, gasoline prices by $0.17 per gallon and jet fuel by $0.17 per gallon compared to the no-policy scenario. However, scenarios with low impacts on blended fuel prices may simply shift policy costs from drivers to taxpayers, as illustrated in Figure 7.

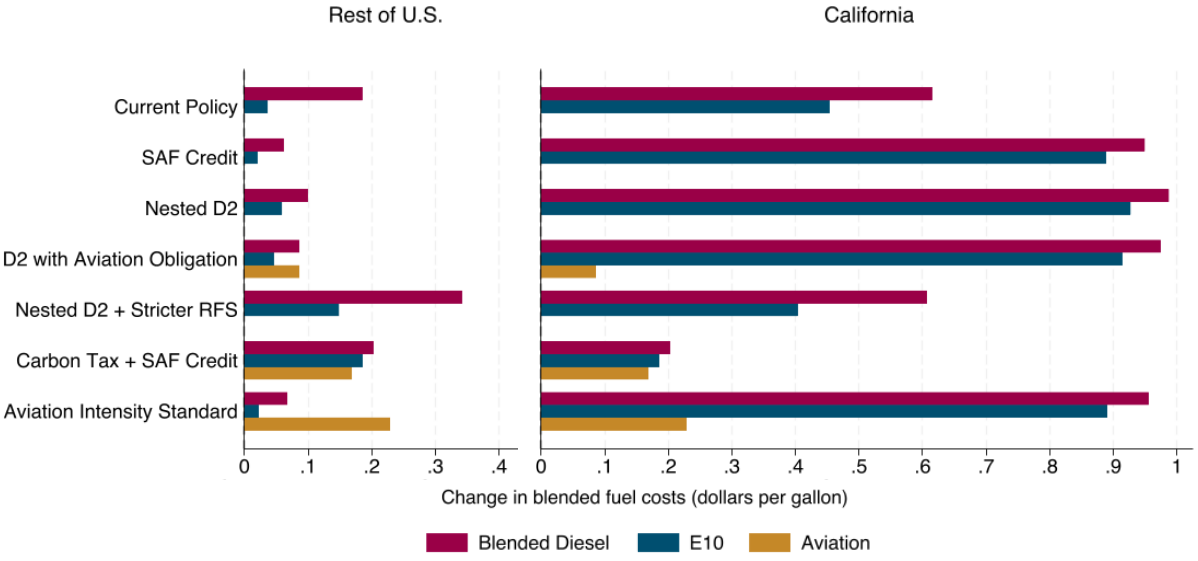


FIGURE 8: Blended fuel cost impacts relative to no policy

Alt text: Two horizontal bar charts of cost change in dollars per gallon, one for California and one for the rest of the United States, where each scenario has separate bars for blended diesel, E10 gasoline and aviation fuel.

Notes: This figure shows changes in fuel cost relative to no policy scenario across fuel types resulting from each policy scenario.

C. Feedstocks

Under current policy, SAF is produced exclusively via the ATJ pathway utilizing corn feedstock and incorporating CCS technology. This represents the lowest cost production pathway when accounting for policy incentives and feedstock competition.

Enacting additional policies to achieve the 3 Bgal SAF target would alter the demand for and mix of feedstocks and result in land use change effects. Achieving the 3 Bgal target without increasing the stringency of the RFS primarily causes a shift in production from HEFA feedstocks (such as vegetable oils, fats, and waste oils) to ATJ feedstocks (including corn and sugarcane), as well as a reallocation of feedstocks from on-road fuels to SAF, with only minor changes in total demand (see Figure 9). For instance, under the SAF credit scenario, overall vegetable oil demand falls by 11%, demand for fats, oils, and greases decreases by 17%, while corn demand rises by

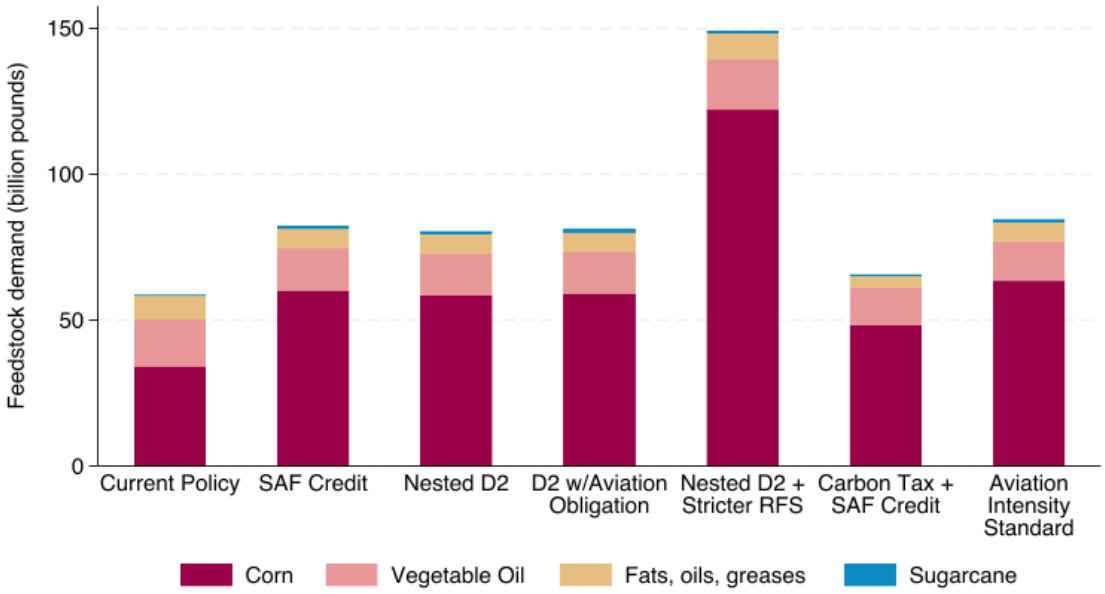


FIGURE 9: Changes in feedstock demand by scenario relative to no policy

Alt text: Stacked bar chart of feedstock demand in billions of pounds where each bar divides into corn, vegetable oil, fats and oils, and sugarcane across seven policy scenarios.

Notes: This figure illustrates how feedstock demand changes under each policy scenario.

9% relative to the current policy scenario. With a more stringent RFS, total feedstock demand increases by 28% compared to current policy while total demand only increases by around 7% across other scenarios where the RFS percentage standards remain the same.

HEFA pathways (including vegetable oil, fats, and waste oils) make up between 43% and 49% of SAF production in most scenarios. One exception is the scenario in which RFS stringency increases and SAF production is additional to mandated road transport biofuel levels; in that case, HEFA feedstocks are used primarily for road transportation and make up only 11% of SAF. These differences illustrate the importance of the structure of biofuel incentives and competition between feedstocks in determining which SAF pathways gain market share. Moreover, dramatically increasing biofuel mandate levels raises feedstock demand from crops, which raises concerns around land-use change and interactions with food markets.

IV. Conclusions and policy implications

Efforts are underway to develop alternative low-emissions aviation technologies such as hydrogen and battery-electric aircraft, but significant technical obstacles and the long lifespan of the existing capital stock mean that fuel substitution remains the most promising pathway for aviation decarbonization in the near term. We show that current policy is insufficient to drive SAF adoption in the United States. Reaching 3 Bgal of SAF by 2030 would have significant costs, and the policy

adopted would have important effects on emissions, prices, cost, cost incidence, and feedstock mix.

Several of the policies we examine, including an aviation intensity standard and two possible regulatory changes to the Renewable Fuel Standard to add an additional compliance category for SAF, yield similar average abatement costs to current policy and a 44-45% increase in emissions reductions. Adding a federal SAF credit to existing policy yields 22% more emissions reductions than current policy at a 24% higher average abatement cost. Combining the addition of a new compliance category for SAF with a stricter RFS yields a substantial increase in emissions reductions (108%) relative to current policy at a similar average abatement cost. The only scenario we examine that results in both lower emissions and a reduction in *total* abatement costs involves replacing existing policy with the combination of a SAF tax credit and a carbon tax on petroleum transportation fuels; this policy results in an 83% increase in emissions reductions at an average abatement cost of $220 per metric ton.

There are several limitations worth noting that merit further research. First, this analysis does not seek to evaluate the land-use change impacts of expanding crop-based feedstocks beyond the land-use change parameters used in the life-cycle emissions models; emissions results may depend on these impacts. Second, we present results for a set of assumed parameter values. We analyze sensitivity to these assumptions in the Appendix, but there remains scope to further investigate the implications of alternative assumptions.

Third, this static analysis does not account for potential innovation in fuel production approaches that may drive down abatement costs. While we do not model innovation directly, considering our results in the context of potential innovation is important, particularly because many SAF technologies are still relatively nascent. Many of the hypothetical policies we study demonstrate high average abatement cost but might help lower future costs by promoting innovation. Recent research indicates, however, that while learning rates for ethanol have been substantial, learning in biodiesel and renewable diesel has been comparatively lower (Scott 2025). Whether biomass-based aviation fuels or alternative fuel production pathways such as power-to-liquids can significantly decrease costs in the medium to long-term, and what policies can most effectively drive innovation in technologies with large decarbonization potential, remains a question for future research and is likely an important factor in SAF adoption trajectories.

The findings from this study highlight the trade-offs inherent in designing effective SAF policies and provide actionable insights for policymakers seeking to encourage aviation decarbonization. We present a novel approach to modeling the complex policy interactions that arise between overlapping biofuel policies, highlight key interactions that are important to consider when designing new biofuel policies or changes to existing policies, and use model results to discuss important outcomes.

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Supplemental Appendix

A. Policy Details

A.1. The Renewable Fuel Standard and California Low Carbon Fuel Standard

Table A1 depicts the fossil fuel carbon intensities used to determine eligibility and credit value under the RFS and CA LCFS.

TABLE A1: Fossil fuel carbon intensities under RFS and CA LCFS

Fuel	Carbon Intensity (gCO_2e/MJ)	
	RFS	CA LCFS
Gasoline	93.08	100.82
Diesel	91.94	100.45
Conventional Jet Fuel	89.00	89.00

Notes: This table shows the carbon intensity values of fossil fuel alternative to biofuels that are used when determining RIN eligibility under the Renewable Fuel Standard and credit value under the California Low Carbon Fuel Standard.

A.2. Tax Credits

In 2025, the Clean Fuel Production Credit (45Z) replaced the 40B credit for SAF and the blenders tax credit for biomass-based diesel. Under 45Z, biofuel produced with emissions intensity at or below 47.4 grams (g) of CO_2e/MJ[1] is eligible to claim a tax credit equal to $1 per gallon multiplied by an emissions factor, which is calculated by comparing the fuel's emission intensity to a baseline of 47.4 gCO_2e/MJ. The 45Z credit also includes requirements that producers meet certain wage and apprenticeship conditions. Those that do not meet the minimum wage and apprenticeship requirements receive $0.35 and $0.20 times the emissions factor per gallon or gallon equivalent for aviation and non-aviation fuels, respectively.

In the original statute, SAF received a higher credit value of $1.75 times the emissions factor; recent amendments to the 45Z rule starting in 2026 reduced the SAF credit level to $1 times the emission factor (equivalent to the road-transportation biofuel incentive). Amendments also reduce the carbon intensity values of fuels by excluding indirect land-use change and limit eligibility to U.S. firms using North American (U.S., Canada, or Mexico) feedstocks (U.S. Congress 2025).

Tax incentives for carbon capture and storage (CCS) technology (45Q) are also available, but they cannot be used in combination with other federal tax credits to provide additional support for the production of biofuels (U.S. Code 2018). Therefore, we assume that biofuel producers that employ CCS will choose the maximum tax credit available to them. Under 45Q, facilities that comply with prevailing wage and apprenticeship requirements are eligible to receive $85 per metric ton of CO_2 that is geologically sequestered.

1. The 45Z threshold is 50 $gCO_2e/MMBtu$. We convert this to CO_2e/MJ using a factor of 1.05506.

Select states have also implemented their own tax credits to encourage the production and use of SAF. Specifically, Hawaii, Illinois, Iowa, Minnesota, Nebraska, and Washington State have broad SAF tax credits in place (see Table **??**). Together, these states produce 11.5 billion gallons of biofuels annually, with nearly 60% of total U.S. ethanol production capacity and 15% of biomass-based diesel production capacity (USDA 2024). Arkansas also has a tax credit for SAF; however, it only applies to SAF produced from woody biomass feedstocks, a process not yet commercially viable, and is therefore excluded from this analysis.

A.3. Policies outside the United States

Canada implemented a federal LCFS in 2023 on top of the already existing LCFS in the province of British Columbia. Notably, recent amendments to British Columbia's LCFS program include a compliance obligation for petroleum jet fuel starting in 2026 requiring a 10% reduction in emissions intensity by 2030 as well as a specific volumetric mandate for SAF to reach 3% of the jet fuel supply by 2030 (Gov. of B.C. 2023).

In contrast to the subsidy-driven approach to support SAF development in the US, the European Union (EU) has instituted a volumetric mandate, known as the RefuelEU Aviation Initiative, that requires an increasing share of SAF to be used in aviation. The mandate starts in 2025 at 2% and increases to 6% in 2030 and 70% in 2050 (EU 2023). Within this requirement, a growing share of aviation fuels must be synthetic fuels made from hydrogen or recaptured carbon, reaching 1.2% in 2030 and 35% in 2050. The policy allows compliance flexibility over the first ten years in which SAF suppliers may provide an oversupply at one airport to compensate for an undersupply at another as capacity expands. Notably, it does not allow for biofuels made from food or feed crops such as corn and soybean oil, but it does allow those produced from animal fats and used cooking oil.

Furthermore, aviation emissions for flights within the European Economic Area are covered by the EU emissions trading system (ETS). Empirical evidence from Fageda and Teixidó (2022) indicates that imposing a carbon price on aviation of less than \$14 per ton CO_2 through the E.U. ETS reduced emissions by 4.7% on covered routes from 2012 to 2016 and 10.7% for flights less than 1,000 km where there may be competition from mode switching.

We do not model policies outside the U.S. in this paper.

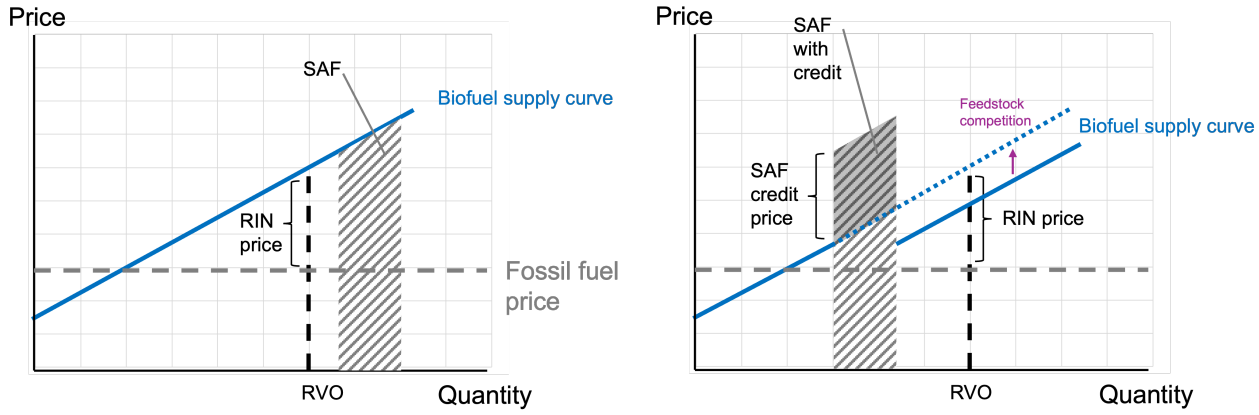
A.4. Illustrative policy interaction

Figure A1 illustrates the interaction between a SAF tax credit and a binding volumetric mandate such as the RFS. Panel A shows the volumetric mandate alone. The RVO fixes the quantity of biofuel, and the RIN price equals the gap between the marginal cost of biofuel at the mandated volume and the fossil fuel price (per energy-equivalent gallon). SAF occupies the high-cost segment of the biofuel supply curve beyond the mandated volume; therefore no SAF is produced.

Panel B adds a SAF tax credit. The credit lowers the effective cost of SAF below that of marginal BBD, so SAF enters the compliance mix. Because the RVO is unchanged, SAF displaces an equivalent RIN gallon volume of BBD. Therefore, only the composition of fuels used to meet

the standard changes. The emissions effect is limited to the difference in carbon intensity between SAF and the displaced BBD, multiplied by the displaced volume. Costs rise through two channels. First, the credit itself is paid by taxpayers. Second, because SAF and BBD compete for the same feedstocks, the additional SAF production shifts the biofuel supply curve upward. Additional interactions with state-level LCFS policies are not depicted here.

FIGURE A1: High-cost SAF displaces BBD under the RFS volumetric requirement



(A) Under current policy, high-cost SAF is not produced

(B) Incentivized SAF displaces BBD under the RFS

B. Data Construction

B.1. Estimate Greenhouse Gas Emissions of Biofuels

Table A2 presents lifecycle analyses of greenhouse gas emissions using different Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) models. The well-to-wheel estimates are expressed as carbon intensity (CI) values, measured in grams of CO_2 equivalent emitted for every megajoule of energy produced or used.

The Environmental Protection Agency (EPA) has published numerical lifecycle analyses for the Renewable Fuel Standard (RFS) program.[2] At present, there is no certified pathway for corn Alcohol-to-Jet (ATJ) fuel in the RFS program. LanzaJet is currently the only certified producer of sugarcane-based ATJ, with a carbon intensity (CI) of 39.99 gCO_2e/MJ.[3] For all other pathways, we use the mean carbon intensity values for "generally applicable pathways". Our analysis excludes production processes that co-process renewable biomass and petroleum. For crop-based vegetable oils, we calculate an average of the values for soybean oil, canola oil, and distillers corn oil. For tallow

2. Summary data for all lifecycle analyses under the RFS are available at: https://www.epa.gov/system/files/documents/2023-05/summary-lca-results-for-web-v1-1-2023-04.xlsx.

3. The completed pathway assessment for the LanzaJet Soperton plant is available at: https://www.epa.gov/system/files/documents/2023-01/lanzajet-d-code-4-rfs-pathway-determination-letter-2023-01-12.pdf.

TABLE A2: Carbon Intensity (CI) in gCO_2e/MJ for different biofuel types across different GREET models

Biofuel type	Technical pathway	Feedstock	Carbon Intensity											
			EPA RFS			CA-GREET			45Z CA			45Z ROUS		
			AO	LUC	Tot	AO	LUC	Tot	AO	LUC	Tot	AO	LUC	Tot
SAF	HEFA	Crop-based veg oils	20.57	15.21	35.77	18.27	29.10	47.37	25.84	11.32	37.15	26.70	11.32	38.01
		Tallow and waste oils	13.04	0.00	13.04	33.60	0.00	33.60	17.46	0.00	17.46	18.32	0.00	18.32
	ATJ	Corn	–	–	–	–	–	–	55.68	6.28	61.96	60.73	6.28	67.01
		Sugarcane	–	–	–	–	–	–	33.99	15.22	49.21	39.04	15.22	54.26
	ATJ+CCS	Corn	–	–	–	–	–	–	25.68	6.28	31.96	30.73	6.28	37.01
		Sugarcane	–	–	–	–	–	–	3.99	15.22	19.21	9.04	15.22	24.26
Biodiesel	Average	Crop-based veg oils	19.38	21.33	40.72	18.43	29.10	47.53	21.64	9.22	30.86	21.95	9.22	31.17
		Tallow and waste oils	13.04	0.00	13.04	23.34	0.00	23.34	17.96	0.00	17.96	18.82	0.00	18.82
Renewable diesel	Average	Crop-based veg oils	19.55	15.23	34.78	20.87	29.10	49.97	24.61	10.44	35.05	25.26	10.44	35.70
		Tallow and waste oils	13.04	0.00	13.04	33.89	0.00	33.89	16.69	0.00	16.69	17.52	0.00	17.52
Ethanol	Average	Corn	46.89	26.32	73.21	49.60	19.80	69.40	40.17	5.78	45.95	42.81	5.78	48.59
		Sugarcane	31.02	5.07	36.10	40.24	11.80	52.04	23.24	14.01	37.25	23.24	14.01	37.25

Notes: 1. AO stands for "All other", LUC for "Land Use Change", and Tot for "Total". 2. Dashes (–) indicate that the pathway is not certified or data is unavailable for that specific model. For example, CARB has not certified any ATJ pathways and average estimates are unavailable for ATJ pathways in CA-GREET.

and waste oils, we use the biogenic waste oils/fats/greases pathway. In our biodiesel assumptions, we do not account for high-yield scenarios per acre. For corn ethanol, we select the dry mill, natural gas pathway, which is the predominant technology in the U.S. For sugarcane ethanol, we assume no trash collection and that marginal electricity is used in processing; additionally, the sugarcane ethanol considered is not produced under the "Caribbean Basin Initiative".

For the California-GREET model, we calculate the weighted-average CI for each technical pathway and feedstock combination, utilizing all currently certified pathways published by CARB.[4] Currently, CARB has not certified any ATJ pathways. As with other analyses, we compute the average CI for crop-based vegetable oils using soybean oil, canola oil, and distillers corn oil. For tallow and waste oils, we average the CI values for tallow, animal fat, and used cooking oil. Pathways that are marked as retired in the 8/25/2025 version are excluded from our analysis, as are all pathways certified under the legacy CA-GREET2.0 model.

The 45ZCF-GREET model is the methodology adopted by the U.S. Department of the Treasury to determine emissions reduction percentages under the Clean Fuel Production Credit (U.S. Code 2022).[5] In our analysis, we distinguish between CI values for biofuels produced in California and those produced in the rest of the United States (ROUS) to capture differences in grid electricity

4. The raw data for the certified fuel pathway table are available at: https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities.

5. The latest version of the model is available at: https://www.energy.gov/sites/default/files/2025-06/45ZCF-GREET%202025%20May.zip

mixes used in fuel production and in transportation distances to final users. It is important to note that the CI values presented here are default values and are representative of typical biofuel production facilities within California and the ROUS; individual facility values may differ based on facility-specific characteristics. For example, factors such as feedstock type, processing efficiencies, and transportation logistics can influence the CI at a specific site. To calculate CI values for each technical pathway and feedstock combination, we utilize sample input parameters detailed in the model's documentation, apply appropriate feedstock input assumptions, and assume no by-product revenue to ensure consistency with our analytical framework.[6] For ROUS regions, the 45ZCF-GREET model provides 14 distinct electricity regions based on the National Transmission Needs Study. We use data from the Midwest region as a proxy for the entire ROUS because it has the highest concentration of biofuel production. Our comparison of CI values across various regions—such as the Plains and Midwest—shows that regional differences in CI are relatively minor.

Corn ethanol producers can choose to integrate carbon capture and geological sequestration (CCS) during the fermentation process. Capturing and permanently storing the high-purity CO_2 produced by ethanol plants can lower direct greenhouse gas emissions by approximately 30 gCO_2e/MJ on average (Yoo, Lee, and Wang 2022; Wang et al. 2023). However, the precise quantity of CO_2 that can be captured and sequestered depends on the specific characteristics of each facility and the technologies employed. In this analysis, we assume that only sustainable aviation fuel (SAF) producers implement CCS, as such measures are needed to achieve the more stringent emissions reduction thresholds under the RFS. We do not consider CCS for conventional corn ethanol producers because they are generally able to satisfy the RFS's 20% emissions reduction requirement without CCS.

Estimated carbon intensity (CI) values can differ substantially between modeling frameworks. For instance, the CA-GREET model yields total net emissions that are at least 30% higher than those calculated using the 45Z-GREET model for all biofuel categories and technical pathways. Some this variation may stem from differences in fuels credited under these programs. For example, while an average across current approved pathways was used to estimate CI values in the LCFS program (CA-GREET), data on producers claiming the 45Z tax credit are not available, so sample inputs provided by the Department of Energy were used to estimate CI values under 45ZCF-GREET. Variation in CI values may also stem from differences in the fuels credited under these programs. For example, the high incentive under the LCFS program may, on-average, drive lower than average carbon intensity fuels under each pathway to enter California, particularly when they are demand-constrained; on the other hand, accounting for the emissions from the transportation of these fuels means that there is a larger incentive for fuels produced in California, all else equal. To improve the comparison in this table, we use sample inputs from fuels produced in California to estimate CI values under the 45ZCF-GREET column; this restriction is not possible when providing estimates from EPA/RFS; here, we use the CI values provided by EPA which are associated with

6. For instance, the 45Z-GREET model uses an input of 8 pounds of soybean oil to produce 1 gallon of sustainable aviation fuel (SAF) or renewable diesel. Our review of the literature indicates that this value typically ranges from 8 to 9 pounds per gallon for SAF production.

the most common technological assumptions under each pathway.

The main source of this divergence, however, is the varying treatment of land use change (LUC) emissions. LUC emissions constitute a significant portion of biofuel CI and are highly sensitive to the methodological choices and assumptions made in different models. For example, estimates of indirect land use change (ILUC) associated with Brazilian sugarcane ethanol range from 5.5 to 46 gCO_2e/MJ, reflecting differences in economic modeling and baseline crop yield assumptions (Liu et al. 2023). Estimates of land use change (LUC) greenhouse gas emissions for corn ethanol range from 6 to 30 gCO_2e/MJ, depending on the model used (Lee et al. 2021). These disparities arise from differences in assumptions regarding crop yield projections, land conversion constraints, crop yield price elasticities, and the relationship between food demand and price changes, as well as variations in the spatial and temporal resolution of each modeling approach. CA-GREET generally assigns higher LUC emissions to crop-based feedstocks, owing to its particular land use modeling procedures. These modeling differences highlight the necessity of carefully selecting assessment models and assumptions when quantifying the environmental impacts of biofuels. For example, Berry, Searchinger, and Yang (2024) argue that GTAP models, which are commonly used to estimate the effect of biofuel production on land use change, including under CA-GREET, substantially underestimate the emissions effects of biofuel production. By contrast, Khanna, Rajagopal, and Zilberman (2021) find that the ILUC factors used in GREET have generally overstated the emissions impacts of biofuel production.

It is also important to note that recent revisions to the Clean Fuel Production Credit have removed ILUC from carbon intensity (CI) calculations (U.S. Congress 2025). Accordingly, we apply the 45ZCF-GREET model—excluding ILUC emissions—when determining eligibility for the 45ZCF tax credit.

B.2. Fuel Supply

We estimate the fixed per-unit production costs of biodiesel and renewable diesel using Argus market prices in California, based on the 2022 average of Los Angeles and San Francisco prices, adjusted for subsidies and soybean oil feedstock costs. For HEFA-derived SAF, we assume an 8-cent per gallon cost premium over renewable diesel (Pearlson, Wollersheim, and Hileman 2013; Dyk and Saddler 2021). Cost estimates for other SAF pathways were derived from a synthesis of technical assessments reported in the literature (IRENA 2021; WEF 2020; ICAO 2024). We assume there is an 11-cent-per-gallon difference between technical assessment estimates and historical data, based on HEFA-derived SAF observations. The additional CCS cost for the ATJ pathway is derived from Gevo's reported CO_2 capture potential (Yoo, Lee, and Wang 2022) together with International Energy Agency (IEA) cost estimates for CO_2 capture, transport, and storage at biorefineries (IEA 2022).[7] In our analysis, we assume a capture cost of $30 per ton and transport plus storage of $15

7. Gevo's estimate is based on a plant operating in the U.S., and we assume that a sugarcane ethanol plant in Brazil would incur similar costs when implementing CCS technology.

per ton.[8] The production cost of ethanol for the corn pathway is obtained from the literature (Irwin 2019, 2025). For the sugarcane pathway, production costs are derived by taking the historical price differential between Brazilian sugarcane ethanol and U.S. corn ethanol reported by Argus, and adjusting it by subtracting the feedstock cost differential documented in the literature (Shapouri and Salassi 2006).

The feedstock transformation parameter ($\theta_{f,s}$) represents the amount of feedstock s required to produce one unit of biofuel f via a specific feedstock-technology pathway $\{f, s\}$, as detailed in Table **??**. For example, producing one gallon of biodiesel requires 7.55 pounds of vegetable oil feedstock (ISU Extension 2024), while renewable diesel production needs 8.5 pounds of feedstock per gallon (Gerveni and Irwin 2023). The HEFA pathway for SAF production uses 9 pounds of vegetable oil to yield one gallon of SAF (Eggert 2023). For the ATJ pathway, one gallon of SAF requires 1.7 gallons of ethanol, and one bushel of corn produces 2.85 gallons of ethanol (19.65 lbs per gallon) (Swanson and Smith 2024).[9] Additionally, one short ton of sugarcane is expected to yield 19.5 gallons of ethanol (102.56 lbs per gallon) (FSA 2006).

We exclude revenue from co-products generated during the production for biodiesel, renewable diesel and sustainable aviation fuel in our analysis, as most of these co-products, such as naphtha and propane from renewable diesel and SAF production and glycerin from biodiesel production, have comparatively low market value. However, we do account for profit from distiller's dried grains with solubles (DDGS) resulting from ethanol production. Because DDGS has a value comparable to corn and is produced at a rate of roughly one-third of the corn input, we simplify the calculation of DDGS revenue by assuming that $\theta_{f,s}$ in equation (**??**) represents only two-thirds of the corn required to produce one gallon of ethanol.

B.3. Feedstock supply calibration

We calibrate the model to the years 2018-2023. We calibrate the supply curve parameters α_s using quantity data reported by the Energy Information Administration (EIA) in the Monthly Biofuels Capacity and Feedstocks Update (EIA 2024), along with price data (USDA 2024) from 2018 to 2023 and the elasticities in Table **??**. As noted in the main text, we use the supply elasticity of soybean oil as a proxy for all crop-based vegetable oils given data constraints and its current dominance of the U.S. crop-based vegetable oil market. It is important to note, however, that supply elasticities for other vegetable oils, such as canola and corn oil, may vary due to differences in production methods, regional factors, and market conditions. For Brazilian sugarcane, since only a small portion of sugarcane ethanol is imported into the U.S., we use the total quantity of

8. These values fall within the ranges reported by the IEA and Smith et al. (2021), which estimate CO_2 transport in the United States at roughly $2–14 per ton and storage at around $10 per ton. Our assumptions are slightly below the median, consistent with cases where CO_2 is stored directly beneath or near the facility, as proposed by some ethanol producers such as Marquis. We assume no pipeline capacity or siting constraints discussed in Davis et al. (2025).

9. Some industry sources suggest that 9.5 or 10 pounds of feedstock per gallon are required to produce HEFA SAF. To account for uncertainty in the SAF conversion coefficients for both pathways, we test the robustness of our results in Supplemental Appendix Section G.3.2.

sugarcane ethanol, as determined from the volume of D5 RINs attributed to sugarcane ethanol. The supply curve is calibrated using the price of Brazilian sugarcane, and the applicable duty is included when calculating the marginal cost (Equation **??**).

For residual supply elasticities, we plug the actual values in Table A3 into equation B1 and solve for residual price elasticity relevant to biofuel production. We also compute supply curve parameters (α) for each feedstock type using equation B2.

$$\beta_s^{Biofuel} = \frac{Q_s^{All}}{Q_s^{Biofuel}}\beta_s^{All} - \frac{Q_s^{Other}}{Q_s^{Biofuel}}\beta_s^{OtherD} \tag{B1}$$

$$\forall s: \quad Q_s^{Biofuel} = \alpha_s P_s^{\beta_s^{Biofuel}} \tag{B2}$$

TABLE A3: Historical feedstock supply and prices (2018-2023)

Year	Crop-based veg oils			Corn			Tallow and waste oils		Sugarcane	
	Quantity used for biofuel	Biofuel %	Price	Quantity used for biofuel	Biofuel %	Price	Quantity used for biofuel	Price	Quantity used for biofuel	Price
2018	10.38	0.35	0.29	5.38	0.38	3.65	3.03	0.32	0.0040	21.63
2019	9.95	0.34	0.30	4.86	0.35	3.52	2.66	0.33	0.0100	22.83
2020	10.62	0.36	0.58	5.03	0.34	4.86	2.33	0.38	0.0095	21.15
2021	12.67	0.39	0.75	5.32	0.36	6.30	5.80	0.64	0.0031	31.44
2022	15.44	0.46	0.67	5.18	0.38	6.54	7.88	0.84	0.0041	27.73
2023	20.29	0.47	0.49	5.48	0.37	4.93	11.87	0.72	0.0011	33.72

Note: Quantities are reported in billion pounds for crop-based vegetable oils, tallow, and waste oils; in billion bushels for corn; and in billion metric tons for Brazilian sugarcane. Prices are expressed in dollars per pound for crop-based vegetable oils and tallow and waste oils, in dollars per bushel for corn, and in U.S. dollars per metric ton for Brazilian sugarcane. For tallow and waste oils, and Brazilian sugarcane, it is assumed that all available quantities are utilized for biofuel production.

For domestic feedstocks—including crop-based vegetable oils, corn, tallow, and waste oils—the percentage allocated to biofuel production and associated price data are sourced from the U.S. Bioenergy Statistics published by the U.S. Department of Agriculture (USDA).[10] We determine the volume-weighted average blended price for crop-based vegetable oils by utilizing supply and price information provided in Table A7 of the Bioenergy Statistics, averaging across inedible corn oil, canola oil, and soybean oil, which together represent nearly the entire crop-based vegetable oil input for biofuel production. Similarly, for tallow and waste oils, we calculate a volume-weighted average price using the data for tallow and lard from Table A7. Feedstock quantities used in biofuel production are aggregated to the annual level using Monthly Biofuels Capacity and Feedstock Updates from the U.S. Energy Information Administration (EIA).[11]

For imported feedstocks such as Brazilian sugarcane, we obtain sugarcane price quotations in Brazilian Reais from the State of São Paulo's Sugarcane, Sugar and Ethanol Growers Council (CONSECANA) and convert them to U.S. dollars using the official exchange rates provided by the Central Bank of Brazil. Only a small share of sugarcane ethanol is imported into the U.S., we

10. Data are available at: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/documentation.
11. Data are available at: https://www.eia.gov/biofuels/biomass/.

estimate the imported quantity based on the total number of D5 RINs generated from Brazilian ethanol. The sugarcane supply curve is calibrated using prices for sugarcane sold at the port of departure in Brazil, exclusive of shipping costs and tariffs. While we recognize that tariffs increase the marginal cost of biofuel production, we assume that the underlying sugarcane supply curve remains unaffected. Notably, on April 2, 2025, the White House announced a 10% ad valorem tariff on all trading partners (White House 2025b), followed by a further announcement on July 30, 2025, of an additional 40% ad valorem tariff specifically on certain Brazilian goods (White House 2025a). The impact of these new duties is incorporated into equation **??**.

With six years of historical data available, we estimate six separate sets of feedstock supply curve parameters, as presented in Table A4. We then use the average of these parameter values to solve for equilibrium prices and quantities. It should be noted that while agricultural supply shocks do occur, our model does not explicitly account for these fluctuations.

TABLE A4: Estimated feedstock supply curve parameters (2018-2023)

	Crop-based veg oils		**Corn**		**Tallow and waste oils**		**Sugarcane**	
Year	$\beta_{biofuel}$	α	$\beta_{biofuel}$	α	β	α	β	α
2018	0.91	32.26	1.03	1.42		30.24		0.002929
2019	0.93	30.09	1.12	1.18		23.74		0.007337
2020	0.89	17.38	1.17	0.79	2	16.51	0.1	0.006999
2021	0.80	15.90	1.10	0.70		14.19		0.002162
2022	0.64	20.02	1.03	0.75		11.04		0.002963
2023	0.63	31.85	1.07	1.00		22.87		0.000766

Note: $\beta_{biofuel}$ represents the residual supply elasticity for biofuel production, β represents the total supply elasticity, and α is the supply curve intercept. Missing values are indicated by –.

B.4. Fuel demand

The AEO reference case assumes an annual U.S. GDP growth rate of 1.8%. To incorporate time-series forecast uncertainty in fuel demand, we construct prediction intervals using annual U.S. real GDP growth from 1990 to 2019, sourced from the Federal Reserve Bank of St. Louis. We use the method in Müller and Watson (2016) to fit the low-frequency component of GDP growth to estimate a forecast distribution for 2030 GDP.[12] To translate prediction intervals for GDP into prediction intervals for baseline travel demand, we run cointegrating regressions of the log of travel demand on the log of GDP.

Utilizing annual data from 1990 to 2019, we perform a linear regression of the logarithm of travel demand—measured as vehicle-miles traveled for on-road transportation and revenue passenger- or ton-miles for aviation—against the logarithm of real GDP. Annual U.S. real gross domestic product

12. We used real gross domestic product data (chain-type quantity index, with 2017 as the base year and index = 100), which were downloaded from https://fred.stlouisfed.org/series/A191RA3A086NBEA. Our analysis begins with 2019 data rather than 2022 to avoid the distorting effects of the COVID-19 pandemic.

data are obtained from the Federal Reserve Bank of St. Louis.[13]

$$ln(Travel_Demand) = \alpha + \beta ln(GDP) \tag{B3}$$

We obtain U.S. total vehicle-miles traveled (VMT) data from the Federal Highway Administration (FHWA).[14] The FHWA classifies vehicles into light-duty vehicles (short wheelbase and long wheelbase),[15] single-unit trucks, combination trucks, buses, and motorcycles. In our analysis, we exclude VMT and fuel consumption data for buses and motorcycles. It is important to note that FHWA's categorization differs from the classifications used by the EIA in the (EIA 2025) and by the California Air Resources Board (CARB) in its 2022 Scoping Plan. The EIA and CARB both categorize vehicles as light-duty vehicles (LDV), medium-duty trucks (MDV), and heavy-duty trucks (HDV). Table A5 provides a mapping of FHWA vehicle types to those used by EIA and CARB. There are several discrepancies between the two categorizations for single-unit and combination trucks. We simplified the categorization by assuming that all single-unit trucks are medium-duty trucks and all combination trucks are heavy-duty trucks.

Table A5: Vehicle categorization

FHWA classification		Duty Classification
Truck	LDV-Short wheelbase	Light Duty
	LDV-Long wheelbase	Light Duty
	Single-unit truck	Medium duty
	Combination truck	Heavy duty
Passenger Cars	LDV-Short wheelbase	Light duty
	LDV-Long wheelbase	Light duty

Note: According to the FHWA classification, a single-unit truck is defined as a single-frame truck with either two axles and at least six tires, or a gross vehicle weight rating exceeding 10,000 pounds. In contrast, a combination truck refers to a truck that is coupled with a trailer or semi-trailer.

We obtain monthly revenue passenger miles (RPM) for all U.S. passenger airline carriers from the Bureau of Transportation Statistic's Airlines and Airports data.[16] RPM figures include both domestic and international scheduled flights. International data includes U.S. carrier operations to and from the U.S. and does not include U.S. carriers' foreign point-to-point flights. In theory, we should use all airline carriers with flights departing from U.S., but it is relatively hard to get data on RPM for other countries flight operators. Instead, we analyze the total CO_2 emissions for 2019, aggregated across all aircraft operators on each state pair, as reported in the CORSIA Central Registry by the International Civil Aviation Organization.[17] With a few country-level

13. We use real gross domestic product (chain-type quantity index, Index 2017 = 100), not seasonally adjusted. Data were sourced from https://fred.stlouisfed.org/series/A191RA3A086NBEA. The sample ends at 2019 to exclude the effects of the COVID-19 pandemic.

14. Data available at https://www.bts.gov/content/us-vehicle-miles.

15. Short wheelbase includes passenger cars, light trucks, vans, and sport utility vehicles with a wheelbase less than or equal to 121 inches; long wheelbase refers to those with a wheelbase greater than 121 inches.

16. Data were downloaded from https://www.transtats.bts.gov/Data_Elements.aspx.

17. Data is obtained from https://www.icao.int/CORSIA/CCR.

exceptions, the total CO_2 emissions from U.S. carrier operations to the U.S. closely match those from international carriers departing the U.S. Therefore, we consider the international data to be a suitable proxy for total flight operations—both U.S. and international carriers—departing from the U.S. Monthly revenue ton miles (RTM) for all U.S. cargo airline carriers are obtained from the BTS monthly traffic press releases.[18] The RTM figures reflect only domestic cargo flights, including both scheduled and non-scheduled services. International cargo flights are excluded due to data limitations.

Table A6 presents the results from estimating the regression of travel demand variables on real GDP, as specified in equation B3.

TABLE A6: Estimated travel demand elasticities with respect to real GDP

		Elasticity β	R^2
VMT	LDV	0.49	0.93
	MDV	1.26	0.88
	HDV	0.92	0.93
RPM	Passenger	1.17	0.96
RTM	Cargo-only	2.00	0.36

Notes: The VMT, RPM and ASM rows regress the contemporaneous series on real GDP over the years shown in the text. The RTM row is estimated on domestic air cargo ton-miles for 2001–2019 against real GDP lagged two years; this is the specification used to calibrate the model.

Drawing on the regression results and the uncertainty in average annual GDP growth rates estimated by (Müller and Watson 2016), we project the corresponding vehicle travel demand for 2030, as presented in Table A7.

B.4.1. Fuel economy

We obtain average fuel efficiency values for light-duty and heavy-duty internal combustion engine (ICE) vehicles from the Bureau of Transportation Statistics and and historical fuel economy trends from Table VM-1 of (FHWA 2023).[19] For light-duty ICE vehicles, fuel efficiency is adjusted to account for a 1.24% penetration of battery electric vehicles.[20] Electrification rates for medium- and heavy-duty vehicles remain negligible before 2023, so we assume them to be zero. We project annual improvements in fuel economy of 0.7% for light-duty ICE vehicles and 1% for medium- and heavy-duty vehicles, based on historical trends from 2000 to 2022.[21]

For U.S. passenger and cargo-only airlines, we estimate fuel economy using monthly data on airline fuel consumption and revenue passenger/ton miles.[22] An annual fuel economy improvement

18. Data retrieved from https://www.transtats.bts.gov/traffic/.
19. Data on average miles traveled per gallon of fuel consumed for each vehicle type were downloaded from https://www.fhwa.dot.gov/policyinformation/statistics/2023/vm1.cfm.
20. Data on the electric vehicle share of the total light-duty vehicle fleet are published by the Alternative Fuels Data Center: https://afdc.energy.gov/vehicle-registration.
21. The increase in average fuel economy is calculated from historical data (2000–2022).
22. Airline fuel cost and consumption data are sourced from https://www.transtats.bts.gov/fuel.asp.

TABLE A7: Forecasts of average GDP growth rate and corresponding 2030 travel demand

		AEO 2025	90% coverage	67% coverage
Average GDP growth rates (%)		1.80	(0.3,4.4)	(1.4,3.5)
Vehicle Miles Traveled (billions)	Light-duty	3141	(2898,3600)	(3074,3435)
	Medium-duty	148	(121,211)	(141,187)
	Heavy-duty	214	(184,276)	(205,253)
Revenue Passenger Miles (billions)	Passenger	1365	(1129,1886)	(1298,1688)
Revenue Ton Miles (billions)	Cargo	58.4	(42.2,101.8)	(53.6,84.2)

Notes: Average GDP growth rates are computed as difference in logarithms in percentage points at annual rate, i.e., $100 \times \ln(X_t/X_{t-1})$ where X_t is the real gross domestic product. VMT, RPM and RTM are all expressed in billions. Coverage intervals are obtained by compounding each GDP growth scenario over the eleven-year horizon, $GDP_k = GDP_{2019}(1+g_k)^{11}$, and mapping it through the elasticities in Table A6; means are anchored to the AEO 2025 reference case and are therefore independent of the elasticities.

rate of 1.5% is assumed for the aviation sector.[23]

Table A8 presents the historical (2023) and projected (2030) fuel economy values. Our projections align closely with the fleet averages reported in AEO 2025, which are shown in the table's last column.

TABLE A8: Fuel efficiency projections and robustness check (AEO 2025) by vehicle and fuel type

Vehicle	Fuel	Units	2023	Growth	2030	Check
LDV	Gasoline	mpg gas equiv	22.30	0.7%	23.42	25.91
	Electric	mpg kw equiv	3.60		4.00[24]	
MDV	Diesel	mpg diesel equiv	7.81	1.0%	8.38	9.67
	Gasoline	mpg gas equiv	7.81	1.0%	8.38	8.89
	Electric	mpg kw equiv			1.00[25]	0.73
HDV	Diesel	mpg diesel equiv	6.68	1.0%	7.16	7.03
	Electric	mpg kw equiv	0.42		0.50[26]	0.38
	Hydrogen	mpg kg equiv			9.30[27]	8.69
Jet passenger	Jet fuel	RPM per gallon	69.36	1.5%	76.98	76.95
Jet Cargo-only	Jet fuel	RTM per gallon	7.32	1.5%	8.12	

23. Estimate is taken from the International Council on Clean Transportation: https://theicct.org/aviation-fuel-efficiency-jan22/ and aligns with our calculations from historical data.

24. Average fuel economy for battery electric vehicles is 3.6 mi/kWh in 2019 (see https://afdc.energy.gov/vehicles/electric-emissions-sources). We used an estimate from the ICCT report, shown here: https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

25. We used data from Ford E-transit and REE automotive P7, which are prototype medium electric vans developed by U.S. based companies.

26. We used data from Tesla semi. This is consistent with the demonstration performed by the Port of Los Angeles. https://web.archive.org/web/20090320010557/http://www.portoflosangeles.org/DOC/Electric_Truck_Fact_Sheet.pdf

27. We used an estimate from an ICCT report, shown here: https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/.

TABLE A9: Percentage of vehicles by vehicle and fuel type in California and the rest of U.S.

		Fleet composition	
		California	Rest of U.S.
Light-duty vehicles (LDV)	BEV	18.9%	11.5%
	ICE-Gasoline	81.1%	88.5%
Medium-duty vehicles (MDV)	BEV	8.2%	1.6%
	ICE-Gasoline	41.6%	37.0%
	ICE-Diesel	50.2%	61.5%
Heavy-duty vehicles (HDV)	BEV	4.5%	
	H_2	4.0%	
	ICE-Diesel	91.5%	100.0%

Notes: This table shows the percent of vehicles in California and the rest of the United States by vehicle and fuel type.

B.5. Fuel demand calibration

We estimate the demand for blended fuels in 2030 using projected travel demand for each region and vehicle type (as shown in Table A7 and Table A9), along with fuel efficiency data. We obtain fuel economy estimates for BEV and H_2 vehicles from the literature (Pierce, Jin, and Searle 2022; Slowik et al. 2022) and company websites. We estimate total electricity demand (in kilowatt-hours) and hydrogen demand (in kilograms) for on-road transportation using these fuel economy values as detailed below.

We project fleet composition in California using the 2022 Scoping Plan Scenario published by the California Air Resources Board. For regions outside California, we apply the AEO 2025 projections. Since AEO 2025 projects a mix that includes H_2 and other alternative technologies, we adopt an 11.5% light-duty battery electric vehicle penetration rate for the U.S. in 2030 (Woody, Keoleian, and Vaishnav 2023).[28] The fleet composition by vehicle class and fuel type, including California's higher EV penetration rates relative to the rest of the U.S., is summarized in Table A9.

We assume on-road and aviation travel demand in California is a fixed proportion of total U.S. travel demand, consistent with evidence that biofuel policies do not significantly affect the geographic distribution of travel demand (Bushnell, Peterman, and Wolfram 2008). California accounts for approximately 9.63% of light-duty VMT and 10.79% of medium- and heavy-duty VMT, based on 2023 data from Table PS-1 of Highway Statistics (FHWA 2023). For air travel, California's share is estimated at 17% of total U.S. jet fuel consumed, using 2023 data from Table F2 of the State Energy Data System (EIA 2023).

For vehicle miles traveled by alternative technologies, we assume that light-duty electric vehicles are driven the same distance as comparable ICE vehicles, while electric freight vehicles travel 75% of the miles covered by their medium- and heavy-duty ICE equivalents (Lade 2023). This assumption

28. We use an estimate of 11.5% BEV share of total LDV VMT in 2030 from (Woody, Keoleian, and Vaishnav 2023). For simplicity, we exclude H_2 and other alternative fuel types from our analysis.

exceeds historical trends, where EVs have typically achieved 60%–70% of the annual mileage of ICE vehicles (Zhao et al. 2023; Davis 2019).

By combining the fuel economy values for on-road ICE vehicles, electric vehicles, and hydrogen trucks from Table A8 with the projected travel demand by region and vehicle type (as shown in Tables A7 and A9), we estimate the total requirements for gasoline and ethanol, as well as diesel and its biomass-based substitutes in both California and other regions of the U.S. We also assess the transportation electricity and hydrogen demand specific to California. A summary of these estimates is provided in Table A10. Note that there is no electricity or hydrogen demand for heavy-duty vehicles outside California, as we assume no penetration of these technologies in that region by 2030.

TABLE A10: Projected 2030 Fuel, Transportation Electricity, and Hydrogen Demand (in Billions)

Series	Region	Mean	90% coverage	67% coverage
Gasoline (gallons)	CA	11.15	(10.21,12.96)	(10.89,12.31)
Diesel (gallons)		4.10	(3.48,5.44)	(3.93,4.94)
Jet fuel (gallons)		4.24	(3.37,6.30)	(3.99,5.49)
Electricity_LDV (kWh)		14.30	(13.20,16.40)	(14.00,15.64)
Electricity_MDV (kWh)		1.12	(0.92,1.60)	(1.06,1.42)
Electricity_HDV(kWh)		1.60	(1.37,2.06)	(1.53,1.89)
Hydrogen_HDV (kg)		0.08	(0.06,0.10)	(0.07,0.09)
Gasoline (gallons)	Rest of U.S.	112.09	(102.91,129.82)	(109.57,123.41)
Diesel (gallons)		37.35	(31.64,49.60)	(35.74,44.99)
Jet fuel (gallons)		20.69	(16.48,30.74)	(19.47,26.80)
Electricity_LDV (kWh)		81.60	(75.30,93.54)	(79.88,89.25)
Electricity_MDV(kWh)		1.73	(1.41,2.46)	(1.64,2.18)

Notes: Coverage intervals follow the same construction as in Table A7.

We calibrate the fuel demand curves in equation D30 by using the projected fuel demand values from Table A10 and fuel demand elasticities reported in the literature, as summarized in Table **??**. We treat the world petroleum fuel price as exogenous, and obtain wholesale rack prices for diesel, gasoline, and jet fuel from AEO 2025. Prices reflect those for motor gasoline, jet fuel, and diesel fuel (distillate fuel oil) used in the transportation sector, expressed in nominal 2024 dollars and adjusted for inflation. The estimated parameters $\alpha_D^{\mathcal{F},j}$ for fuel type $\mathcal{F}$ in location j are presented in Table A11.

C. Policy constraints

C.1. RFS constraints

In the current policy scenario, we assume that the percentage standards for biomass-based diesel (BBD) and the total renewable fuel pool in 2030 remain the same as in 2025, with the BBD (D4)

TABLE A11: Estimated fuel demand curve parameters $\alpha_D^{\mathcal{F},j}$ by fuel type and location

Fuel type	Location	AEO 2025	90% coverage	67% coverage
Diesel	CA	4.10	(4.02,4.19)	(4.06,4.15)
	NC	37.35	(36.56,38.12)	(36.97,37.77)
Gasoline	CA	11.15	(11.02,11.27)	(11.09,11.21)
	NC	112.09	(110.87,113.28)	(111.51,112.75)
Jet	CA	4.24	(4.11,4.36)	(4.18,4.30)
	NC	20.69	(20.09,21.28)	(20.40,21.01)

pool set at 3.15% and the renewable fuel (D6) pool at 13.13%.

When a new RIN category, D2, is established for SAF, the percentage standard for the D2 pool is determined in the same manner as for the existing D4 and D6 pools, as outlined in equation C1. Specifically, the percentage standard for the D2 pool is calculated as follows:

$$\phi_{D2} = \frac{1.6 RFV_{D2}}{\text{TotalFF}} \tag{C1}$$

Here, the factor of 1.6 adjusts for the higher energy content of SAF relative to ethanol. We set RFV_{D2} at 3 billion gallons.

In the "nested D2" scenario, we assume that petroleum jet fuel is exempt from any compliance obligations. D2 RINs may be used to meet both the BBD and total renewable fuel mandates. When calculating the percentage standards, TotalFF includes only the projected consumption of petroleum gasoline and diesel. The per-gallon cost of the bundled RINs needed for compliance with petroleum gasoline and diesel requirements is given by:

$$\text{PolicyCost}_{FF}^{RFS} = \phi_{D2} P_{D2} + (\phi_{D4} - \phi_{D2}) P_{D4} + (\phi_{D6} - \phi_{D4}) P_{D6} \tag{C2}$$

Under the "nested D2" scenario, the volumetric requirements for BBD and total renewable fuel are the same as in the current policy scenario, while under the "nested D2 + stricter RFS" scenario, these requirements increase by 3 Bgal.

For the "D2 with aviation obligation" scenario, we assume petroleum jet fuel becomes an obligated fuel. We assume D2 RINs can only be used to satisfy the total renewable fuel mandate (D6) not the biomass-based diesel mandate (D4). When calculating percentage standard, TotalFF includes projected petroleum gasoline, diesel and jet fuel consumption. The per-gallon cost of the bundled RINs required to fulfill compliance for petroleum gasoline, diesel and jet fuel is given by:

$$\text{PolicyCost}^{RFS} FF = \phi_{D2} P_{D2} + \phi_{D4} P_{D4} + (\phi_{D6} - \phi_{D2} - \phi_{D4}) P_{D6} \tag{C3}$$

The volumetric requirement for D6 remains unchanged from the current policy scenario, while the D4 requirement decreases by 3 Bgal since SAF no longer contributes to the D4 pool.

C.2. Tax incentives

As described in Section **??**, the value of the subsidy provided to a fuel under the 45Z depends on the carbon intensity of the fuel relative to a threshold. Notably the carbon intensity values used for 45Z ($CI_{f,s}^{45Z}$) exclude indirect land-use change (see Table **??**). The tax incentive takes the form:

$$TC_{f,s}^{45Z} = \begin{cases} 0 & \text{if } \overline{CI_{f,s}^{45Z}} > 47.39, \\ 1 \times \frac{47.39 - \overline{CI_{f,s}^{45Z}}}{47.39} & \text{if } \overline{CI_{f,s}^{45Z}} \leq 47.39. \end{cases} \tag{C4}$$

The 45Q tax credit is only applicable to SAF with technical pathways using CCS technology. Producers using CCS can claim either 45Q or 45Z but not both. We assume CCS technology captures 30 gCO_2e/MJ per gallon of SAF produced. That is:

$$TC_{SAF,s}^{45Q} = \begin{cases} \frac{85 \times 30 \times \overline{ED_{SAF}}}{10^6} & \text{if ATJ+CCS technology,} \\ 0 & \text{Otherwise .} \end{cases} \tag{C5}$$

State level tax incentives vary by state in terms of the value, eligibility,[29] and recipient, as described in Table **??**. We model the availability of state subsidies as a step function based on the average magnitude of the incentive and potential fuel quantity eligible. Where producers receive the subsidy, this setup assumes that SAF production will first occur in the jurisdiction with the largest available subsidy. Similarly, where consumers are the recipient, we assume SAF is sold into the jurisdiction with the largest available subsidy. The potential quantity of SAF eligible to receive the subsidy at each value step is determined either by (i) volumetric or maximum-expenditure limits specified in the policy, when such limits are present, or (ii) the maximum in-state level of consumption (set at 50% of all jet fuel consumption in year 2030) where recipients are eligible and no spending limit is specified. We allow for the possibility of arbitrage between states to maximize the subsidy received based on eligibility constraints. For example, a producer in Nebraska could receive the $0.78 production subsidy and sell to a consumer in Illinois who receives the $1.50 consumption subsidy, for a cumulative subsidy of $2.28 per gallon.

State tax credit eligibility varies by region; for example, Illinois requires SAF to be consumed within the state, while Nebraska mandates in-state production. These differences create opportunities for cross-state arbitrage—such as SAF produced in Nebraska being shipped to Illinois to benefit from tax credits in both states. Our model incorporates this potential for arbitrage.

For states that restrict tax credits to in-state use, we define the maximum eligible fuel quantity as 50% of the state's total jet fuel consumption. This "blending limit" reflects technical limitations and safety concerns related to SAF blends in commercial aviation. State-level jet fuel consumption is estimated by applying each state's 2023 share of national consumption to the projected 2030

29. Because most states do not provide certified pathways or state-specific GREET models, we rely on the 45ZCF-GREET model to determine eligibility. Most states require at least a 50% reduction in total greenhouse gas emissions and disqualify ATJ pathways without CCS from receiving tax credits.

total shown in Table A10.

For states that set an annual cap on total tax credits, we apply this limit directly and calculate eligible fuel accordingly.

In states that require in-state production for tax eligibility, we do not place constraints on the total quantity of eligible fuel, as production facilities are expected to maximize use of available tax credits. Moreover, currently announced SAF capacity in these states is nearly sufficient to meet the maximum eligible fuel volume.

TABLE A12: Announced SAF production capacity and maximum eligible fuel quantity by payout limit and consumption limit (in billions of gallons)

State	Announced SAF capacity	Maximum payout volume	Maximum consumption volume
Illinois	0.27		0.58
Minnesota	0.19	0.0049	0.17
Washington	0.30		0.40
Nebraska	0.27	0.0006	0.02
Hawaii	0.06	0.0563	0.35
Iowa	0.04	0.0400	0.02

Based on maximum eligible fuel quantity shown in Table A12, we get the step-wise state tax credit structure shown in Table A13. The table outlines the constraints that become active at each step, the maximum SAF volume that can benefit from the tax credit at that step, and the regions eligible for production and consumption of SAF to qualify for the credit. This step-wise structure is incorporated into our model as a step function, as described in equation **??**.

TABLE A13: State tax credit step analysis

Step #	State tax Credit	Constraint	Max SAF Volume	Production	Consumption
1	2.28	NE cap on subsidy provided	0.0006	NE	IL
2	1.75	NE and IA cap on subsidy	0.0406	NE or IA	IL
3	1.50	IL consumption + MN cap on subsidy	0.5898	NE or IA or IL or MN	IL or MN
4	1.38	IL consumption + WA consumption + MN cap on subsidy	0.9988	NE or IA or IL or MN or WA	IL or MN or WA
5	0.36	IL + WA consumption + MN and HI caps on subsidy	1.0551	Anywhere	IL or MN or WA or HI

C.3. Interactions between LCFS and state-level tax incentives

When California LCFS credits are more valuable than state-level tax incentives elsewhere, SAF producers may exploit this by producing fuel outside California and selling it in the California market. This form of arbitrage creates two additional possibilities for SAF to benefit from tax

credits, shown in Table A14. The first case assumes that the California LCFS market can absorb all SAF produced in Iowa and Nebraska (0.0406 billion gallons), while the second case assumes it cannot. Each case outlines the constraints that become active at each step, the maximum SAF volume that can benefit from both LCFS and state tax credits at that step, and the regions eligible for the production and consumption of SAF qualifying for these incentives.

TABLE A14: Step-wise state-level tax function if LCFS and state tax credit interacts

(a) Case 1: LCFS credit for SAF exceeds $1.5/gal and CA LCFS can take in full IA/NE volume (0.0406 Bgal)

Step #	State tax Credit + LCFS	Constraint	Max SAF Volume	Production	Consumption
1	0.78+LCFS	NE cap on subsidy provided.	0.0006	NE	CA
2	0.25+LCFS	NE and IA cap on subsidy	0.0406	NE or IA	CA
3	1.50	IL consumption + MN cap on subsidy	0.5898	NE or IA or IL or MN	IL or MN
4	1.38	IL consumption + WA consumption + MN cap on subsidy	0.9988	NE or IA or IL or MN or WA	IL or MN or WA
5	0.36	IL + WA consumption + MN and HI caps on subsidy	1.0551	Anywhere	IL or WA or MN or HI

(b) Case 2: LCFS credit for SAF exceeds $1.5/gal and CA LCFS cannot take in full IA/NE 0.0406 volume (0.0406 Bgal)

Step #	State tax Credit	Constraint	Max SAF Volume	Production	Consumption
1	0.78+LCFS	NE cap on subsidy provided.	0.0006	NE	CA
2	0.25+LCFS	LCFS CA max capacity	max CA LCFS can take in	NE or IA	CA
3	1.75	NE and IA cap on subsidy	0.0406	NE or IA	IL
4	1.50	IL consumption + MN cap on subsidy	0.5898	NE or IA or IL or MN	IL or MN
5	1.38	IL consumption + WA consumption + MN cap on subsidy	0.9988	NE or IA or IL or MN or WA	IL or MN or WA
6	0.36	IL + WA consumption + MN and HI caps on subsidy	1.0551	Anywhere	IL or WA or MN or HI

D. Model

This section presents the complete set of model equations and inequalities summarized in Section II.F of the main text. The current policy model has 108 exogenous prices or parameters (e.g., global fossil fuel prices, LCFS intensity standard), 40 endogenous quantities (including biofuel, fossil fuel, and blended fuel quantities, as well as feedstock quantities), 27 endogenous prices (including RIN and LCFS prices, biofuel, fossil fuel, and blended fuel prices, as well as feedstock prices), and 34 Lagrangian multipliers for the constrained profit maximization problem. The inequalities include non-negativity constraints on pathway quantities, nesting constraints on RIN prices, technical blending constraints, HEFA pathway production blending limits, and dual feasibility conditions for the Lagrangian multipliers.

D.1. Fuel supply

Representative biofuel producers for each pathway seek to maximize profits, subject to non-negativity constraints, technical blending limits, and production capacity restrictions. This optimization problem can be formulated as follows:

$$\begin{aligned}
\max_{Q^j_{f,s}} \text{Profit}(Q) = &\max_{Q^j_{f,s}} \sum_j \sum_{f,s} [P^j_f Q^j_{f,s} - C^j_{f,s} Q^j_{f,s} - \text{PolicyCost}^j_{f,s} \cdot Q^j_{f,s}], \\
&s.t. \quad Q^j_{f,s} \geq 0, \quad \forall \{f,s,j\} \\
&\sum_s Q^j_{f,s} \leq \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j}, \quad \forall \{f,j\} \\
&\sum_j Q^j_{SAF,s} \leq \frac{0.55}{0.25} \sum_j Q^j_{RD,s} \quad \text{for all } s \in \{vegoil, fatsgreases\}.
\end{aligned}$$

Here, P^j_f is the price of biofuel f (such as biodiesel, renewable diesel, sustainable aviation fuel, or ethanol) in region j; Q is the quantity produced using feedstock s; C represents the marginal production cost; and $\text{PolicyCost}^j_{f,s}$ denotes the negative of the per-unit subsidy stack available to producers. The technical blending constraint, $\overline{BL_{f,j}}$, depends on the biofuel type and policy or engine limits: it is 20% for biodiesel in the rest of the U.S., 7.5% for biodiesel in California, 1 for renewable diesel, 50% for SAF, and 15% for ethanol.

HEFA processing primarily yields renewable diesel, with SAF typically representing only about 15% of the total liquid output. With plant modifications, SAF production can increase to up to 55% of the liquid yield, with renewable diesel accounting for 25%. The remainder consists of "light ends" with lower economic value. To reflect this technical limit, the model ensures that total SAF output does not exceed 2.2 times the renewable diesel output when using HEFA pathways (i.e., vegetable oil, animal fats, or yellow greases as feedstocks).

We translate the above optimization problem into its Karush-Kuhn-Tucker (KKT) conditions, which include the first-order conditions, complementary slackness conditions, and primal feasibility conditions. These KKT conditions are then integrated into the overall market equilibrium model. The Karush-Kuhn-Tucker conditions associated with the optimization problem are:
Stationarity conditions (totaling 24 equations):

$$\forall \{f,s,j\} : P^j_f = \text{PolicyCost}^j_{f,s} + C^j_{f,s} - \mu^j_{f,s} + \nu^j_f + \text{HEFA}_{s \in \{vegoil, fatsgreases\}} \tag{D1}$$

where $\mu^j_{f,s}$, ν^j_f, and HEFA_s are the dual variables associated with the non-negativity, blending limit, and HEFA technical constraints, respectively.

Complementary slackness conditions (totaling 24 + 8 + 2 equations):

$$\forall\{f,s,j\} : \mu^j_{f,s} Q^j_{f,s} = 0 \tag{D2}$$

$$\forall\{f,j\} : \nu^j_f \Big(\sum_s Q^j_{f,s} - \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j} \Big) = 0 \tag{D3}$$

$$\text{for all } s \in \{vegoil, fatsgreases\} : \text{HEFA}_s \Big(\sum_j Q^j_{SAF,s} - \frac{0.55}{0.25} \sum_j Q^j_{RD,s} \Big) = 0 \tag{D4}$$

Primal feasibility conditions (totaling 24 + 8 + 2 inequalities):

$$\forall\{f,s,j\} : Q^j_{f,s} \geq 0 \tag{D5}$$

$$\forall\{f,j\} : \sum_s Q^j_{f,s} \leq \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j} \tag{D6}$$

$$\text{for all } s \in \{vegoil, fatsgreases\} : \sum_j Q^j_{SAF,s} \leq \frac{0.55}{0.25} \sum_j Q^j_{RD,s} \tag{D7}$$

Dual feasibility (totaling 24 + 8 + 2 inequalities):

$$\forall\{f,s,j\} : \mu^j_{f,s} \geq 0 \tag{D8}$$

$$\forall\{f,s,j\} : \nu^j_f \geq 0 \tag{D9}$$

$$\text{for all } s \in \{vegoil, fatsgreases\} : \text{HEFA}_s \geq 0 \tag{D10}$$

Fossil fuel supply is assumed to be perfectly elastic at the wholesale rack price $P^j_{\mathcal{F}0}$, which equals the world petroleum fuel price $\overline{PC_{\mathcal{F}0}}$ plus any applicable policy costs. The relevant equations, totaling 6, are provided below:

$$\forall \mathcal{F} : \quad P^j_{\mathcal{F}0} = \overline{PC_{\mathcal{F}0}} + \text{PolicyCost}^j_{\mathcal{F}0}. \tag{D11}$$

Feedstock supply is modeled using a constant elasticity supply function. Residual supply elasticities specific to biofuel production are calculated as described in Section B.3. The relevant equations, totaling 4, are provided below:

$$\forall s : \quad Q^{Biofuel}_s = \alpha_s P_s^{\beta_s^{Biofuel}} \tag{D12}$$

D.2. Fuel demand

Demand for transportation fuel is responsive to price based on a constant elasticity of demand function (totaling 6 equations):

$$\forall\{\mathcal{F},j\} : \quad Q_{\mathcal{F},j} = \alpha^D_{\mathcal{F},j} P^{\beta^D_{\mathcal{F}}}_{\mathcal{F},j} \tag{D13}$$

where $Q_{\mathcal{F},j}$ is the quantity demanded for fuel type $\mathcal{F}$ (e.g., diesel and substitutes, gasoline and substitutes, or jet fuel and substitutes) in region j (e.g., California or ROUS) as a function of the blended fuel price ($P_{\mathcal{F},j}$).

Blended fuel prices are calculated as the weighted average of the prices of fossil and biofuels, based on their respective market shares (totaling 6 equations).

$$\forall\{\mathcal{F},j\}: \quad P_{\mathcal{F},j} = \frac{Q^j_{\mathcal{F}0}\cdot P^j_{\mathcal{F}0} + \sum_{f\in\mathcal{F}} Q^j_{f,s}\cdot P^j_f}{Q^j_{\mathcal{F}0} + \sum_{f\in\mathcal{F}} Q^j_{f,s}} \tag{D14}$$

Demand for biodiesel, renewable diesel, and sustainable aviation fuel is perfectly elastic at the price equal to that of their petroleum alternatives after adjusting for the energy content difference (totaling 6 equations):

$$\forall f \in \{B100, RD, SAF\}: P^j_f = \phi_f P^j_{\mathcal{F}0} \tag{D15}$$

where ϕ_f is the energy content adjustment factor for biofuel f relative to its petroleum counterpart $\mathcal{F}0$. The values of ϕ_f are 0.93 for biodiesel, 0.96 for renewable diesel, and 1 for SAF.

Demand for ethanol is modeled using an inverse demand curve to account for blending ratio of approximately 10% in traditional combustion engines (totaling 2 equations):

$$\forall j, \quad P^j_{E100} = \theta P^j_{\mathcal{G}0}\left[1 - \mathbb{1}\Big(\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s} + Q^j_{\mathcal{G}0}} \geq 0.1\Big)\Big(e^{\left(\frac{\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s}+Q^j_{\mathcal{G}0}} - 0.1}{0.02}\ln 2\right)} - 1\Big)\right] \tag{D16}$$

where P^j_{E100} is the price of ethanol in region j and $Q^j_{E100,s}$ is the amount of ethanol consumed in region j using feedstock s (e.g., corn or sugarcane). The 0.01 term is included to prevent discontinuities in the inverse demand curve.

D.3. Policy constraints:

The model incorporates various policy constraints, including those related to the Renewable Fuel Standard (RFS) and the Low Carbon Fuel Standard (LCFS). These constraints are represented through a combination of inequality and equality equations.

The RFS constraints are represented by the following set of inequalities:

$$\sum_{f\in(B100,RD,SAF),s} Q^j_{f,s} \geq RFV_{D4} \tag{D17}$$

$$\sum_{f,s} \kappa_f Q^j_{f,s} \geq RFV_{D6} \tag{D18}$$

$$P_{D4} \geq P_{D6} \tag{D19}$$

$$P_{D6} \geq 0 \tag{D20}$$

where κ_f represents the energy densities of each biofuel type relative to ethanol, with values of 1.5 for biodiesel, 1.7 for renewable diesel, and 1.6 for SAF. Due to the nested structure of the RFS mandates, the price of D4 RINs (P_{D4}) must always be greater than or equal to the price of D6 RINs (P_{D6}).

When the total renewable fuel mandate (D6) is non-binding, the price of D6 RINs is zero. If the biomass-based diesel mandate (D4) is non-binding while D6 is binding, the prices of D4 and D6 RINs are equal. When both D4 and D6 mandates are binding, the price of D6 RINs is less than that of D4 RINs. These three cases are represented by the following set of equations (totaling two equations):

$$P_{D6}(\sum_{f,s} \kappa_f Q^j_{f,s} - RFV_{D6}) = 0 \tag{D21}$$

$$(P_{D4} - P_{D6})(\sum_{f \in (B100,RD,SAF),s} Q^j_{f,s} - RFV_{D4}) = 0 \tag{D22}$$

The LCFS constraint is formulated as the following inequality:

$$\sum CI_{deficits} \leq \sum CI_{credits} \tag{D23}$$

$$P_{LCFS} \leq \overline{P_{Cap}} \tag{D24}$$

$$P_{LCFS} \geq 0 \tag{D25}$$

Here, $\sum CI_{deficits}$ denotes the total carbon intensity deficits from petroleum diesel consumption, while $\sum CI_{credits}$ represents the total carbon intensity credits generated from biofuel consumption and other credit-generating activities. Details on the calculation of LCFS credits and deficits are provided in Section **??** The LCFS price (P_{LCFS}) is subject to a regulatory cap, denoted by the maximum value $\overline{P_{Cap}}$.

If credits exceed deficits, the LCFS price (P_{LCFS}) is set to zero. If deficits exceed credits, the LCFS price is capped at $\overline{P_{Cap}}$. These two scenarios are captured by the following set of equations (comprising one equation and two inequalities):

$$P_{LCFS} \cdot (P_{LCFS} - \overline{P_{Cap}}) \cdot (\sum CI_{deficits} - \sum CI_{credits}) = 0 \tag{D26}$$

$$P_{LCFS} \cdot (\sum CI_{deficits} - \sum CI_{credits}) \geq 0 \tag{D27}$$

$$(P_{LCFS} - \overline{P_{Cap}}) \cdot (\sum CI_{deficits} - \sum CI_{credits}) \geq 0 \tag{D28}$$

D.4. Market clearing conditions:

Feedstock demand is set equal to the quantities of biofuels produced from each respective feedstock (totaling 4 equations):

$$\forall s: \quad Q_s = \sum_j \sum_{f \in \{f:\ f\text{-}s \text{ is feasible}\}} \theta_{f,s} Q^j_{f,s} \tag{D29}$$

Total fuel demand is defined as the sum of fossil fuel consumption and its biomass-based substitutes (totaling 6 equations):

$$\forall \{\mathcal{F}, j\}: \sum_{f \in \mathcal{F}, s} Q^j_{f,s} + Q^j_{\mathcal{F}0} = \overline{Q^j_{\mathcal{F}}} \tag{D30}$$

D.5. Model summary

We substitute PolicyCost and the marginal production cost $C^j_{f,s}$ with a combination of exogenous inputs and variables to be determined—details of which are provided in Section **??**. These terms are therefore not included as unknowns or equations. In total, the model includes 101 unknowns. These consist of 40 quantity variables (6 fossil fuels $Q^j_{\mathcal{F}0}$, 4 feedstocks Q_s, 6 blended fuels $Q^j_{\mathcal{F}}$, and 24 biofuel quantities $Q^j_{f,s}$), 27 price variables (6 fossil fuel prices $P^j_{\mathcal{F}0}$, 4 feedstock prices P_s, 6 blended fuel prices $P^j_{\mathcal{F}}$, 8 biofuel prices P^j_f, 2 RIN prices P_{D4} and P_{D6}, and the LCFS price P_{LCFS}), and 34 dual variables associated with the KKT conditions (24 non-negativity multipliers $\mu^j_{f,s}$, 8 blending limit multipliers ν^j_f, and 2 HEFA technical constraints HEFA_s). Accordingly, the model consists of 101 equations and 77 inequalities.

E. Numerical solver

E.1. Mixed integer programming

Our set of equations includes linear, log-linear, and more complex nonlinear forms. In particular, many are derived from the complementarity constraints of the KKT conditions, taking the form $a \cdot b = 0$ where both a and b are non-negative variables to be determined. Such nonlinear complementarity constraints pose significant challenges for numerical solvers, as they introduce non-convex feasible regions and can lead to multiple local optima.

To address these nonlinear complementarity constraints, we use a mixed-integer programming (MIP) approach. This method incorporates binary variables that indicate whether each variable in the product is zero or positive, enabling linearization of the complementarity conditions. Below, we present a simple example to illustrate this process. Let $y \in \{0, 1\}$ be a binary variable, and let M_a and M_b be sufficiently large upper bounds on a and b, respectively. To represent the constraint

$a \cdot b = 0$ with $a \geq 0$ and $b \geq 0$, we can reformulate it as follows:

$$
\begin{aligned}
& a \leq M_a y \\
& b \leq M_b (1 - y) \\
& a \geq 0 \\
& b \geq 0
\end{aligned}
$$

Similarly, for stepwise functions, binary variables can be employed to indicate the specific interval or step in which the solution resides. For example, consider a stepwise function $f(x)$ defined as follows:

$$
f(x) = \begin{cases} c_1 & \text{if } x \in [a_0, a_1) \\ c_2 & \text{if } x \in [a_1, a_2) \\ \vdots & \\ c_N & \text{if } x \in [a_{N-1}, a_N] \end{cases}
$$

Define binary variables $y_i \in \{0, 1\}$ for $i = 1, \ldots, N$, ensuring that exactly one y_i is equal to 1:

$$
\sum_{i=1}^{N} y_i = 1
$$

For each i, impose the following constraints with a sufficiently large M:

$$
\begin{aligned}
& x \geq a_{i-1} y_i \\
& x \leq a_i y_i + M(1 - y_i)
\end{aligned}
$$

With this formulation, the stepwise function can be modeled as:

$$
f(x) = \sum_{i=1}^{N} c_i y_i
$$

E.2. Numerical solver

Given that our model contains both mixed-integer and nonlinear components, we use the *Gurobi* Optimizer (version 12.0.0) to solve it. *Gurobi* is highly efficient for MIP problems. The model is implemented in *Python* (version 3.12.7) using the *Gurobi Python* API, which offers a flexible and robust framework for formulating and solving optimization problems. The complete replication code is available here.

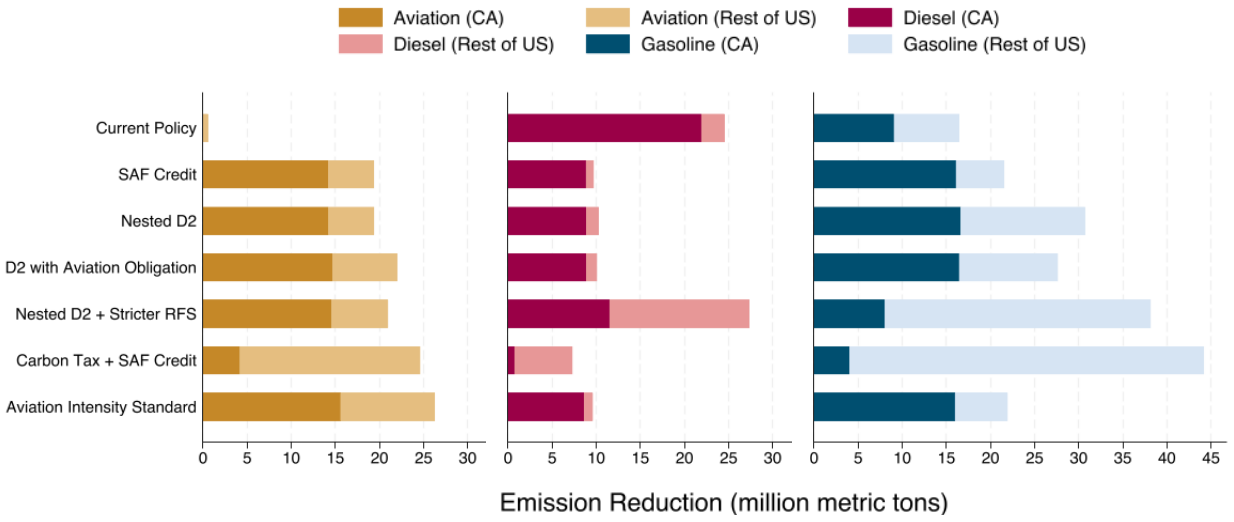


FIGURE A2: Emission Reduction relative to no policy

Notes: This figure shows the total emissions reduction, in billion metric tons, achieved under each policy scenario, relative to the no-policy scenario and disaggregated by fuel type and region.

F. Additional results

F.1. Emission reduction

Figure A2 summarizes how emission reductions are distributed across sectors under each policy scenario. Emission reductions arise from two main channels: (i) increased use of biofuels driven by policy incentives, and (ii) reduced petroleum fuel consumption induced by the implicit carbon tax.

On-road light-duty transportation contributes 38%–58% of total abatement, with the upper end occurring under the "carbon tax + SAF credit" scenario, where a carbon charge on petroleum gasoline in the rest of the United States plays a key role. There is substitution between on-road heavy-duty and aviation fuels as these sectors compete for the same feedstocks. Under current policy, most emission reductions come from the diesel sector, which accounts for roughly 59% of total abatement, reflecting the substitution of renewable diesel for petroleum diesel in California. When a 3 Bgal SAF target is imposed, the aviation sector provides around 30% of total emission reductions, except under the "Nested D2 + Stricter RFS" scenario, where higher RFS volumes require additional biodiesel consumption in the rest of the United States.

Although California represents only about 10% of total heavy-duty fuel demand, it accounts for roughly 90% of total emission reductions in the diesel sector, except under the "Nested D2 + Stricter RFS" scenario. This reflects the role of the LCFS, which penalizes petroleum diesel and encourages the adoption of renewable diesel. Because ethanol blending is limited by the inverse demand curve[30], California contributes only about 55%–75% of total emission reductions in the gasoline sector, primarily through reduced demand for petroleum gasoline subject to LCFS obligations. California accounts for around 17% of total aviation travel demand but delivers 60%–

30. Our inverse demand curve assumes the ethanol price falls to zero once the blend share reaches 12%.

73% of total emission reductions in aviation, driven by LCFS credits available to SAF producers selling into the California market.

F.2. Cap-and-trade Interaction

As discussed in Section **??**, it is possible that interactions between a national SAF policy and California's LCFS and cap-and-trade (CAT) programs may result in a decrease in emissions in non-transportation sectors in California.

Specifically, an increase in SAF consumption in California induced by a national-level policy would be used to meet compliance with the state's LCFS, displacing other biofuels (particularly renewable diesel) that would otherwise be used to comply with the LCFS. To meet transportation demand, more fossil fuel (e.g., diesel) would therefore be consumed in California to replace the displaced biofuel. CAT allowance demand would then increase to cover these additional emissions (note also that most lifecycle emissions from displaced biofuels are also not covered under CAT). By increasing demand for CAT allowances, additional SAF consumption in California could therefore cause a reduction in emissions in other capped sectors. Here we present a simplified calculation to explore the potential magnitude of this effect.

Table A15 presents the change in California road transportation fuel consumption relative to Current Policy (in billion gallons) across alternative policy scenarios that achieve the national SAF target.

TABLE A15: Change in California fuel consumption relative to current policy (billion gallons)

Fuel	SAF Credit	Nested D2	D2 w/ Av. Ob.	Nested D2 + Stricter RFS	Carbon tax + SAF credit	Av. Intensity Standard
Biodiesel	-0.01	-0.01	-0.01	0.00	–	-0.01
Renewable Diesel	-1.91	-1.91	-1.91	-1.63	–	-1.94
Diesel	1.81	1.81	1.81	1.57	–	1.84
Ethanol	-0.13	-0.13	-0.13	0.03	–	-0.12
Gasoline	-0.52	-0.56	-0.54	0.07	–	-0.52
SAF	2.02	2.02	2.02	2.02	–	2.02
Jet fuel	-2.02	-2.02	-2.06	-2.02	–	-2.12

Notes: Under the carbon tax scenario, neither the LCFS nor the RFS is in place, so California is not modeled as a separate fuel market and the change in California consumption is not reported.

While the LCFS accounts for the lifecycle emissions of fuels, the CAT only requires compliance obligations from a limited scope of emissions from biofuels, specifically non-CO_2 end-use combustion emissions and non-biogenic production emissions from covered facilities emitting more than 25,000 metric tons annually within California. Table A16 presents the lifecycle carbon intensity of transportation fuels based on CA-GREET as well as their approximate emissions allowance obligation under the CAT program (Scott 2024). Note that fossil jet is not an obligated fuel under LCFS or CAT.

To calculate the change in allowance demand under California's CAT program, we multiply the change in fuel volumes in Table A15 by the energy density of the fuels and the CAT allowance

TABLE A16: Emissions coverage under CAT

	Lifecycle Emissions	CAT Allowance Requirement
	(g CO_2e per MJ)	
Biodiesel	47.53	7
Renewable Diesel	49.97	7
Diesel	100.45	100.45
Ethanol	69.40	9.32
Gasoline	99.44	99.44
SAF	47.37	0
Fossil Jet	89.00	0

Notes: While the lifecycle emissions of fossil jet are shown in this table, fossil jet is not an obligated fuel under CA LCFS or CAT. The lifecycle carbon intensity of gasoline (99.44) and the CAT allowance requirement for ethanol (9.32) are taken directly from Scott (2024); all other lifecycle values are the CA-GREET column of Table **??**.

requirement in A16. To illustrate the potential cost implications of this displacement effect, we define abatement in other sectors to have an average cost of $30 per ton. Table A17 shows estimates of the emissions and cost effects assuming all additional demand for CAT allowances from transportation results in an equivalent decrease in emissions from other sectors.

TABLE A17: Effect of LCFS CAT interactions on emissions and abatement costs

Fuel	**SAF Credit**	**Nested D2**	**D2 w/ Av. Ob.**	**Nested D2 + Stricter RFS**	**Carbon tax + SAF credit**	**Av. Intensity Standard**
Change in total emissions (MMT)	-16.4	-15.9	-16.1	-20.9	-	-16.7
Change in avg. abatement cost ($ per ton)	-$132.60	-$93.63	-$96.47	-$78.96	-	-$105.95

These estimates depend importantly on two simplifying assumptions. First, we assume that the emissions cap represents a binding constraint on emissions. The displacement of emissions from other sectors due to increased fossil fuel consumption would only occur if total emissions are constrained to force reductions elsewhere. In practice, additional policies and technology development will determine whether future cap levels are binding and the existing large bank of allowance credits in the program could dampen this displacement effect.

Second, this calculation does not account for any potential demand response in transportation if CAT allowance prices increase. If the emission cap is binding, higher demand for CAT allowances from transportation would increase the allowance price and correspondingly increase the price of fossil transport fuels, eliciting some reduction in consumption. For simplicity, we assume that supply of allowances is relatively elastic and any price transmission response would be negligible.

The impact on our results is presented in Figure A3. The overall effect is to increase emissions reductions and lower abatement costs in scenarios that reach the SAF target with both the LCFS and CAT in place in California. Across scenarios, this could result in an additional emissions reduction of 15-21 million metric tons (representing 19%-24% larger reductions) with average

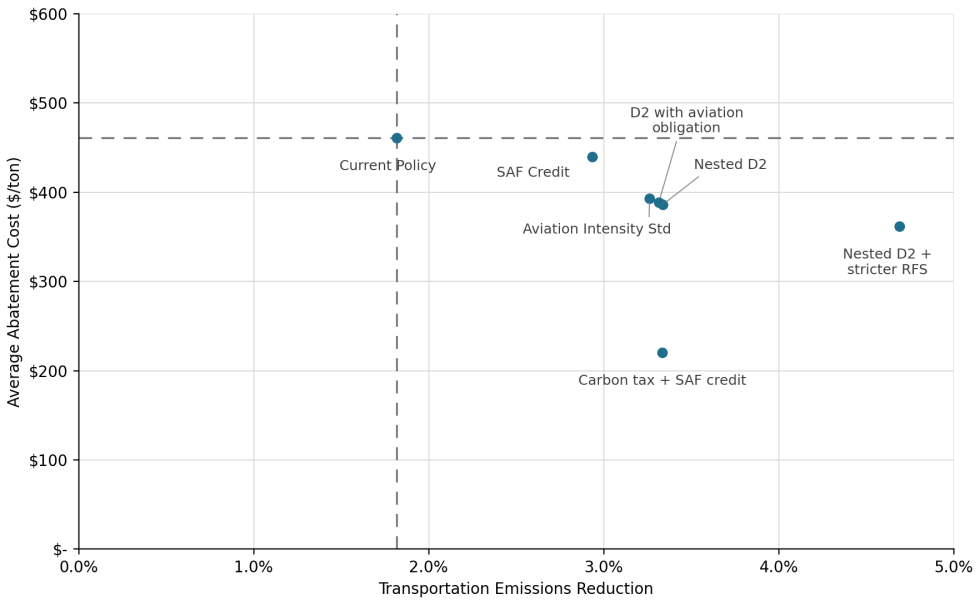


FIGURE A3: Modified results with CAT displacement effect

abatement costs 18%-23% lower. The most notable difference is that achieving the SAF target has lower average abatement costs across scenarios than the current policy scenario.

G. Sensitivity analysis

G.1. Role of CCS

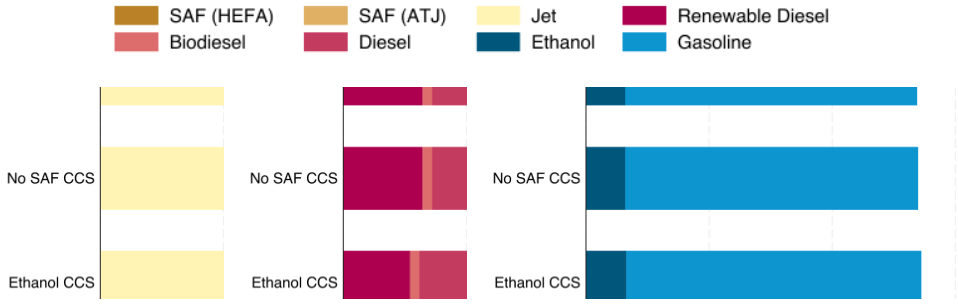
When CCS technology is not available for ATJ-SAF, no ATJ-SAF is produced under the current policy scenario, and approximately 76.7 million gallons of HEFA-SAF are produced (Figure A4).[31] In this case, the D4 RIN price rises as demand for vegetable oils and animal fats and greases increases, while the D6 RIN price and the LCFS credit price decline. This pattern is also reflected in Figure A5, where the policy cost shares borne by diesel and gasoline consumers in the rest of the United States increase when CCS technology is unavailable.

When CCS is also available for ethanol in surface transportation, the ethanol blending share rises.[32] Because CCS ethanol is eligible for the Clean Fuel Production Credit, the share of policy costs borne by taxpayers increases to about 46%, compared with only about 9% in the baseline scenario (Figure A5).

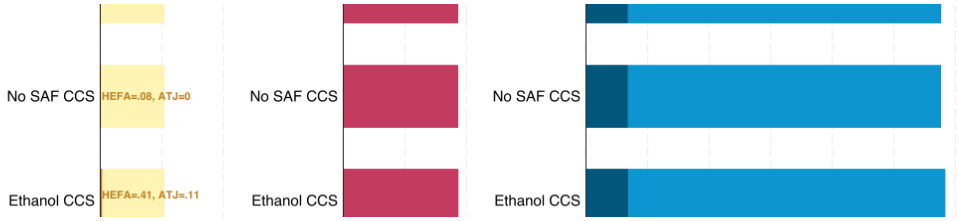
G.2. Role of state-level SAF tax subsidy

When the state-level SAF tax is removed, no SAF is produced under any technical pathway in the current policy scenarios (Figure A6). Relative to the baseline, renewable diesel production rises by

31. No ATJ-SAF is produced under the other policy scenarios that mandate 3 Bgal of SAF.
32. The ethanol blend increases by about 0.3 percentage points from the 10.8% baseline ratio.



(a) California Volume (billion gallons)



(b) Rest of U.S. Volume (billion gallons)

FIGURE A4: Fuel volumes across CCS technology options under current policy

Notes: These figures show the volumes of petroleum fuels and biofuels, by type, produced under different CCS technology options under current policy. We examine three CCS configurations: "Baseline," which reflects our main results and assumes CCS is available only for the SAF ETJ pathway; "No SAF CCS," where CCS is unavailable for SAF ETJ; and "Ethanol CCS," where CCS is also available for surface transportation. Pipeline constraints are excluded in all scenarios.

approximately 2.9% because more feedstock becomes available. SAF incentive prices (including the federal tax credit, D2 RIN, and the aviation intensity standard) increase by at least 30% (Table A18).

TABLE A18: Policy incentive values across policy scenarios in the absence of state-level SAF tax

Scenario	**State Credit** ($/gal)	**SAF Tax Credit** ($/gal)	**D2 RIN** ($/RIN)	**D4 RIN** ($/RIN)	**D6 RIN** ($/RIN)	**LCFS Credit** ($/ton)	**Av. Std. Credit** ($/ton)	**Carbon Tax** ($/ton)
Current Policy	-	-	-	1.84	1.31	91.65	-	
SAF Credit	-	2.96	-	0.47	0.47	250	-	
Nested D2	-	-	2.31	0.41	0.41	250	-	
D2 with aviation obligation	-	-	2.25	0.43	0.43	250	-	
Nested D2 + stricter RFS	-	-	2.90	1.95	1.95	68.63	-	
Carbon Tax + SAF credit	-	4.40	-	-	-	-	-	15.00
Aviation Intensity Std	-	-	-	0.52	0.52	250	437.37	

G.3. Alternative technical conversion factors for biofuel pathways

There is continued debate over the appropriate feedstock-to-fuel conversion rates for biofuels produced through HEFA and ATJ pathways. To assess how these assumptions influence fuel output, we conduct sensitivity analyses in which we vary these conversion factors.

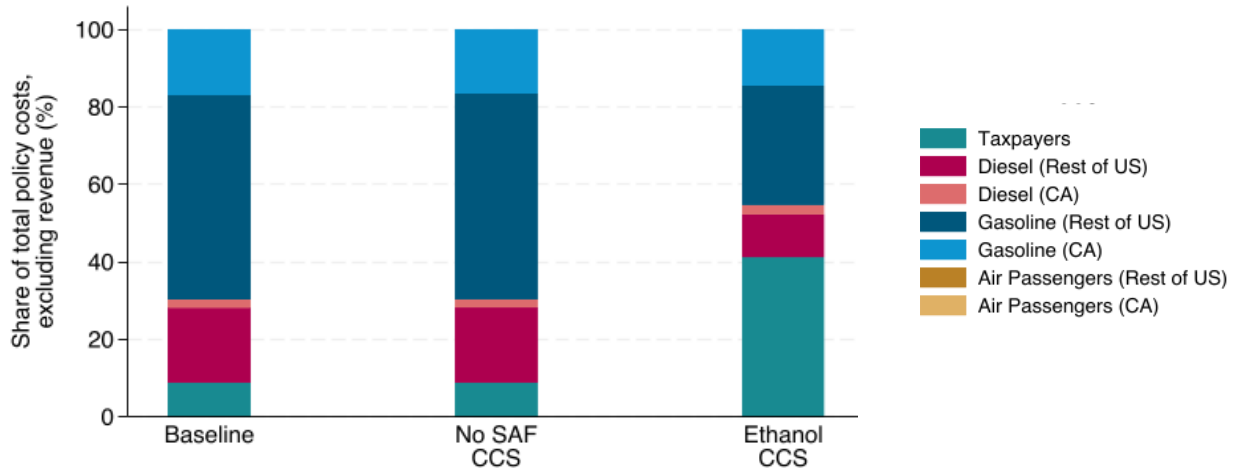


FIGURE A5: Policy cost distribution shares across CCS technology options under current policy

Notes: This figure shows the distribution of policy cost under different CCS technology options. The cost is distributed between taxpayers (who fund tax credits), and consumers of diesel, gasoline, and air travel (who experience price changes).

G.3.1. Reducing feedstock conversion factors needed for HEFA pathways

In one scenario, we assume that producing 1 gallon of renewable diesel requires 8 lbs of vegetable oil and animal fat/tallow instead of 8.5 lbs, and that producing 1 gallon of SAF requires 8.5 lbs of vegetable oil and animal fat instead of 9 lbs. With these more favorable conversion efficiencies, HEFA SAF becomes less costly and its production increases in all scenarios. Under the current policy scenario, approximately 87.8 million gallons of HEFA SAF are produced, while ATJ SAF production remains zero (Figure A7).

G.3.2. Increasing feedstock needed for all SAF pathways

In an alternative scenario, we increase the conversion factors for all SAF pathways. For HEFA-SAF, instead of assuming 9 lbs, we assume that 9.5 lbs of vegetable oils and animal fats are required to produce 1 gallon of SAF. Biofuel production volumes under each policy scenario are shown in Figure A8. For ATJ-SAF, we assume a 25% higher conversion rate. With these higher technical conversion factors, under the current policy scenario only 40.6 million gallons of SAF are produced, which is 46% lower than in the baseline scenario. The share of HEFA-SAF also declines: under the current policy scenario, approximately 34.1 million gallons of SAF (84% of total SAF) are produced via HEFA-SAF. Given the high degree of uncertainty surrounding ATJ-SAF conversion rates, the share of SAF supplied through ATJ pathways remains uncertain.

G.4. Alternative co-production limits

According to an industry report, the maximum SAF yield can reach approximately 75–80%, compared with the 55% threshold assumed in the baseline. To evaluate this alternative co-production

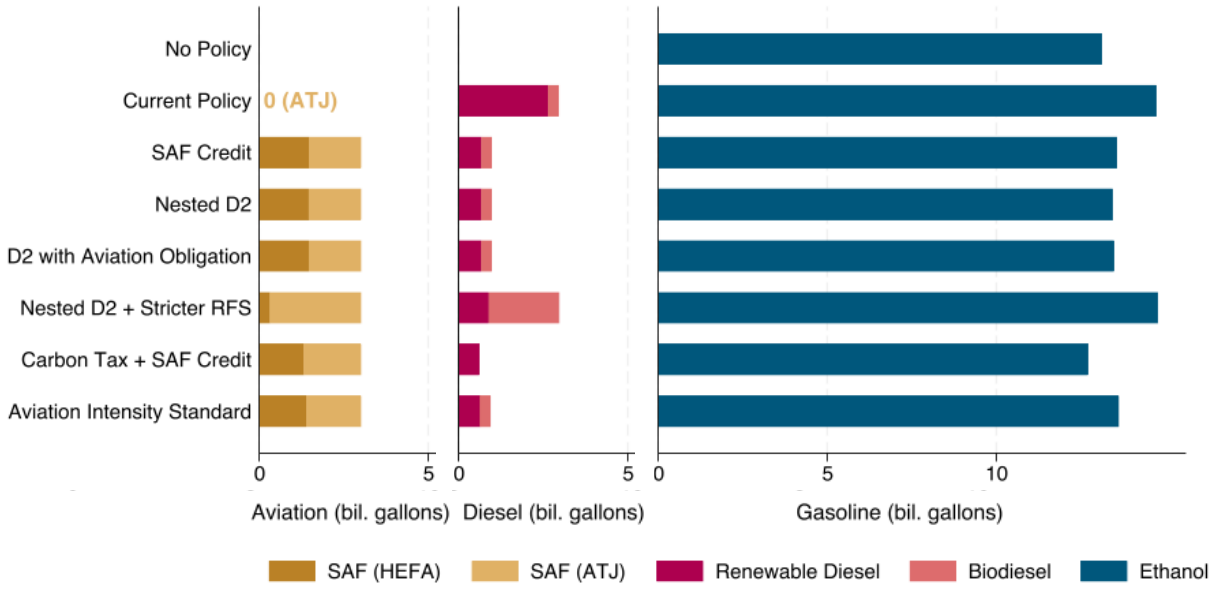


FIGURE A6: Biofuel quantity by policy scenario when state-level SAF tax no longer exists

Notes: This figure shows the volumes of biofuels, by type, produced under each policy scenario. We assume state-level SAF tax no longer exists.

limit, we assume that when plant configurations are optimized to maximize SAF output, they can achieve an 80% SAF yield and 10% RD, with the remainder going to fuel gas, renewable LPG, and renewable naphtha. Under these revised liquid-on-liquid yields, the share of HEFA-SAF increases to about 54–63% at a 3-billion-gallon mandate, compared to only about 40–50% in the baseline. This increase is driven by the reduction in co-produced HEFA-RD during the production process. Amount of co-produced RD decreased by around 25% to 50%. However, under the current policy scenario, ATJ-SAF remains more profitable than the HEFA pathway and is the only SAF produced, with about 74.7 million gallons of ATJ-SAF generated (Figure A9).

G.5. Alternative indirect land use change values

We vary ILUC values to examine how changes in these parameters affect emission reductions and abatement costs. Throughout this analysis, we hold eligibility for RINs, LCFS credits, and tax credits constant. In the "high ILUC" case, ILUC values are doubled for oilseed pathways and multiplied by 1.2 for all other pathways relative to the current policy. In the "low ILUC" case, ILUC values for all pathways are set to 0.8 times those in the current policy scenario. Because policy eligibility is unchanged, prices and quantities remain the same under all ILUC assumptions. When ILUC values increase, all points in Figure **??** shift up and to the left (Figure A10): transportation emission reductions fall, while average abatement costs rise. Conversely, lower ILUC values reduce average abatement costs and increase the percentage reduction in transportation emissions.

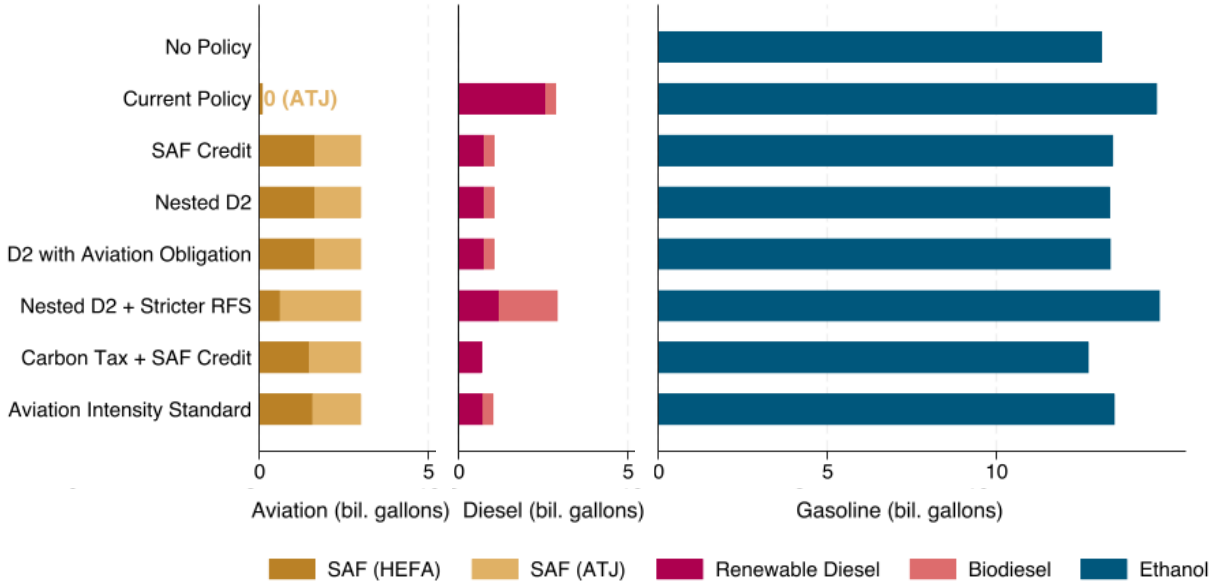


FIGURE A7: Biofuel quantity by policy scenario with alternative feedstock conversion rates

Notes: This figure shows the volumes of biofuels, by type, produced under each policy scenario. We assume that producing 1 gallon of renewable diesel requires 8 lbs of vegetable oil and animal fat/tallow, and that producing 1 gallon of SAF requires 8.5 lbs of vegetable oil and animal fat.

G.6. Alternative RIN assumptions

In the June 2025 proposed RVO rulemaking, the EPA proposed reducing the equivalence value for most RD to 1.6. Compared with the baseline value of 1.7, this leads to higher RIN prices across all policy scenarios (Table A19).

TABLE A19: Policy incentive values across policy scenarios under alternative RFS RVO

Scenario	**State Credit** ($/gal)	**SAF Tax Credit** ($/gal)	**D2 RIN** ($/RIN)	**D4 RIN** ($/RIN)	**D6 RIN** ($/RIN)	**LCFS Credit** ($/ton)	**Av. Std. Credit** ($/ton)	**Carbon Tax** ($/ton)
Current Policy	1.50	-	-	1.77	1.44	88.35	-	-
Current Policy	1.50	-	-	1.66	1.61	140.38	-	
SAF Credit	1.38	2.04	-	0.51	0.51	250	-	
Nested D2	1.38	-	1.78	0.47	0.47	250	-	
D2 with aviation obligation	1.38	-	1.72	0.49	0.49	250	-	
Nested D2 + stricter RFS	1.38	-	2.53	1.95	1.95	93.96	-	
Carbon Tax + SAF credit	-	4.40	-	-	-	-	-	15.00
Aviation Intensity Std	1.38	-	-	0.55	0.55	250	275.32	

G.7. Alternative LCFS assumptions

In the baseline scenario, we assume a total credit bank of 28.69 million metric tons from exogenous, non-biofuel sources. In the sensitivity analysis, we add 4 million metric tons of credits from exogenous sources, including electricity, hydrogen, off-road electricity, methane, and infrastructure credits. With additional exogenous LCFS credits available, the LCFS credit price no longer hits

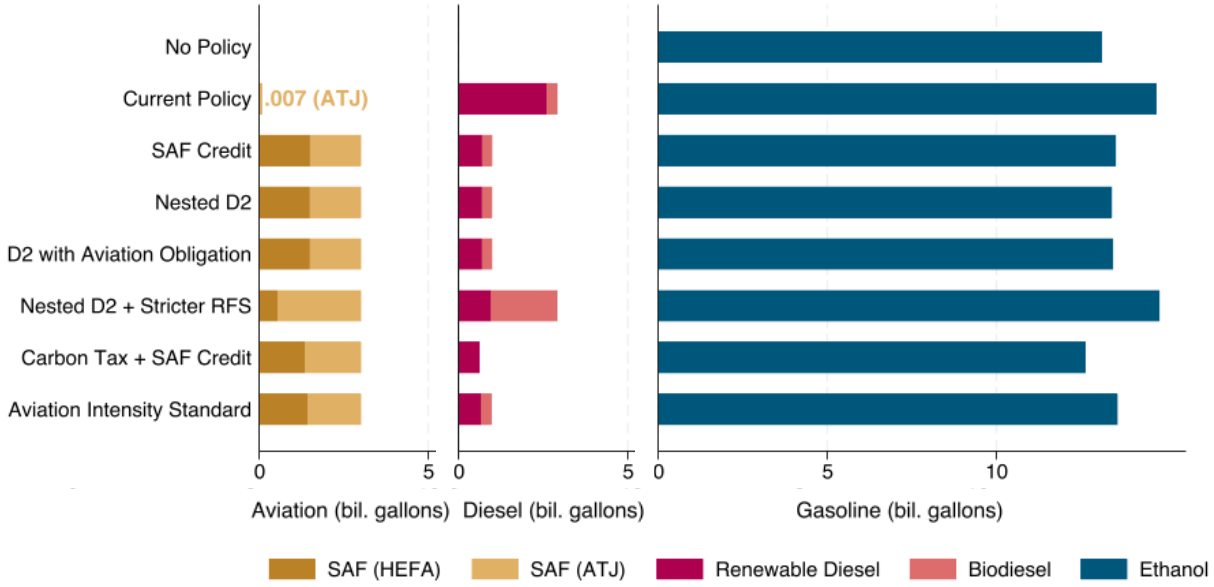


FIGURE A8: Biofuel quantity by policy scenario with alternative feedstock conversion rates for SAF pathways

Notes: This figure shows the volumes of biofuels, by type, produced under each policy scenario. We assume that producing 1 gallon of HEFA-SAF requires 9.5 lbs of vegetable oils and animal fats. Conversion factors for all ATJ pathways are increased by 25%.

the $250 per metric ton ceiling and instead ranges between $69 and $166 per metric ton (See Figure A20).

TABLE A20: Policy incentive values across policy scenarios under alternative LCFS assumption

Scenario	**State Credit** ($/gal)	**SAF Tax Credit** ($/gal)	**D2 RIN** ($/RIN)	**D4 RIN** ($/RIN)	**D6 RIN** ($/RIN)	**LCFS Credit** ($/ton)	**Av. Std. Credit** ($/ton)	**Carbon Tax** ($/ton)
Current Policy	1.50	-	-	1.77	1.44	88.35	-	-
SAF Credit	1.38	2.30	-	0.63	0.63	166.19	-	-
Nested D2	1.38	-	2.06	0.61	0.61	164.18	-	-
D2 with aviation obligation	1.38	-	2.00	0.61	0.61	164.97	-	-
Nested D2 + stricter RFS	1.38	-	2.61	1.95	1.95	68.52	-	-
Carbon Tax + SAF credit	-	4.40	-	-	-	-	-	15.00
Aviation Intensity Std	1.38	-	-	0.62	0.62	162.55	324.65	-

With the decline in LCFS prices, petroleum diesel and gasoline no longer face LCFS obligations of roughly 90 cents per gallon; instead, the obligation falls to about 60 cents per gallon. As a result, the difference in blended fuel costs between the current policy and the policy scenarios that mandate 3 Bgal of SAF becomes much smaller (Figure A11).

G.8. Alternative diesel demand elasticity

In the baseline scenario, we assume a diesel demand price elasticity of $\beta_D = -0.07$. We examine sensitivity to this assumption by testing the bounds of the reported range: $\beta_D = -0.038$ (Wine-

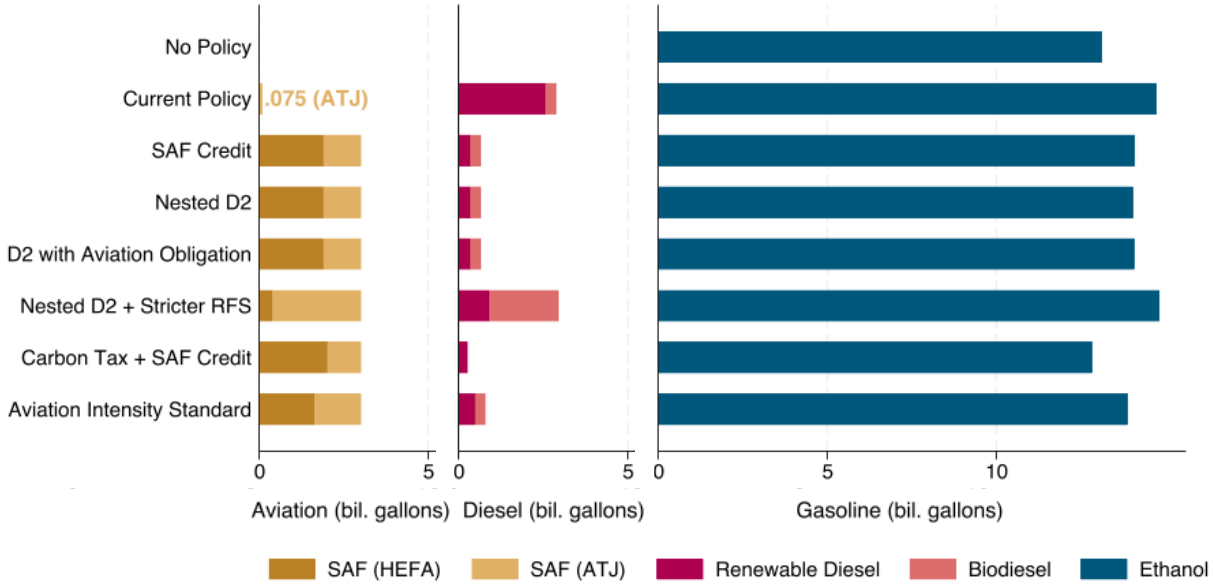


FIGURE A9: Biofuel quantity by policy scenario with alternative co-production limits

Notes: This figure shows the volumes of biofuels, by type, produced under each policy scenario. We assume that liquid-to-liquid yields of a typical HEFA plant when maximizing SAF output is 80%, with the remaing 10% to RD and 10% to light ends.

brake et al. 2015) and $\beta_D = -0.38$ (Gillingham and Munk-Nielsen 2019), bracketing our baseline assumption.

Table A21 reports results across three dimensions. California's driver share of the on-road consumer burden (Panel A) ranges from 47–58% at baseline for most mandate scenarios, consistent with the main paper, and falls by at most 2 percentage points under more price-responsive demand. The LCFS price ceiling result is also robust: the LCFS price remains at the \$250/ton ceiling for most mandate scenarios under both bounds (Panel B), with the exception of Nested D2 + Stricter RFS which falls from \$74.6 to \$68.4/ton (−8.3%) under more price-responsive demand. Blended diesel prices in California change by at most 5.5% at the bounds of the reported range, with the ranking of price impacts across policy scenarios preserved under both bounds (Panel C).

G.9. Alternative tallow and waste oils supply elasticity

In the baseline scenario, we assume a tallow and waste oils supply elasticity of $\beta_{\text{tallow}} = 2.0$. Due to limited published estimates for this parameter, we examine sensitivity by testing $\beta_{\text{tallow}} = 0.5$ (very inelastic) and $\beta_{\text{tallow}} = 5.0$ (very elastic), bracketing our baseline assumption. We also test corn supply elasticity bounds ($\beta_{\text{corn}} = 0.14$ to 0.50) for comparison.

Table A22 reports the HEFA share of SAF production under these alternative assumptions. Two findings emerge. First, under Current Policy, pathway composition is sensitive to the tallow elasticity assumption: under very inelastic tallow supply, the HEFA share falls as the model shifts toward ATJ corn-CCS, while under very elastic tallow supply, cheap tallow makes HEFA competi-

TABLE A21: Cost incidence and LCFS compliance under alternative diesel demand elasticity assumptions. Baseline: $\beta_D = -0.07$.

Scenario	Baseline	Diesel demand elasticity	
		Inelastic ($\beta_D = -0.038$)	**More price-responsive** ($\beta_D = -0.38$)
Panel A: California driver share of on-road consumer burden (%)			
Current Policy	21.0	21.1 [+1%]	21.5 [+2%]
SAF Credit	58.2	58.1 [−0%]	58.9 [+1%]
Nested D2	47.2	47.1 [−0%]	46.3 [−2%]
D2 with aviation obligation	50.3	50.3 [−0%]	49.6 [−1%]
Nested D2 + stricter RFS	14.2	14.4 [+1%]	14.0 [−2%]
Carbon Tax + SAF credit	n/a	n/a	n/a
Aviation Intensity Std	56.1	56.0 [−0%]	56.7 [+1%]
Panel B: LCFS credit price ($/ton)			
Current Policy	120.9	122.6 [+1.4%]	121.0 [+0.1%]
SAF Credit	250.0	250.0 [+0.0%]	247.5 [−1.0%]
Nested D2	250.0	250.0 [+0.0%]	238.3 [−4.7%]
D2 with aviation obligation	250.0	250.0 [+0.0%]	241.2 [−3.5%]
Nested D2 + stricter RFS	74.6	76.5 [+2.5%]	68.4 [−8.3%]
Carbon Tax + SAF credit	n/a	n/a	n/a
Aviation Intensity Std	250.0	250.0 [+0.0%]	250.0 [+0.0%]
Panel C: Blended diesel price CA, relative to no-policy baseline ($/gal)			
Current Policy	0.61	0.62 [+1.1%]	0.61 [−1.4%]
SAF Credit	0.95	0.95 [+0.1%]	0.94 [−1.4%]
Nested D2	0.99	0.99 [+0.1%]	0.94 [−4.5%]
D2 with aviation obligation	0.97	0.98 [+0.0%]	0.94 [−3.5%]
Nested D2 + stricter RFS	0.61	0.61 [+1.1%]	0.57 [−5.5%]
Carbon Tax + SAF credit	0.20	0.20 [+0.0%]	0.20 [+0.0%]
Aviation Intensity Std	0.96	0.96 [+0.1%]	0.95 [−0.3%]

Notes: Panel A: California driver share = (Diesel CA + Gasoline CA) / (Diesel CA + Gasoline CA + Diesel RoUS + Gasoline RoUS) × 100, consistent with Figure 7 in the main paper. Carbon Tax + SAF credit does not include the CA LCFS program, so the California driver share is not applicable (n/a). Panel B: LCFS credit price ($/ton); n/a for Carbon Tax + SAF credit as this scenario does not include the CA LCFS program. Panel C: blended diesel price CA ($/gal), change relative to no-policy baseline, consistent with Figure 8 in the main paper. Percentage changes relative to baseline in brackets.

tive even without a mandate, shifting production entirely to HEFA. Second, for scenarios reaching the 3 Bgal target, the HEFA share remains within 43–49% across both elasticity bounds for most mandate scenarios, as the mandate structure determines pathway mix more than feedstock prices alone. The Nested D2 + Stricter RFS scenario exhibits the largest sensitivity: the HEFA share collapses from 11.3% to 1.5% under inelastic tallow because the stricter RFS obligation requires large volumes of road biodiesel, which competes with SAF HEFA for scarce tallow, leaving almost no tallow available for SAF HEFA production. Corn supply elasticity changes the HEFA share by at most 2 percentage points across all mandate scenarios, confirming that tallow and waste oils supply is the primary driver of HEFA versus ATJ competitiveness.

Table A23 reports that policy cost rankings are preserved under all tallow elasticity assumptions.

TABLE A22: HEFA share of SAF production (%) under alternative tallow and waste oils supply elasticity assumptions. Baseline: $\beta_{\text{tallow}} = 2.0$, $\beta_{\text{corn}} = 0.264$.

Scenario	Baseline	Tallow/waste oils elasticity		Corn elasticity	
		Inelastic ($\beta = 0.5$)	Elastic ($\beta = 5.0$)	Inelastic ($\beta = 0.14$)	Elastic ($\beta = 0.50$)
Current Policy	0.0	0.0 [—]	100.0 [—]	0.0 [—]	0.0 [—]
SAF Credit	48.6	45.9 [−5%]	72.0 [+48%]	49.5 [+2%]	47.6 [−2%]
Nested D2	48.4	45.8 [−5%]	71.9 [+49%]	49.2 [+2%]	47.4 [−2%]
D2 with aviation obligation	48.4	45.9 [−5%]	71.9 [+49%]	49.3 [+2%]	47.5 [−2%]
Nested D2 + stricter RFS	11.3	1.5 [−87%]	75.4 [+568%]	14.9 [+32%]	8.7 [−23%]
Carbon Tax + SAF credit	43.5	45.8 [+5%]	48.2 [+11%]	43.8 [+1%]	43.0 [−1%]
Aviation Intensity Std	46.3	43.8 [−6%]	67.4 [+46%]	47.2 [+2%]	45.3 [−2.2%]

Notes: HEFA share = $Q_{\text{HEFA}}/(Q_{\text{HEFA}} + Q_{\text{ATJ}}) \times 100$, where Q_{HEFA} and Q_{ATJ} are SAF production volumes (Bgal) via HEFA and ATJ pathways respectively. Percentage changes relative to baseline in brackets. Current Policy does not impose a SAF mandate. Under Current Policy, total SAF production: at baseline, $Q_{\text{HEFA}} = 0$ Bgal and $Q_{\text{ATJ}} = 0.07$ Bgal; under inelastic tallow/waste oils supply ($\beta = 0.5$), $Q_{\text{HEFA}} = 0$ Bgal and $Q_{\text{ATJ}} = 0.17$ Bgal; under elastic tallow/waste oils supply ($\beta = 5.0$), $Q_{\text{HEFA}} = 0.58$ Bgal and $Q_{\text{ATJ}} = 0$ Bgal; under inelastic corn supply ($\beta = 0.14$), $Q_{\text{HEFA}} = 0$ Bgal and $Q_{\text{ATJ}} = 0.07$ Bgal; under elastic corn supply ($\beta = 0.50$), $Q_{\text{HEFA}} = 0$ Bgal and $Q_{\text{ATJ}} = 0.08$ Bgal.

G.10. Alternative non-biofuel demand elasticity

In the baseline scenario, we assume $\beta_{\text{other}} = -0.2$ for soybean oil and corn non-biofuel demand, and $\beta_{\text{other}} = 0$ for tallow, waste oils, and imported Brazilian sugarcane ethanol non-biofuel demand. The value of -0.2 is consistent with recent estimates of global vegetable oil demand elasticities (Chen, Sexton, and Smith 2025) and corn feed demand elasticities (McPhail and Babcock 2012; Adjemian and Smith 2012). Table A24 reports feedstock prices under $\beta_{\text{other}} = 0$ (no non-biofuel demand response) and $\beta_{\text{other}} = -0.4$ (strong response), bracketing our baseline assumption. Feedstock prices respond in the expected direction: soyoil prices change by 0.9–5.5% and corn prices by 2.1–14.1% across policy scenarios. Tallow and waste oil prices also change through a cross-market spillover from soyoil, as explained in the table notes. Policy cost rankings are preserved under all assumptions.

G.11. Joint elasticities bounds

Tables A25 and A26 report results when all key demand and supply elasticities are set simultaneously to their lower and upper bounds. This joint test is more conservative than individual sensitivity analyses as it amplifies all effects at once. All lower bounds set $\beta_D = -0.038$, $\beta_G = -0.20$, $\beta_J = -0.166$, $\beta_{\text{tallow}} = 0.5$, $\beta_{\text{corn}} = 0.14$, $\beta_{\text{sugarcane}} = 0.04$, and $\beta_{\text{other}} = 0$. All upper bounds set $\beta_D = -0.38$, $\beta_G = -0.50$, $\beta_J = -0.35$, $\beta_{\text{tallow}} = 5.0$, $\beta_{\text{corn}} = 0.50$, $\beta_{\text{sugarcane}} = 0.20$, and $\beta_{\text{other}} = -0.4$.

Policy cost rankings are preserved under both joint bounds: Carbon Tax + SAF credit remains the most cost-effective policy at \$173/ton (upper bounds) and \$358/ton (lower bounds), approximately 13–29% lower and 36–62% higher than the corresponding baseline scenario respectively.

TABLE A23: Average abatement cost ($/ton CO_2) under alternative tallow and waste oils supply elasticity assumptions. Baseline assumption: $\beta_{\text{tallow}} = 2.0$.

		Tallow/waste oils elasticity	
Scenario	**Baseline**	**Inelastic** ($\beta = 0.5$)	**Elastic** ($\beta = 5.0$)
Current Policy	461	503 [+9%]	432 [−6%]
SAF Credit	572	573 [+0%]	562 [−2%]
Nested D2	479	483 [+1%]	445 [−7%]
D2 with aviation obligation	485	489 [+1%]	449 [−7%]
Nested D2 + stricter RFS	441	447 [+1%]	414 [−6%]
Carbon Tax + SAF credit	220	218 [−1%]	216 [−2%]
Aviation Intensity Std	498	501 [+1%]	463 [−7%]

Notes: AAC = average abatement cost ($/metric ton CO_2). Ranking (lowest to highest AAC): Carbon Tax + SAF credit < Nested D2 + stricter RFS < Nested D2 ≈ D2 with aviation obligation ≈ Aviation Intensity Std < SAF Credit. Ranking is preserved under both inelastic and elastic tallow supply assumptions. Percentage changes relative to baseline in brackets.

The 3 Bgal SAF mandate is met under all assumptions for all mandate scenarios. The HEFA share varies from 46% at lower bounds to 75% at upper bounds, consistent with the tallow elasticity sensitivity in Table A22. California's disproportionate on-road consumer burden persists under both bounds, with California's share remaining well above its 10% national benchmark in all cases. LCFS prices remain at the $250/ton ceiling for most mandate scenarios under lower bounds, while falling 13–17% under upper bounds. Blended diesel prices in California remain substantially above the no-policy baseline across all scenarios and bounds, consistent with the main paper's finding that the LCFS creates a disproportionate cost burden in California.

G.12. Accelerated EV adoption

In the baseline scenario, LDV EV fleet shares are set to AEO 2025 projected 2030 values (18.9% in California, 11.5% in the rest of the US). Table A27 reports results under an accelerated electrification scenarios in which LDV EV share rises to 25% in California and 23% in the rest of the US, consistent with a trajectory above the AEO 2025 reference case. Under accelerated EV adoption, the LCFS compliance value falls by 19–51% across all scenarios as the smaller road fuel market reduces the road sector LCFS deficit (Panel C). D4 and D6 RIN prices rise by 23–35% for most mandate scenarios (Panel E) to compensate for the lower LCFS value — as LCFS falls, road biofuels require higher RIN prices to remain competitive. AAC falls by 0.5–6.5% for most mandate scenarios but rises for Carbon Tax + SAF credit (+2.6%) and Current Policy (+9.6%). Emissions reductions fall for most mandate scenarios (−9 to −13%) as the smaller fossil fuel baseline reduces the measured percentage emissions reduction, but rise for Nested D2 + Stricter RFS (+3%) and Carbon Tax + SAF credit (+1%) (Panel B). California's disproportionate on-road consumer burden falls under accelerated electrification but remains substantially above its 10% national benchmark for most mandate scenarios (Panel D). The Carbon Tax + SAF credit advantage over Current Policy widens from $241/ton to $279/ton, confirming that our baseline Carbon Tax results are

TABLE A24: Feedstock prices under alternative non-biofuel demand elasticity assumptions for soybean oil and corn (β_{other}). Baseline: $\beta_{\text{other}} = -0.2$ for soybean oil and corn.

		Non-biofuel demand elasticity for soybean oil and corn (β_{other})	
Scenario	Baseline	$\beta = 0$ (no competition)	$\beta = -0.4$ (strong competition)
Soybean oil price ($/lb)			
Current Policy	0.59	0.61 [+3.2%]	0.57 [−4.1%]
SAF Credit	0.51	0.52 [+2.4%]	0.50 [−1.8%]
Nested D2	0.51	0.52 [+2.3%]	0.50 [−1.7%]
D2 with aviation obligation	0.51	0.52 [+2.3%]	0.50 [−1.8%]
Nested D2 + stricter RFS	0.64	0.68 [+5.5%]	0.62 [−3.0%]
Carbon Tax + SAF credit	0.45	0.45 [+0.9%]	0.44 [−0.7%]
Aviation Intensity Std	0.47	0.48 [+2.3%]	0.46 [−1.7%]
Tallow and waste oils price ($/lb)			
Current Policy	0.64	0.66 [+3.6%]	0.62 [−3.6%]
SAF Credit	0.58	0.59 [+2.1%]	0.57 [−1.6%]
Nested D2	0.58	0.59 [+2.0%]	0.57 [−1.5%]
D2 with aviation obligation	0.58	0.59 [+2.0%]	0.57 [−1.5%]
Nested D2 + stricter RFS	0.67	0.70 [+4.3%]	0.65 [−2.7%]
Carbon Tax + SAF credit	0.45	0.45 [+0.9%]	0.44 [−0.7%]
Aviation Intensity Std	0.58	0.59 [+1.9%]	0.57 [−1.4%]
Corn price ($/bushel equiv.)			
Current Policy	4.66	4.75 [+2.1%]	4.59 [−1.5%]
SAF Credit	5.04	5.30 [+5.1%]	4.87 [−3.3%]
Nested D2	5.02	5.26 [+4.9%]	4.86 [−3.2%]
D2 with aviation obligation	5.03	5.28 [+5.0%]	4.86 [−3.3%]
Nested D2 + stricter RFS	5.94	6.78 [+14.1%]	5.49 [−7.6%]
Carbon Tax + SAF credit	4.87	4.99 [+2.6%]	4.77 [−2.0%]
Aviation Intensity Std	5.09	5.34 [+5.0%]	4.92 [−3.2%]

Notes: Tallow, waste oils, and imported Brazilian sugarcane ethanol are held at $\beta_{\text{other}} = 0$ in all scenarios as these feedstocks have no competing non-biofuel demand. Percentage changes relative to baseline in brackets. Tallow price changes reflect cross-market spillovers from soybean oil rather than a direct effect. Percentage changes relative to baseline in brackets.

conservative.

G.13. Alternative demand growth projections

In the baseline scenario, we calibrate demand using the AEO 2025 reference case corresponding to approximately 1.8% annual GDP growth. Following the method of Müller and Watson (2016), we construct a forecast distribution for 2030 GDP from historical U.S. real GDP growth data (1990–2019) and translate it into prediction intervals for baseline travel demand using a cointegrating regression of the log of travel demand on the log of GDP, as described in Supplemental Appendix Section B.4. The Low growth (1.5%/yr, 33th quantile) and High growth (4.0%/yr, 67th quantile) scenarios approximate the Low and High Economic Growth cases respectively. This calibration does not rely on AEO demand projections directly. Results are reported in Appendix Table A28.

Policy rankings are preserved across both quantiles: Carbon Tax + SAF credit remains the

TABLE A25: Average abatement cost, SAF volumes, HEFA share, and emissions reduction under joint elasticity bounds.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +Str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
All lower bounds	776 [+36%]	697 [+45%]	700 [+44%]	712 [+62%]	358 [+62%]	704 [+41%]	713 [+55%]
All upper bounds	499 [−13%]	384 [−20%]	387 [−20%]	320 [−27%]	173 [−21%]	408 [−18%]	329 [−29%]
Panel B: Total SAF (Bgal)							
Baseline	3.00	3.00	3.00	3.00	3.00	3.00	0.07
All lower bounds	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	0.27 [+261%]
All upper bounds	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	0.58 [+677%]
Panel C: HEFA share (%)							
Baseline	48.6	48.4	48.4	11.3	43.5	46.3	0.0
All lower bounds	46.1 [−5%]	46.0 [−5%]	46.0 [−5%]	1.2 [−89%]	46.2 [+6%]	44.8 [−3%]	0.0 [—]
All upper bounds	74.8 [+54%]	75.0 [+55%]	74.9 [+55%]	72.1 [+539%]	47.8 [+10%]	68.0 [+47%]	100.0 [—]
Panel D: Transportation Emissions reduction (%), compared to no policy							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
All lower bounds	2.03 [−8%]	2.25 [−15%]	2.25 [−14%]	3.88 [+3%]	2.41 [−28%]	2.23 [−12%]	1.82 [−0%]
All upper bounds	2.17 [−2%]	2.82 [+7%]	2.80 [+7%]	4.11 [+8%]	3.96 [+19%]	2.77 [+9%]	2.22 [+22%]

Notes: Baseline: $\beta_D = -0.07$, $\beta_G = -0.35$, $\beta_J = -0.25$, $\beta_{\text{tallow}} = 2.0$, $\beta_{\text{corn}} = 0.264$, $\beta_{\text{sugarcane}} = 0.10$, $\beta_{\text{other}} = -0.2$. All lower bounds: $\beta_D = -0.038$, $\beta_G = -0.20$, $\beta_J = -0.166$, $\beta_{\text{tallow}} = 0.5$, $\beta_{\text{corn}} = 0.14$, $\beta_{\text{sugarcane}} = 0.04$, $\beta_{\text{other}} = 0$. All upper bounds: $\beta_D = -0.38$, $\beta_G = -0.50$, $\beta_J = -0.35$, $\beta_{\text{tallow}} = 5.0$, $\beta_{\text{corn}} = 0.50$, $\beta_{\text{sugarcane}} = 0.20$, $\beta_{\text{other}} = -0.4$. The 3 Bgal SAF mandate is met under all assumptions for all mandate scenarios. Percentage changes relative to Baseline in brackets.

most cost-effective policy and the 3 Bgal SAF mandate is met for all mandate scenarios at both growth rates. SAF as a percentage of jet fuel falls from 13% at 1.5%/yr to 9% at 4.0%/yr (Panel C). The LCFS price remains at the $250/ton ceiling for most mandate scenarios under both quantiles (Panel E), confirming this as a structural feature of the LCFS independent of the AEO reference case. California's disproportionate on-road consumer burden persists at both quantiles (Panel D), with California's share remaining well above its 10% national benchmark in all cases.

G.14. Aviation demand reduction

Table A29 reports results under a jet demand reduction scenario in which the aviation demand intercept is scaled by 0.80, representing a 20% reduction in baseline aviation demand consistent with structural shifts such as remote work patterns.

The 3 Bgal SAF mandate is met under all mandate scenarios. The mandate becomes more stringent relative to the smaller jet market: SAF as a percentage of jet fuel rises from 12% to 15% (+25%) across all scenarios (Panel C). SAF Credit AAC rises most (+8.9%) because the fixed mandate cost is spread over a smaller aviation sector, while most other mandate scenario AAC changes are modest (−1 to +2%) (Panel A). Greater emissions reductions are observed for most mandate scenarios (+1 to +12%) as the smaller fossil jet fuel baseline amplifies the relative impact of SAF substitution (Panel B). The HEFA share rises slightly (+3%) as the smaller jet market

TABLE A26: Cost incidence and LCFS compliance under joint elasticity bounds.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Taxpayer burden ($B)							
Baseline	10.96	4.65	4.65	5.82	13.19	4.64	3.16
All lower bounds	10.91 [−1%]	4.64 [−0%]	4.64 [−0%]	5.76 [−1%]	13.67 [+4%]	4.63 [−0%]	3.10 [−2%]
All upper bounds	12.46 [+14%]	4.83 [+4%]	4.83 [+4%]	6.16 [+6%]	12.90 [−2%]	4.83 [+4%]	4.05 [+28%]
Panel B: Air passenger burden CA ($B)							
Baseline	n/a	n/a	0.19	n/a	n/a	0.48	n/a
All lower bounds	n/a	n/a	0.26 [+38%]	n/a	n/a	0.49 [+1%]	n/a
All upper bounds	n/a	n/a	0.13 [−31%]	n/a	n/a	0.72 [+48%]	n/a
Panel C: Air passenger burden RoUS ($B)							
Baseline	n/a	n/a	1.68	n/a	n/a	4.39	n/a
All lower bounds	n/a	n/a	2.31 [+37%]	n/a	n/a	4.42 [+1%]	n/a
All upper bounds	n/a	n/a	1.16 [−31%]	n/a	n/a	6.65 [+51%]	n/a
Panel D: California driver share of on-road consumer burden (%)							
Baseline	58.2	47.2	50.3	14.2	n/a	56.1	21.0
All lower bounds	48.5 [−17%]	41.5 [−12%]	44.4 [−12%]	13.1 [−8%]	n/a	47.4 [−15%]	30.7 [+46%]
All upper bounds	75.9 [+30%]	52.0 [+10%]	55.2 [+10%]	13.3 [−7%]	n/a	71.9 [+28%]	27.1 [+29%]
Panel E: LCFS credit price ($/ton)							
Baseline	250.0	250.0	250.0	74.6	n/a	250.0	120.9
All lower bounds	250.0 [+0%]	250.0 [+0%]	250.0 [+0%]	84.3 [+13%]	n/a	250.0 [+0%]	250.0 [+107%]
All upper bounds	217.7 [−13%]	218.5 [−13%]	218.3 [−13%]	51.1 [−32%]	n/a	207.6 [−17%]	133.9 [+11%]
Panel F: Blended diesel price CA, relative to no-policy baseline ($/gal)							
Baseline	0.95	0.99	0.97	0.61	0.20	0.96	0.61
All lower bounds	0.99 [+4%]	1.02 [+4%]	1.01 [+3%]	0.78 [+28%]	0.20 [+0%]	0.99 [+4%]	1.09 [+77%]
All upper bounds	0.80 [−16%]	0.84 [−14%]	0.84 [−14%]	0.46 [−23%]	0.20 [+0%]	0.76 [−20%]	0.61 [−1%]

Notes: Panels B–C: air passenger burden is non-zero only for D2 with Aviation Obligation and Aviation Intensity Standard, which impose jet fuel compliance obligations; n/a for all other scenarios. Panel D: California driver share = (Diesel CA + Gasoline CA) / (Diesel CA + Gasoline CA + Diesel RoUS + Gasoline RoUS) × 100, consistent with Figure 7 in the main paper. Carbon Tax + SAF credit does not include the CA LCFS program (n/a for Panels D and E). Panel F: blended diesel price CA ($/gal), change relative to no-policy baseline, consistent with Figure 8 in the main paper. Percentage changes relative to baseline in brackets.

slightly reduces feedstock competition from ATJ corn pathways (Panel D). Policy rankings are preserved.

G.15. Aviation demand growth

Table A30 reports results under a jet demand growth scenario in which the aviation demand intercept is scaled by 1.20, representing a 20% increase consistent with post-pandemic rebound forecasts.

The 3 Bgal mandate is met under all mandate scenarios. The mandate becomes less stringent relative to the larger jet market: SAF as a percentage of jet fuel falls from 12% to 10% (−17%) across all scenarios (Panel C). Average abatement costs are essentially unchanged (0 to −1%) for all scenarios (Panel A) and emissions reductions fall modestly (−1 to −2%) as the larger fossil jet fuel baseline means SAF displaces a smaller share of total emissions (Panel B). Feedstock competition

TABLE A27: Key results under accelerated EV adoption.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
EV high	569 [−0.5%]	448 [−6.5%]	457 [−5.8%]	431 [−2.2%]	226 [+2.6%]	467 [−6.1%]	505 [+9.6%]
Panel B: Transportation Emissions reduction (%), compared to no policy							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
EV high	1.92 [−13%]	2.40 [−9%]	2.37 [−9%]	3.88 [+3%]	3.36 [+1%]	2.29 [−10%]	1.65 [−9%]
Panel C: LCFS credit price ($/ton)							
Baseline	250.0	250.0	250.0	74.6	n/a	250.0	120.9
EV high	134.4 [−46%]	122.7 [−51%]	127.3 [−49%]	52.8 [−29%]	n/a	122.9 [−51%]	98.0 [−19%]
Panel D: California driver share of on-road consumer burden (%)							
Baseline	58.2	47.2	50.3	14.2	n/a	56.1	21.0
EV high	40.7 [−30%]	30.4 [−36%]	33.7 [−33%]	13.8 [−3%]	n/a	38.4 [−32%]	19.0 [−10%]
Panel E: RIN prices ($/RIN)							
D4 RIN							
Baseline	0.466	0.429	0.442	1.962	n/a	0.513	1.644
EV high	0.613 [+32%]	0.581 [+35%]	0.593 [+34%]	1.933 [−2%]	n/a	0.632 [+23%]	1.628 [−1%]
D6 RIN							
Baseline	0.466	0.429	0.442	1.962	n/a	0.513	1.335
EV high	0.613 [+32%]	0.581 [+35%]	0.593 [+34%]	1.933 [−2%]	n/a	0.632 [+23%]	1.628 [+22%]
Panel F: Total SAF (Bgal) and HEFA share (%)							
Total SAF (Bgal)							
Baseline	3.00	3.00	3.00	3.00	3.00	3.00	0.07
EV high	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	3.00 [+0%]	0.76 [+912%]
HEFA share (%)							
Baseline	48.6	48.4	48.4	11.3	43.5	46.3	0.0
EV high	51.7 [+6%]	51.3 [+6%]	51.4 [+6%]	8.3 [−27%]	42.2 [−3%]	47.7 [+3%]	82.1 [—]
Panel G: Blended diesel price CA ($/gal), relative to no-policy baseline							
Baseline	0.95	0.99	0.97	0.61	0.20	0.96	0.61
EV high	0.56 [−41%]	0.56 [−43%]	0.56 [−42%]	0.53 [−12%]	0.20 [+0%]	0.52 [−46%]	0.56 [−9%]

Notes: High electrification penetration scenario raises LDV EV fleet share from 18.9% to 25% in California and from 11.5% to 23% in the rest of the US, consistent with an accelerated electrification trajectory relative to the AEO 2025 reference case. All other parameters held at baseline values. Panel C and E: Carbon Tax + SAF credit does not include road biofuel mandates or the CA LCFS program, so LCFS credit prices and RIN prices are not applicable (n/a). Panel D: California driver share = (Diesel CA + Gasoline CA) / (Diesel CA + Gasoline CA + Diesel RoUS + Gasoline RoUS) × 100. Carbon Tax + SAF credit does not include the CA LCFS program (n/a). Percentage changes relative to baseline in brackets.

is largely unaffected: the HEFA share is unchanged at 43–49% across all mandate scenarios (Panel D), with the exception of Nested D2 + Stricter RFS which shows no change from its baseline of 11.3%, and soybean oil, tallow, and corn demands change by less than 0.2% from baseline. Policy rankings are preserved.

TABLE A28: Results under alternative demand growth projections.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Low growth	586 [+2%]	461 [−4%]	473 [−2%]	425 [−4%]	222 [+1%]	500 [+0%]	456 [−1%]
Baseline	572	479	485	441	220	498	461
High growth	565 [−1%]	510 [+6%]	520 [+7%]	459 [+4%]	211 [−4%]	517 [+4%]	524 [+14%]
Panel B: Transportation Emissions reduction (%), compared to no policy							
Low growth	2.19 [−1%]	2.78 [+5%]	2.86 [+9%]	3.83 [+1%]	3.38 [+2%]	2.72 [+8%]	1.82 [−0%]
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
High growth	2.34 [+5%]	2.59 [−2%]	2.55 [−3%]	3.73 [−2%]	3.14 [−6%]	2.54 [+0%]	1.96 [+8%]
Panel C: SAF as % of jet fuel							
Low growth	12.8 [+6%]	12.8 [+6%]	12.9 [+6%]	12.8 [+6%]	13.0 [+6%]	13.4 [+8%]	0.6 [+110%]
Baseline	12.0	12.0	12.1	12.0	12.3	12.3	0.3
High growth	9.3 [−23%]	9.3 [−23%]	9.4 [−22%]	9.3 [−23%]	9.5 [−23%]	9.4 [−24%]	0.1 [−58%]
Panel D: California driver share of on-road consumer burden (%)							
Low growth	67.1	48.7	49.4	13.9	n/a	64.2	22.0
Baseline	58.2	47.2	50.3	14.2	n/a	56.1	21.0
High growth	40.9	37.4	40.7	14.2	n/a	41.2	22.2
Panel E: LCFS credit price ($/ton)							
Low growth	250.0 [+0%]	250.0 [+0%]	250.0 [+0%]	68.5 [−8%]	n/a	250.0 [+0%]	122.1 [+1%]
Baseline	250.0	250.0	250.0	74.6	n/a	250.0	120.9
High growth	250.0 [+0%]	250.0 [+0%]	250.0 [+0%]	83.8 [+12%]	n/a	250.0 [+0%]	173.9 [+44%]
Panel F: Blended diesel CA ($/gal), relative to no-policy baseline							
Low growth	0.93 [−2%]	0.98 [−1%]	0.98 [+0%]	0.58 [−4%]	0.20 [+0%]	0.94 [−2%]	0.61 [−1%]
Baseline	0.95	0.99	0.97	0.61	0.20	0.96	0.61
High growth	1.02 [+7%]	1.04 [+6%]	1.02 [+5%]	0.65 [+8%]	0.20 [+0%]	1.02 [+6%]	0.87 [+41%]

Notes: Low growth (1.5%/yr) and High growth (4.0%/yr) correspond to the 33th and 67th quantiles of the predicted 2030 GDP distribution from a cointegrating regression of log of VMT on log of GDP (T=11 d.f.) The AEO 2025 reference case (1.8%/yr) serves as the baseline. Panel D: California driver share = (Diesel CA + Gasoline CA) / (Diesel CA + Gasoline CA + Diesel RoUS + Gasoline RoUS) × 100, consistent with Figure 7. Carbon Tax + SAF credit does not include the CA LCFS program (n/a). Percentage changes relative to baseline in brackets.

G.16. Alternative fossil Fuel Price Scenarios

Tables A31 and A32 report results under low and high fossil fuel price scenarios respectively. The low price scenario sets fossil fuel prices to P_world × 0.90 (−10%) and the high price scenario sets fossil fuel prices to P_world × 1.10 (+10%).

Under low fossil fuel prices, all mandate scenarios remain feasible and the 3 Bgal target is met. Average abatement costs fall modestly (−2 to −4%) and emissions reductions rise by 7–10% as lower fossil prices increase baseline fossil fuel consumption, raising the required biofuel volume under the RFS percentage standards and hence the total emissions reduction from biofuel substitution. Government spending changes by at most ±1%, confirming subsidy levels are robust to fossil price assumptions. D4 and D6 RIN prices rise by 23–27% as higher road fuel demand raises the RVO and per-gallon RIN values. LCFS prices remain at the $250/ton ceiling for most scenarios. California's disproportionate on-road consumer burden falls modestly (−5 to −9%) as lower fossil prices reduce

TABLE A29: Results under aviation demand reduction scenario.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
Jet demand −20%	623 [+9%]	473 [−1%]	478 [−1%]	435 [−1%]	223 [+1%]	507 [+2%]	461 [−0%]
Panel B: Emissions reduction (%)							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
Jet demand −20%	2.26 [+2%]	2.97 [+12%]	2.94 [+12%]	4.00 [+6%]	3.37 [+1%]	2.77 [+9%]	1.86 [+3%]
Panel C: SAF as % of jet fuel							
Baseline	12.0	12.0	12.1	12.0	12.3	12.3	0.3
Jet demand −20%	15.0 [+25%]	15.0 [+25%]	15.2 [+25%]	15.0 [+25%]	15.3 [+25%]	15.8 [+28%]	0.4 [+25%]
Panel D: HEFA share (%)							
Baseline	48.6	48.4	48.4	11.3	43.5	46.3	0.0
Jet demand −20%	50.1 [+3%]	49.8 [+3%]	49.9 [+3%]	12.7 [+13%]	43.5 [+0%]	46.5 [+0%]	0.0 [—]

Notes: Jet demand −20% scales the aviation demand intercept α_J by 0.80, consistent with structural demand shifts such as remote work patterns. The 3 Bgal SAF mandate is met under all mandate scenarios. Percentage changes relative to baseline in brackets.

absolute LCFS compliance costs. Policy rankings are preserved.

Under high fossil fuel prices, consumers reduce baseline fossil fuel consumption, shrinking baseline emissions and the required biofuel volume under the RFS percentage standards. Emissions reductions fall by 6–7% and AAC rises modestly (+2 to +3%) as greater reliance on high-cost biofuel substitution raises abatement costs. D4 and D6 RIN prices fall by 23–28% as higher fossil prices make biofuels more competitive. LCFS prices remain at the $250/ton ceiling for most scenarios. California's on-road consumer burden rises modestly (+7 to +12%). Policy rankings are preserved.

H. Current industry landscape

Beyond HEFA and ATJ, several other SAF production pathways are under development, including synthetic isoparaffins, catalytic hydrothermolysis, co-processing, and processes using feedstocks such as forest and agricultural wastes. ASTM International, which evaluates and certifies SAF conversion processes, has approved 11 SAF production methods, but only five are expected to result in significant production by 2030 (Rosales Calderon et al. 2024).

Table A33 summarizes announced and planned ATJ-SAF projects in the United States by state, developer, and nameplate capacity. At present, only LanzaJet's Freedom Pines Fuels plant in Georgia is operational, with a capacity of 10 million gallons per year. Projects classified as provisional account for 540 million gallons of announced capacity and typically have identified sites and capacities, and in many cases have secured substantial financing, permits, or are targeting near-term FIDs. Very provisional projects add another 264 million gallons and reflect earlier-stage efforts with limited progress beyond MOUs or public announcements and, in some cases, no

TABLE A30: Results under aviation demand growth scenario.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
Jet demand +20%	572 [−0%]	479 [+0%]	486 [+0%]	441 [+0%]	218 [−1%]	497 [−0%]	461 [−0%]
Panel B: Emissions reduction (%)							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
Jet demand +20%	2.17 [−2%]	2.58 [−2%]	2.55 [−3%]	3.70 [−2%]	3.30 [−1%]	2.47 [−2%]	1.77 [−2%]
Panel C: SAF as % of jet fuel							
Baseline	12.0	12.0	12.1	12.0	12.3	12.3	0.3
Jet demand +20%	10.0 [−17%]	10.0 [−17%]	10.1 [−17%]	10.0 [−17%]	10.2 [−17%]	10.2 [−17%]	0.2 [−17%]
Panel D: HEFA share (%)							
Baseline	48.6	48.4	48.4	11.3	43.5	46.3	0.0
Jet demand +20%	48.6 [+0%]	48.4 [+0%]	48.4 [+0%]	11.3 [+0%]	43.5 [+0%]	46.3 [+0%]	0.0 [—]

Notes: Jet demand +20% scales the aviation demand intercept α_J by 1.20, consistent with post-pandemic rebound forecasts. The 3 Bgal SAF mandate is met under all mandate scenarios. Feedstock demands (soybean oil, tallow, corn) change by less than 0.2% from baseline under all scenarios. Percentage changes relative to baseline in brackets.

TABLE A31: Results under low fossil fuel prices.

	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
Price low (−10%)	553 [−3%]	462 [−4%]	468 [−4%]	427 [−3%]	215 [−2%]	480 [−4%]	445 [−3%]
Panel B: Emissions reduction							
As % of transportation emissions							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
Price low (−10%)	2.40 [+8%]	2.88 [+9%]	2.84 [+9%]	4.08 [+8%]	3.56 [+7%]	2.76 [+9%]	1.99 [+10%]
Absolute (GT CO_2)							
Baseline	0.0506	0.0604	0.0597	0.0865	0.0761	0.0578	0.0415
Price low (−10%)	0.0548 [+8%]	0.0657 [+9%]	0.0648 [+9%]	0.0932 [+8%]	0.0813 [+7%]	0.0629 [+9%]	0.0454 [+10%]
Panel C: Gov spending ($B)							
Baseline	10.96	4.65	4.65	5.82	13.19	4.64	3.16
Price low (−10%)	11.07 [+1%]	4.64 [−0%]	4.64 [−0%]	5.79 [−1%]	13.80 [+5%]	4.63 [−0%]	3.19 [+1%]
Panel D: Credit prices							
D4 RIN ($/RIN)							
Baseline	0.466	0.429	0.442	1.962	n/a	0.513	1.644
Price low (−10%)	0.585 [+26%]	0.547 [+27%]	0.562 [+27%]	2.086 [+6%]	n/a	0.630 [+23%]	1.788 [+9%]
LCFS ($/ton)							
Baseline	250.0	250.0	250.0	74.6	n/a	250.0	120.9
Price low (−10%)	250.0 [+0%]	250.0 [+0%]	250.0 [+0%]	65.9 [−12%]	n/a	250.0 [+0%]	115.2 [−5%]
Panel E: California driver share of on-road consumer burden (%)							
Baseline	58.2	47.2	50.3	14.2	n/a	56.1	21.0
Price low (−10%)	52.7 [−9%]	43.6 [−8%]	46.6 [−7%]	13.4 [−6%]	n/a	51.1 [−9%]	19.9 [−6%]

Notes: Low petroleum price scenario sets fossil fuel prices to P_world × 0.90 (−10%). The 3 Bgal SAF mandate is met under all mandate scenarios. Carbon Tax + SAF credit does not include the CA LCFS program (n/a for Panels D and E). Percentage changes relative to baseline in brackets.

TABLE A32: Results under high fossil fuel prices.

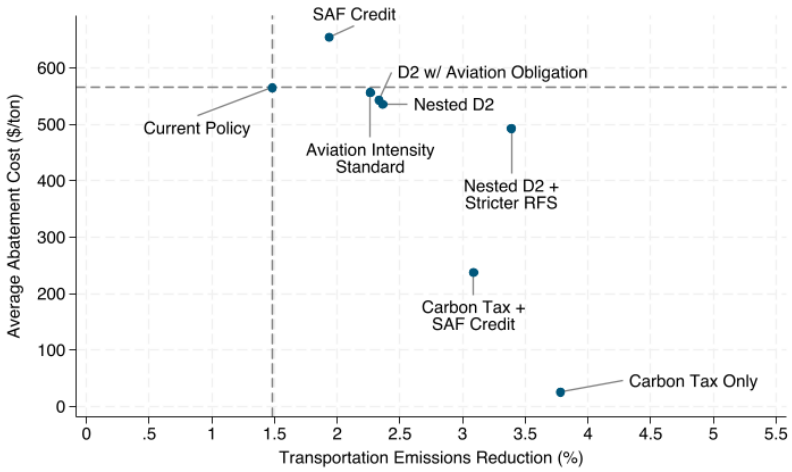
	SAF Credit	Nested D2	D2 w/ Avi Obl	Nested D2 +str RFS	Carbon Tax+SAF	Aviation Std	Current Policy
Panel A: Average abatement cost ($/ton CO_2)							
Baseline	572	479	485	441	220	498	461
Price high (+10%)	584 [+2%]	493 [+3%]	497 [+3%]	450 [+2%]	223 [+2%]	511 [+3%]	474 [+3%]
Panel B: Emissions reduction							
As % of transportation emissions							
Baseline	2.22	2.64	2.62	3.79	3.33	2.53	1.82
Price high (+10%)	2.08 [−6%]	2.46 [−7%]	2.44 [−7%]	3.57 [−6%]	3.15 [−6%]	2.36 [−7%]	1.69 [−7%]
Absolute (GT CO_2)							
Baseline	0.0506	0.0604	0.0597	0.0865	0.0761	0.0578	0.0415
Price high (+10%)	0.0475 [−6%]	0.0563 [−7%]	0.0558 [−7%]	0.0816 [−6%]	0.0719 [−6%]	0.0539 [−7%]	0.0387 [−7%]
Panel C: Gov spending ($B)							
Baseline	10.96	4.65	4.65	5.82	13.19	4.64	3.16
Price high (+10%)	10.86 [−1%]	4.66 [+0%]	4.66 [+0%]	5.86 [+1%]	12.56 [−5%]	4.64 [+0%]	3.15 [−0%]
Panel D: Credit prices							
D4 RIN ($/RIN)							
Baseline	0.466	0.429	0.442	1.962	n/a	0.513	1.644
Price high (+10%)	0.346 [−26%]	0.311 [−28%]	0.321 [−27%]	1.838 [−6%]	n/a	0.395 [−23%]	1.499 [−9%]
LCFS ($/ton)							
Baseline	250.0	250.0	250.0	74.6	n/a	250.0	120.9
Price high (+10%)	250.0 [+0%]	250.0 [+0%]	250.0 [+0%]	83.5 [+12%]	n/a	250.0 [+0%]	129.3 [+7%]
Panel E: California driver share of on-road consumer burden (%)							
Baseline	58.2	47.2	50.3	14.2	n/a	56.1	21.0
Price high (+10%)	65.0 [+12%]	51.5 [+9%]	54.7 [+9%]	15.3 [+7%]	n/a	62.2 [+11%]	22.6 [+7%]

Notes: High petroleum price scenario sets fossil fuel prices to P_world × 1.10 (+10%). The 3 Bgal SAF mandate is met under all mandate scenarios. Carbon Tax + SAF credit does not include the CA LCFS program (n/a for Panels D and E). Percentage changes relative to baseline in brackets.

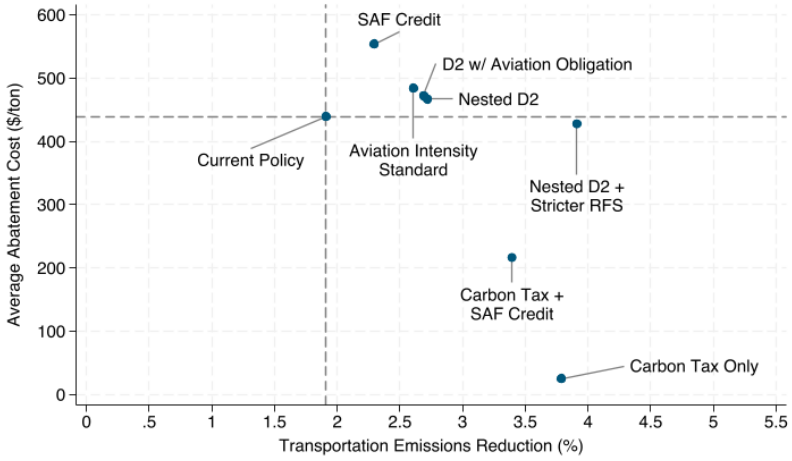
recent updates. One project (Gevo Net-Zero 1) has been postponed or cancelled. In total, the operational, provisional, and very provisional projects represent 814 million gallons of potential ATJ-SAF capacity—just over half of the roughly 1.5 billion gallons of ATJ-SAF production in our policy scenarios.

TABLE A33: Planned and operational ATJ-SAF projects in the United States

State	Company–Project	Capacity (million USG)	Stage	Status details
Georgia	LanzaJet Freedom Pines Fuels	10	Operational	Operational
California	Sugar Valley Energy (California Ethanol + Power)	60	Provisional	Finalizing project financing
Illinois	Crysalis Biosciences Sauget	30	Provisional	Secured $239.5 million in financing in 2024
Illinois	Avina Clean Hydrogen	120	Provisional	Announced an $820 million investment in 2024
North Dakota	Gevo Richardton	30	Provisional	Targeting FID in mid-2026
Texas	Summit Agriculture Group	250	Provisional	Secured all capital needed to reach FID in 2025
Washington	SkyNRG	50	Provisional	Permits obtained; received a $1.5 million grant
Illinois	LanzaJet/Marquis Hennepin	120	Very provisional	Entered into a memorandum of understanding in 2022
Pacific Northwest	LOTUS (SkyNRG, LanzaJet)	10	Very provisional	No updates since 2023
Midwest	Green Plains Blue Blade Energy	134	Very provisional	No updates since 2023
South Dakota	Gevo/Net-Zero 1 Lake Preston	60	Cancelled	Postponed/Cancelled



(A) High ILUC



(B) Low ILUC

FIGURE A10: Emissions reductions and average abatement costs across policy scenarios under alternative indirect land use change (ILUC) assumptions

Notes: These figures show, for each policy scenario, the percentage reduction in transportation emissions (relative to the no-policy case) and the corresponding average abatement cost, measured in dollars per ton. In the "high ILUC" case, we assume ILUC values are doubled for oilseed pathways and multiplied by 1.2 for all other pathways relative to the current policy. In the "low ILUC" case, we assume ILUC values for all pathways are 0.8 times those in the current policy scenario.

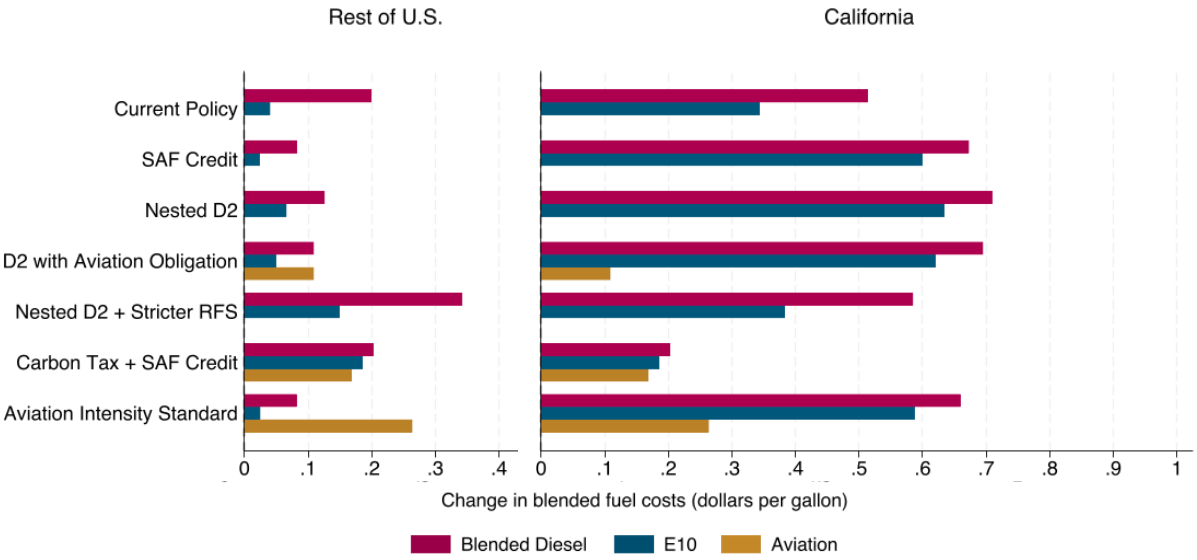


FIGURE A11: Blended fuel cost impacts relative to no policy under alternative LCFS assumption
Notes: This figure shows changes in fuel cost relative to no policy scenario across fuel types resulting from each policy scenario.

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