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ABSTRACT

Decarbonizing aviation in the short term will likely entail replacing large quantities of petroleum jet fuel with sustainable aviation fuels (SAFs), which are predominantly biofuels. In the United States, biofuels are currently used as substitutes for gasoline and diesel in road transportation and are supported by a complex set of federal and state policies including the Renewable Fuel Standard (RFS), state low carbon fuel standards, and state and federal tax credits. Policies promoting SAF therefore interact with surface transport biofuel policies. In this paper, we use a new detailed partial equilibrium model of road and air transportation fuel markets to compare various policy options designed to achieve a target of 3 billion gallons of SAF by 2030. Our results suggest that the target is attainable with current technology but not with current policy. Several potential federal policies, including modifications to the existing RFS, a federal SAF tax credit, or a clean aviation standard could meet the 3 billion gallon target with similar emissions reductions and costs but different incidence. The lowest cost policy we study entails replacing all current biofuels policies with a modest carbon tax on fossil transportation fuels paired with a SAF tax credit.

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1 Introduction

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, they 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, and 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 need long-term policy support to be widely adopted.

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 Biden Administration launched the SAF Grand Challenge, which set an annual production target of 3 Bgal by 2030 and 35 Bgal by 2050 (White House, 2021). 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, 2024b). Company announcements and trade press suggest that capacity has since seen a dramatic increase reaching approximately 460 million gallons per year by mid-2025 representing 15.3% of the 2030 target and 2% of current U.S. jet fuel supply (EIA, 2025).

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 fall on drivers, surface freight shippers, or taxpayers. Together these policies create a subsidy stack, which varies by feedstock, type of fuel, carbon intensity, and the location of production and/or consumption. Any proposed SAF policy must be developed and assessed in the context of existing biofuel policies. The mix of policies in place help 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.

This paper examines 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. To analyze SAF policy options, we develop a detailed partial equilibrium model of the road and air transportation fuel sectors. 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 then use this model to 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, 60 million gallons of SAF are produced in 2030, and a large amount of biodiesel feedstock that could be used for SAF is converted instead to less-expensive renewable diesel, which is used to replace 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 biodiesel, (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 bio-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 current policy, at least in a static sense and as long as biofuel policy maintains a mandated level of total biofuel use. The static 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 topic not present in our model.

This paper contributes to a small but growing literature on the techno-economic feasibility of decarbonizing aviation under various SAF pathways (Bardon, Massol, and Thomas, 2025; Delbecq et al., 2023). It also relates to literature on U.S. policy options for stimulating SAF production, both refereed (Winchester, McConnachie, et al., 2013; Winchester, Malina, et al., 2015; Jiang and Yang, 2021; Zheng, Wang, and Jiang, 2024) and in the gray literature (Pavlenko and Zheng, 2024; Navarrete, Pavlenko, and O'Malley, 2024). 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.

The remainder of this paper is organized as follows: Section 2 provides background on the fuel technologies and policies under consideration. Section 3 describes the model, data, and scenarios used. Section 4 describes the results and Section 5 concludes and provides policy implications.

2 Background

2.1 Fuel Pathways

Sustainable aviation fuels (SAFs) refer to a range of hydrocarbon fuels made from non-petroleum feedstocks that result in lower GHG emissions from air transportation. Two SAF production technologies are currently operational in the US: (i) hydroprocessed esters and fatty acids (HEFA), which is produced from vegetable oils and waste fats, and (ii) alcohol-to-jet (ATJ), which is typically produced from ethanol or isobutanol from biomass sources such as corn and sugarcane. Other pathways, including Fischer-Tropsch (FT), power-to-liquid (PTL), synthetic isoparaffins (SIP), catalytic hydrothermolysis (CHJ), co-processing, and pathways that use feedstocks like forest and agricultural wastes, are still under development and beyond the scope of this study. SAF conversion processes are evaluated and certified by organizations like ASTM International. There are 11 ASTM-approved production methods, but just 5 pathways are expected to result in significant production by 2030 (Rosales Calderon et al., 2024).

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, as well as indirect emissions resulting from induced land-use change, shifts in non-feedstock crop production (such as methane emissions from rice paddies) and changes in livestock production (Lark et al., 2022).

To evaluate emissions under each policy scenario, we rely on the models used by the California Air Resources Board for LCFS implementation (CA-GREET model). Life-cycle greenhouse gas emissions from biofuels, including SAFs, are difficult to estimate, in part because supply chains are often complex, and especially because there is substantial debate around the appropriate way to model indirect land-use change (ILUC) emissions, which arise when increased demand for feedstocks displaces existing agricultural production, leading to the conversion of additional land elsewhere and the subsequent release carbon previously stored in vegetation and soils into the atmosphere. These emissions can be particularly large when biofuel production results in tropical deforestation in, for example, Brazil to grow soybeans or Indonesia to grow oil palm. The carbon intensity is lower for waste feedstocks such as animal fat (tallow) or used cooking oil, and it is higher for crop-based feedstocks such as corn or soy, which are grown specifically for producing biofuel. While we have chosen to rely on estimates from CA-GREET for the purpose of this paper, it is important to note that these estimates depend on model assumptions. 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 (Berry, Searchinger, and Yang, 2024; Lark et al., 2022; Searchinger et al., 2018).

The three most common road transportation biofuels are ethanol, biodiesel and renewable diesel. Ethanol is almost entirely produced from the starch in corn or sugarcane, although a small amount is made from cellulosic feedstock. Biodiesel and renewable diesel feedstocks include crop-based vegetable oil (e.g., soybean oil, canola), tallow, or used cooking oil. Biodiesel is produced through a chemical process called transesterification, in which organic oils and fats are reacted with alcohols and catalysts. Biodiesel use is somewhat limited by its lower energy density compared to petroleum diesel, its greater sensitivity to cold, and the potential for it 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%. Like SAF, renewable diesel is a hydrocarbon fuel produced through HEFA. The HEFA process 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. Renewable diesel is chemically similar to petroleum diesel and can be used in diesel engines without restriction. SAF can be mixed with conventional jet fuel at currently approved levels of up to 50% (ASTM International, 2022), making it compatible with existing aircraft and requiring no modifications to current fueling infrastructure. HEFA production facilities are increasingly being designed to be capable of producing both renewable diesel and SAF. When optimizing plant infrastructure for SAF, SAF production can reach a maximum of 55% of the total liquid yield, with RD making up 25%, and the remainder being composed of "light ends" (Rosales Calderon et al., 2024).

In this study, we model the 12 most common biofuel production pathways, which are listed in Table 1. For SAF, we consider HEFA, ATJ, and ATJ with carbon capture and storage (CCS). We consider four feedstock categories: crop-based vegetable oils (soybean oil, canola oil and distillers' corn oil), and tallow and waste oils for HEFA or biodiesel production, and corn and sugarcane for ethanol or ATJ production. Due to the complementary production of HEFA SAF and RD through the HEFA process, we model HEFA producers as capable of producing both fuels with choice variables over both the quantity of production and ratio of SAF to RD, subject to the 55% SAF yield constraint.

The estimated carbon intensity (CI) of these pathways depends on a variety of factors, including feedstock source, choices made during the production process, and the model used to estimate life-cycle emissions. Biofuel producers can lower their carbon intensity through methods such as using renewable natural gas for process heat, incorporating low-carbon intensity hydrogen into HEFA production, or capturing and sequestering process emissions that would otherwise be released. 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 California Air Resources Board 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 U.S. Renewable Fuel Standard (RFS) program. Some of the variation shown in the table may stem from differences in pathway assumptions that we made when estimating these values; 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

Table 1: Biofuel pathways and estimated carbon intensities

			Carbon Intensity (gCO_2e/MJ)		
Fuel	**Production Process**	**Feedstock**	**EPA LCA (RFS)**	**CA-GREET**	**45ZCF-GREET (CA Fuels)**
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 most common biofuel production pathways that are modeled in this study and the estimated carbon intensity of a representative set of fuels within each pathway under EPA RFS, CA-GREET (LCFS), and 45ZCF-GREET (only CA fuels). For EPA RFS, we include carbon intensity values for the most common technology listed for each feedstock-fuel combination. For CA-GREET, we calculate the average carbon intensity from the list of currently approved pathways under LCFS. For 45ZCF-GREET, we calculate carbon intensity using sample inputs, adjusting for feedstock input, and assuming no by-products to be consistent with our model setup. These values are calculated assuming production facilities are located in California; this allows for a clearer side-by-side comparison between the two GREET models. Some CA-GREET and EPA LCA estimates are not available for SAF fuels that are not widely produced. For these fuels (indicated by *) we include carbon intensity (CI) values calculated using the 45ZCF-GREET model for California and including indirect land use change (ILUC) effects. The average estimated CI for corn ethanol in California under CA-GREET (LCFS) is 69.68 gCO_2e/MJ. We force it to be 69.40, which is the CARB gasoline standard for year 2030 (indicated by ** in the table). It is unlikely that corn ethanol would generate deficits in the CARB pool, and corn ethanol producers have reduced the CI of their products over recent years. Details about the assumptions made and data sources used to construct this table are provided in Appendix section A1.

the comparison in this table, we use sample inputs from fuels produced in California to estimate CI values under 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 most common technological assumptions under each pathway.

The majority of the differences between carbon intensity estimates shown in Table 1, however, likely derives from differences in LCA modeling methodology. For example, recent amendments to 45Z resulted in the exclusion of ILUC from emissions accounting (Pub. L. 119-21 § 70521, 2025), resulting in significantly lower carbon intensity values. In our modeling, to align with how policies are actually implemented, we use carbon intensity values from 45ZCF-GREET (excluding ILUC emissions) for the 45Z federal tax credit, the EPA LCA model for the RFS program and CA-GREET for California's Low Carbon Fuel Standard. For the 45ZCF-GREET model, we estimated CI values for both California and the rest of U.S., taking into account region-specific factors such as the electricity grid mix. For simplicity, we assume non-California fuels are produced in the Midwest, which is the primary biofuel production region; resulting CI values are similar between the Midwest and the Great Plains. We use the 45ZCF-GREET model (including ILUC emissions) to determine eligibility for both state tax and hypothetical federal SAF tax credits. To evaluate the emissions impact under different hypothetical policies, we use CI values from CA-GREET. It is important to note that the 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. 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, provide estimates that substantially underestimate the emissions effects of biofuel production.

2.2 Policy Context

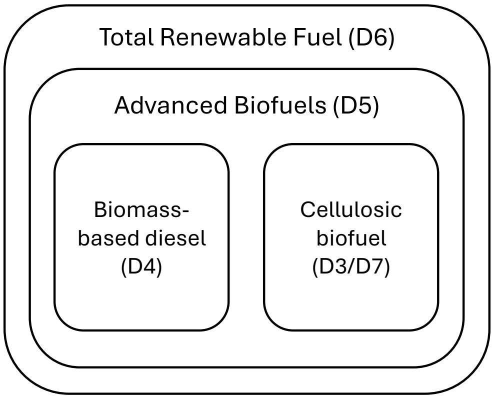
Policy efforts to incentivize the development and deployment of biofuels in the United States have largely targeted road transportation in the form of volumetric mandates, tax incentives, and emissions intensity standards. We describe each of the major policies below.

2.2.1 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 biofuel for road transportation. It has a nested structure, as depicted in Figure 1. First, it requires a total quantity of renewable fuel (D6) to be used (21.54 Bgal in 2024). These biofuels must have life-cycle carbon emissions intensities at least 20% below their petroleum alternatives (see Table 2). Second, a specified portion of this renewable fuel must be advanced biofuels (D5), which have at least 50% lower carbon emissions than petroleum (6.54 Bgal in 2024). Corn ethanol is the only widely used biofuel that qualifies for the total mandate but not the advanced mandate. Third, a specified portion of advanced biofuels must be cellulosic biofuels (D3/D7), which are made from the inedible parts of plants and have at least 60% lower carbon emissions than petroleum. Finally, a portion of advanced biofuels must be biomass-based diesel (D4) fuels (3.04 Bgal in 2024).

To implement the RFS, EPA uses a system of tradeable credits. Each year, EPA divides the volumetric RFS mandates by the amount of gasoline and diesel expected to be used. This generates 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 the renewable identification number (RIN) system. When a firm produces a gallon of biofuel it generates a unique RIN, which may be surrendered to EPA to demonstrate RFS compliance or sold to an obligated supplier of petroleum gasoline and diesel that needs to demonstrate RFS compliance. RINs

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



Notes: This figure shows the nested structure of the Renewable Fuel Standard and RIN D-codes that are associated with each required fuel type.

Table 2: 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.

are classified into five D-codes representing the nested classes of biofuel (see Figure 1). For example, a D4 RIN generated by the blending of biomass-based diesel can be used to fulfill the biomass-based diesel requirement, the advanced biofuel requirement, or the total renewable fuel requirement.

The RIN market 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 are passed through to fuel prices by fossil fuel suppliers (Knittel, Meiselman, and Stock, 2017, Li and Stock, 2019, Mazzone, Smith, and Witcover, 2022).

Currently, SAF is eligible to generate RINs under the RFS, typically in either D4 or D6 categories. However, there is no volumetric requirement for SAF production and petroleum-based jet fuel suppliers face no compliance obligation. As we show in this paper, the nested design structure of the RFS has important implications for how hypothetical SAF policies would interact with the existing incentives for road transportation biofuels.

2.2.2 Tax Credits

Under the Inflation Reduction Act of 2022, a sustainable aviation fuel tax credit (40B) was available in 2023 and 2024. This credit provided \$1.25 per gallon for SAF produced with a carbon intensity that was at least 50% below petroleum jet fuel and an additional \$0.01 for each additional percentage point of carbon intensity reduction (IRS, 2023).

In 2025, the Clean Fuel Production Tax 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 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.

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 feedstocks (Pub. L. 119-21 § 70521, 2025).

Tax incentives for carbon capture and storage (CCS) technology (45Q) are also available, but cannot be used in combination with other federal tax credits to provide additional support for the production of biofuels (U.S. Code § 45Z, 2022). 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.

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 3). 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.

2.2.3 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

Table 3: State-level tax credits for sustainable aviation fuel

State	**Avg Subsidy** ($/gal)	**Nominal Value** ($/gal)	**Eligibility**	**Recipient**	**Maximum Payout**
Illinois	1.50	1.5	In state use	Purchaser	N/A
Minnesota	1.50	1.5	In state production & use	Producer/ blender	$7.4M total 2025, $2.1M total 2026-27; unused funds roll over
Washington	1.38	1 +0.02 per % below 50%	In state production/ blending or use	Purchaser or Producer/ blender	N/A
Nebraska	0.78	0.75 +0.01 per % below 50%	In state production	Producer	$500K/year total
Hawaii	0.36	$0.20 per 76K Btu	In state production & sold	Producer	$3.5M/year to individual recipients, $20M/year total
Iowa	0.25	0.25	In state production	Producer	Max $1M/year per plant. Total $10M allocated across renewable chemical & SAF programs

Notes: This table shows details about current state-level tax credits for sustainable aviation fuel. In-state use means consumed at an airport within the state for in-flight combustion.

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 under an LCFS credits are traded in terms of metric tons of CO_2e rather than gallons of fuel.

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, 2024). The LCFS does allow SAF suppliers to "opt-in" to generate compliance credits for producing fuel below the benchmark emissions intensity, which has made California the first choice destination market for SAF. However, the new state-level tax incentives shown in Table 3 may induce SAF use outside California.

2.2.4 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 (British Columbia, 2023).

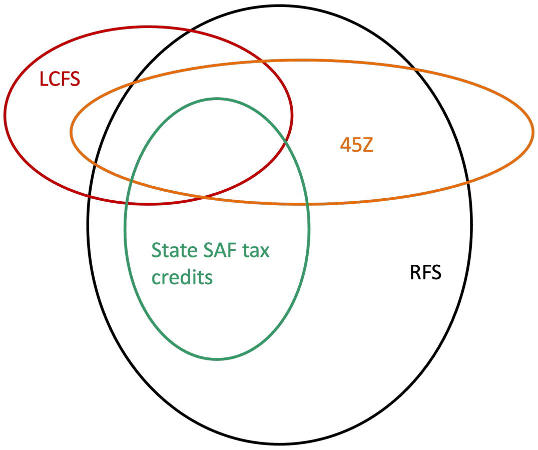
In contrast to the subsidy-driven approach to support SAF development in the US, the European Union has instituted a volumetric mandate, known as the RefuelEU Aviation Initiative, that requires an increasing share of SAF to be used in aviation. The mandate starts in 2025 at 2% and increases to 6% in 2030 and 70% in 2050 (EU, 2023). Within this requirement, a growing share of aviation fuels must be from 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 where 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 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 E.U. 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.

2.3 Policy Interactions

Figure 2: Overlapping policies



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.

The many policies in place result in a complex landscape of overlapping incentives (see Figure 2). The use of multiple policies to incentivize the deployment of renewable fuels can lead to important interaction dynamics and may 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. Similarly, if the RFS is binding, tax credits for required fuels may decrease RIN prices and affect the mix of feedstocks and fuels within each RIN category but would not change total quantity of renewable fuel produced (Irwin, McCormack, and Stock, 2020). Policies that provide greater incentives for fuels with lower carbon intensity (e.g. California's LCFS, 45Z tax credits) may also alter mix and composition of fuel pathways used to meet a volumetric standard, even if volumes are unchanged. Therefore, representing the complex mix of policies in place including their specific design and emissions accounting procedures is necessary to assess potential policy outcomes.

3 Model

To assess the cost, emissions, and fuel-feedstock mix that results 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.[1] Total demand for transportation is set exogenously from forecasts in the Energy Information Administration Annual Energy Outlook, 2025 (AEO 2025) 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 2.2.3).

3.1 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

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[1] We assume that all production takes place in the U.S. and that all feedstocks are domestically sourced, with the exception of Brazilian sugarcane ethanol. Historically, imported renewable diesel has represented approximately 20-40% of total U.S. consumption.

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 of gasoline 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 3.3.

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

$$\text{Profit}(Q) = \sum_j \sum_{f,s} [P^j_f Q^j_{f,s} - C^j_{f,s} Q^j_{f,s} - \text{PolicyCost}^j_{f,s} \cdot Q^j_{f,s}], \tag{2}$$

where P^j_f represents the price of biofuel f (e.g. biodiesel, renewable diesel, sustainable aviation fuel or ethanol) in region j,[2] Q represents the quantity of fuel produced with feedstock, s, and C represents the marginal cost of production (detailed in equation (3)). $\text{PolicyCost}^j_{f,s}$ represents the negative of the per-unit subsidy stack available to a biofuel producer, described in Section 3.3.

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 though the price of the feedstock. Accordingly, the marginal cost of biofuel production is:

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

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. The variable component equals the feedstock price P_s multiplied by the feedstock transformation parameter $\theta_{f,s}$. Table 4 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.

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

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[2] 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 (3) represents only two-thirds of the corn required to produce one gallon of ethanol.

Table 4: 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 The White House, 2025a. This presidential action includes sugarcane ethanol. The figures presented in Table 4 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.

for subsidies and soybean oil feedstock costs. For HEFA-derived SAF, we assume an 8-cent per gallon cost premium over renewable diesel (Dyk and Saddler, 2021; Pearlson, Wollersheim, and Hileman, 2013). Cost estimates for other SAF pathways were derived from a synthesis of technical assessments reported in the literature (International Civil Aviation Organization, 2024; International Renewable Energy Agency, 2021; McKinsey & Company and World Economic Forum, 2020). 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 cost associated with CCS was estimated based on Gevo's reported capture potential for the ATJ pathway (Yoo, Lee, and Wang, 2022), combined with IEA estimates for carbon capture, transportation, and storage costs at biorefineries (International Energy Agency, 2022).[3] 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 (Hossein and Michael, 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 4. For example, producing one gallon of biodiesel requires 7.55 pounds of vegetable oil feedstock (Iowa State University Extension and Outreach, 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

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[3] 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.

of vegetable oil to yield one gallon of SAF (Timothy 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)(American Enterprise Institute, 2024). Additionally, one short ton of sugarcane is expected to yield 19.5 gallons of ethanol (102.56 lbs per gallon) (United States Department of Agriculture, Farm Service Agency, 2006).

3.1.1 Feedstock supply

In the production of bio-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 5. 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. We use the supply elasticity of soybean oil as a proxy for the supply response of all crop-based vegetable oils, given data constraints and the dominance of soybean oil in the U.S. market. However, it is important to note 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 non-biofuel demand elasticities, we assume a value of 0.2 for soybean oil and corn, and 0 for tallow, waste oils, and imported Brazilian sugarcane.

We calibrate the supply curve parameters α_s using quantity data reported by the EIA in the Monthly Biofuels Capacity and Feedstocks Update (EIA, 2024a), along with price data (USDA, 2024) from 2018 to 2023 and the elasticities in Table 5. For Brazilian sugarcane, since only a small portion of sugarcane ethanol is imported into the U.S., we use the total quantity of sugarcane ethanol, as

Table 5: 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 (0.29 to 0.50)	Goyal, Adjemian, and Secor, 2022; Hendricks, Smith, and Sumner, 2014; Kim and Moschini, 2018
Sugarcane	1.1	Babcock, Barr, and Carriquiry, 2010

Notes: * We use the supply elasticity of soybean oil as a proxy for all crop-based vegetable oil.

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 3). Detailed methodology for calculating the average residual elasticity and supply curve parameters is provided in the Appendix section A2.

3.2 Fuel demand

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

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

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 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 6.

Table 6: 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; Knittel and Tanaka, 2021	2.07
Diesel	-0.07 (-0.36 to 0)	Dahl, 2012; 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 work fossil fuel price in 2024 dollars for each fuel type.

We calibrate the demand curve parameters $\alpha^{D}_{\mathcal{F},j}$ using projections of 2030 travel demand, fuel economy, fleet composition, and world fossil fuel prices. Projections of total vehicle miles traveled

(VMT) for light-duty, medium-duty, and heavy-duty vehicle classes are taken from the reference case of the AEO 2025. We then adjust for projected changes in fuel economy and projected 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 this same report.[4] We adjust for projected fuel economy changes to obtain baseline jet fuel consumption.

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.[5] 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. Further information on calibrating the regressions and projecting travel demand based on various average GDP growth rates can be found in Appendix section A3.1. Table 7 presents projections of 2030 of VMT for light-, medium-, and heavy-duty vehicles, as well as RPM for passenger airlines and RTM for cargo-only airlines, based on the projected GDP growth. Results based on alternative demand forecasts are presented in the online Appendix as a robustness check.

We assume on-road and aviation travel demand in California is a fixed proportion of total U.S. travel demand. The percentage of VMT in California is determined based on its observed 2023 share (Table PS-1 of Federal Highway Administration Highway Statistics Series Publications, 2023), with the state accounting for approximately 9.63% of light-duty VMT and 10.79% of medium- and heavy-duty VMT. For air travel, California's share is estimated to be 17% of total U.S. jet fuel consumed using 2023 data (Table F2 of Energy Information Administration State Energy Data System, 2023).

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. To estimate the contribution of zero-emission vehicles to on-road travel, we make assumptions about the adoption rates of battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (H_2 vehicles). Fleet composition projections for California are based on the 2022 Scoping Plan Scenario published by the California Air Resources Board (CARB). We use fleet composition

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[4] 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 included in our analysis.

[5] 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.

TABLE 7: 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	(3108,3172)	(3125,3158)
	Medium-duty	148	(145,152)	(147,150)
	Heavy-duty	214	(210,218)	(212,216)
Revenue Passenger Miles (billions)	Passenger	1365	(1332,1397)	(1349,1383)
Revenue Ton Miles (billions)	Cargo	58.5	(56.0,60.8)	(57.3,59.7)

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.

TABLE 8: 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.

projections for the ROUS from the AEO 2025.[6] Share of vehicle class by fuel type is shown in Table 8. We assume that average light-duty electric vehicles will be driven the same number of miles as average internal combustion engine (ICE) vehicles. For freight vehicles, we assume that electric and hydrogen fuel cell vehicles will travel 75% of the mileage of their internal combustion medium- and heavy-duty counterparts.[7]

Ongoing improvements in fuel economy are anticipated to lower the amount of fuel needed to meet the projected VMT. We estimate the average fuel efficiency for light-duty, medium-duty, and heavy-duty ICE vehicles in 2030 based on historical fuel economy trends from Table VM-1 of Federal Highway Administration Highway Statistics Series Publications, 2023.[8] We assume an annual fuel economy improvement of 0.7% for light-duty ICE vehicles, and 1% per year for medium- and heavy-duty vehicles, based on historical trends from 2000 to 2022. For U.S. passenger and cargo-only airlines, we calculate fuel economy using monthly data on airline fuel consumption and revenue passenger miles or revenue ton miles.[9] We assume that fuel economy in the aviation sector improves by 1.5% per

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[6] For BEV penetration in light-duty vehicles in the ROUS, we use an estimate of 11.5% BEV share of total LDV VMT in 2030 from Woody, Keoleian, and Vaishnav, 2023, as AEO 2025 projects a mix that also includes H_2 and other technologies. For simplicity, we exclude these other fuel types from our analysis.

[7] This assumption exceeds historical estimates, as average annual miles driven by electric vehicles have typically ranged from 60% to 70% of those for conventional vehicles (Davis, 2019; Zhao et al., 2023).

[8] We adjusted light-duty vehicle fuel efficiency assuming a 1.24% BEV penetration rate in 2023. This percentage was calculated using light-duty vehicle registration data from the Alternative Fuels Data Center.

[9] Data on airline fuel costs and consumption were obtained from https://www.transtats.bts.gov/fuel.asp?20=E.

year (Graver, 2022). Our projected fuel efficiency values for each vehicle type are presented in the Appendix section A3.2, and are comparable to the fleet average fuel economy levels projected in AEO 2025. We estimate the demand for blended fuels in 2030 using projected travel demand for each region and vehicle type (as shown in Table 7 and Table 8), 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. Further details on blended fuel demand, as well as electricity and hydrogen travel demand for California and the rest of the U.S., are provided in Appendix section A3.3.

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[10] so long as they remain under the technical blend constraints and that biofuel subsidies accrue to producers (Knittel, Meiselman, and Stock, 2017). Because the supply of petroleum fuels is assumed to be perfectly elastic, demand for biofuels is therefore 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%,[11] biodiesel is set at 7.5% for California[12] and 20% for ROUS (National Renewable Energy Laboratory, 2021), and SAF is set 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).

Demand for ethanol occurs in three ways. It may be blended with gasoline up to the blend limit of approximately 10% and used in traditional combustion engines (E10), it may be sold as E15 where available, or it may be 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 and therefore 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 should not be valued only for its energy content as ethanol has value as an octane enhancer (Babcock, Barr, and Carriquiry, 2010; Irwin and Good, 2017a). Based on observed rack prices

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

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

[12] From 2018 to 2023, biodiesel blends accounted for approximately 7.5% of the market in California after 2020, and less than 5% prior to 2019.

for ethanol and gasoline,[13] from May 2020 through November 2021, we found that—after accounting for the volumetric ethanol excise tax credit—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 due to the limitations on widespread use. To account for this we employ an inverse demand curve for ethanol of the form:

$$\forall j, \quad P^j_{E100} = \theta P^j_{\mathcal{G}0}\left[1 - \mathbb{1}\left(\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s} + Q^j_{\mathcal{G}0}} \geq 0.1\right)\left(e^{\left(\frac{\frac{\sum Q^j_{E100,s}}{\sum Q^j_{E100,s}+Q^j_{\mathcal{G}0}} - 0.01}{0.02}\ln 2\right)} - 1\right)\right] \tag{7}$$

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 0.01 term is included to prevent discontinuities in the inverse demand curve.

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.

3.3 Policy constraints

As discussed in Section 2.2, 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.

3.3.1 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,[14] so we exclude D3 and D5 RINs from the model. The percentage standard for the two RIN categories are:

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

where RFV_i 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 unit of all RINs are ethanol-equivalent gallons.

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[13] Data on monthly rack level prices 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.

[14] 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.

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

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

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

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

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

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

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

The scale factors 1.5, 1.7, and 1.6 reflect the energy densities of biodiesel, renewable diesel and SAF relative to ethanol. 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, the price of a D6 RIN will never exceed that of a D4 RIN, because less expensive D4 RINs could be used to meet the D6 requirement (Irwin, McCormack, and Stock, 2020). Therefore, RIN prices are subject to the constraint $P_{D6} \leq P_{D4}$.

3.3.2 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 production 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.

As described in Section 2.2.2, the value of the subsidy provided to a fuel under the Clean Fuel Production Tax Credit (45Z) depends on the carbon intensity of the fuel relative to a threshold level.

Notably the carbon intensity values used for 45Z ($CI^{45Z}_{f,s}$) exclude indirect land-use change (see Table 1. The tax incentive takes the form:

$$TC^{45Z}_{f,s} = \begin{cases} 0 & \text{if } \overline{CI^{45Z}_{f,s}} > 47.39, \\ 1 \times \frac{47.39 - \overline{CI^{45Z}_{f,s}}}{47.39} & \text{if } \overline{CI^{45Z}_{f,s}} \leq 47.39. \end{cases} \tag{16}$$

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

$$TC^{45Q}_{SAF,s} = \begin{cases} \frac{85 \times 30 \times \overline{ED_{SAF}}}{10^6} & \text{if ATJ+CCS technology}, \\ 0 & \text{Otherwise .} \end{cases} \tag{17}$$

State level tax incentives vary by state in terms of the value, eligibility,[15] and recipient, as described in Table 3. 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 by volumetric or maximum expenditure limits under the policy when present or 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 included. Details on the calculation of the maximum eligible fuel quantity are provided in Appendix section A4.2. 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).

The state tax credit value function ($TC^{State}_{SAF,s,ROUS}$) takes the form:[16]

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[15] 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.

[16] 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. We discuss in Appendix section A4.3 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.

$$\text{TC}_{state} = \begin{cases} 2.28, & \text{if } \sum Q^{ROUS}_{SAF,s} \leq 0.0006Bgal \\ 1.75, & \text{if } 0.0006Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.0406Bgal \\ 1.50, & \text{if } 0.0406Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.5803Bgal \\ 1.38, & \text{if } 0.5803Bgal < \sum Q^{ROUS}_{SAF,s} \leq 0.9826Bgal \\ 0.36, & \text{if } 0.9826Bgal < \sum Q^{ROUS}_{SAF,s} \leq 1.0389Bgal \\ 0, & \text{if } 1.0389Bgal < \sum Q^{ROUS}_{SAF,s} \end{cases} \tag{18}$$

We assume the marginal cost of public funds equals one, meaning we do not adjust for the opportunity cost of the public revenue that is being paid in subsidies from the federal or state budget.

3.3.3 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., that total credits from low-carbon fuels are greater than or equal to total deficits from petroleum gasoline and diesel. The formula for deficits is

$$Deficits = \sum_{f} (CI_f - CI^*_{\mathcal{F}}) Q_f \overline{ED}_f \times 10^{-6} \tag{19}$$

where CI_f is the carbon intensity of petroleum fuel $f \in \{gasoline, diesel\}$ shown in Table 2, $CI^*_{\mathcal{F}}$ is the carbon intensity target, Q_f is fuel quantity in gallons, $\overline{ED}_f$ is energy density (to convert the units from gallons to grams), and 10^{-6} is a scale factor to convert grams to tons.

The formula for credits is

$$\begin{aligned} Credits = & \sum_{f,s} (CI^*_{\mathcal{F}} - CI_{f,s}) Q_{f,s} \overline{ED_{f,s}} \times 10^{-6} \\ & + \left(CI^*_{\mathcal{G}} - \frac{CI_{Elec}}{EER_{Elec,G}} \right) Q_{Elec,LDV} \overline{EER_{Elec,G}} \times \overline{ED_{Elec}} \times 10^{-6} \\ & + \sum_{Elec,MDV/LDV} \left(CI^*_{\mathcal{D}} - \frac{CI_{Elec}}{EER_{Elec,D}} \right) Q_{Elec,MDV/HDV} \times \overline{EER_{Elec,D}} \times \overline{ED_{Elec}} \times 10^{-6} \\ & + \left(CI^*_{\mathcal{D}} - \frac{CI_{Hydro}}{EER_{Hydro,D}} \right) Q_{Hydro,HDV} \overline{EER_{Hydro,D}} \times \overline{ED_{Hydro}} \times 10^{-6} \\ & + \overline{Methane} + \overline{Other} + \overline{Infrastructure} + \overline{Bank} \end{aligned} \tag{20}$$

where we sum over the 12 fuels and pathways in Table 1. Several other pathways can also generate credits in the LCFS, and we include these in the formula above. *Elec* represents the credits generated from light-, medium-, heavy-duty electric vehicles, and *Hydro* represents the 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). The EER represents the relative energy efficiency of alternative fuel vehicles compared to conventional vehicles. Details on how electricity and hydrogen demand are calculated for each vehicle category are provided in Section 3.2. $\overline{Methane}$ 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 that credits generated from methane will reach 10 million metric tons by 2030.[17] Infrastructure project credits are assumed to remain at the 2024 level, with a total of 0.29 million metric tons per year. Similarly, credits from other projects are held constant at their 2024 value, amounting to 2.30 million metric tons annually. We also assume annual $\overline{Banked}$ credits 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 in the online Appendix.

As described in Section 2.2.3, an LCFS acts as an implicit tax for 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:

$$\text{PolicyCost}_{f,s}^{LCFS} = P_{LCFS}(CI_{f,s} - CI_{\mathcal{F}}^{*})\overline{ED_{f,s}}10^{-6} \tag{21}$$

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 system. However, SAF can opt-in to generate LCFS credits based on an aviation benchmark aligned with the diesel standard. The price of LCFS credits 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 (20) are insufficient to cover the deficits from obligated fuels, we assume CARB will issue credit allowances at the capped ceiling price.

3.4 Scenarios

To reach 3 Bgal of SAF in 2030, we examine alternative policy scenarios in terms of their cost, emissions impact, fuel mix, and feedstock input requirements. The active policies in each scenario are

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[17] 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 9: 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.

summarized in Table 9.

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 the existing RFS, LCFS, state-level tax incentives, and subsidies from the Clean Fuel Production Credit. We assume that the 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 carbon intensity benchmarks outlined for 2030 in the California Low Carbon Fuel Standard (California Air Resources Board, 2024). State-level tax incentives are also assumed to remain in effect in 2030. Furthermore, we expect the 45Z tax credit to be extended through the end of 2030.

2. **SAF credit:** A taxpayer-funded subsidy is provided in order to reach 3 Bgal of SAF. Current policies remains in place, and SAF generates compliance credits under the RFS and LCFS. Eligibility to receive a SAF credit is determined in the same way as the 45Z tax credit (using a 47.39 gCO_2e/MJ carbon intensity threshold), but unlike 45Z, a fixed credit value per gallon is offered to all fuel produced at a carbon intensity below this threshold. Unlike the 45Z tax credit, we use CI values that include ILUC 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 billion gallon target. As noted in Section 2.2.1, the RFS essentially subsidizes biofuels through the generation and sale of RINs, which are required to be purchased by petroleum sellers for compliance. Eligibility to generate D2 RINs is restricted to SAFs 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 the use of CCS). The U.S. EPA has the authority to introduce new RIN earning pathways such as D2 for SAF through regulation, 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:[18]

   (a) **Nested D2**: An additional D2 RIN category is put in place requiring 3 Bgal of SAF and nested within D4. There is no compliance obligation for petroleum jet fuel.

   (b) **D2 with aviation obligation**: An additional D2 RIN category is put in place requiring 3 Bgal of SAF. The D2 RIN is nested within the 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 describe in equation (9).

   (c) **Nested D2 + stricter RFS**: An additional D2 RIN category is put in place requiring 3 Bgal of SAF, with volumetric requirements for bio-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 in order 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 at a level 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.

3.5 Model Summary

Not counting hypothetical policies, the current policy model has 108 exogenous parameters (e.g. global fossil fuel prices, LCFS intensity standard), 40 endogenous quantities (including biofuel, fossil fuel and blended fuel quantity, as well as feedstock quantity), 27 endogenous prices (including RIN and LCFS prices, biofuel, fossil fuel and blended fuel prices, as well as feedstock prices) and 34 Lagrangian multiplers for the constrained profit maximization problem 28. We have a total of 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,

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[18] Details on the definition of percentage standards and volumetric requirements for each policy scenario are provided in Appendix section A4.1. This section also contains updated equations used to calculate compliance obligations for each scenario.

and dual feasibility conditions for the Lagrangian multipliers. Appendix section A5.1 presents the complete set of equations and inequalities to be solved.

The system of equations consists of linear, log-linear, and more complex nonlinear components. In particular, the presence of non-differentiable stepwise functions and complementarity constraints arising from the profit maximization problems leads to a non-convex optimization problem. We use mixed-integer programming techniques for two main purposes: (i) to model stepwise relationships, such as those in equation 18, and (ii) to impose complementarity constraints expressed as $a \times b = 0$. We use the *Gurobi* solver to obtain solutions for this mixed-integer nonlinear optimization problem. Further details are provided in Appendix section A5.2.

4 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 60 million gallons 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.

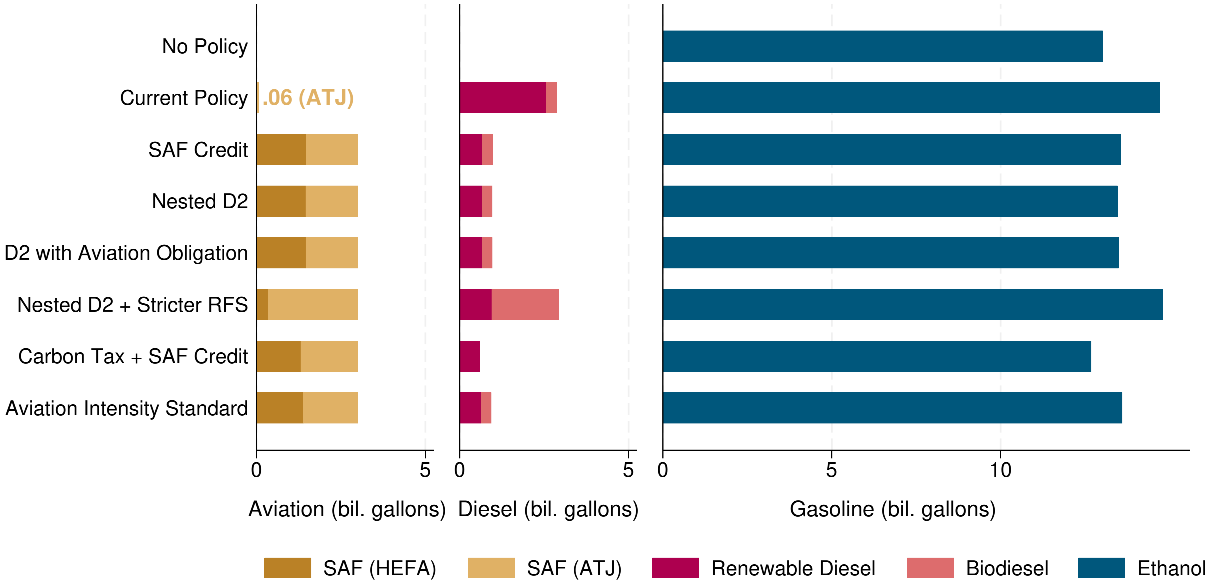

FIGURE 3: Percent biofuel by policy scenario

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 feedstocks 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 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 ATC+CCS outside of California, which is why both pathways are adopted across scenarios reaching the 3 Bgal target.[19]

In practice, the current policy mix has resulted in some SAF production growth in recent years despite this disadvantage. 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)

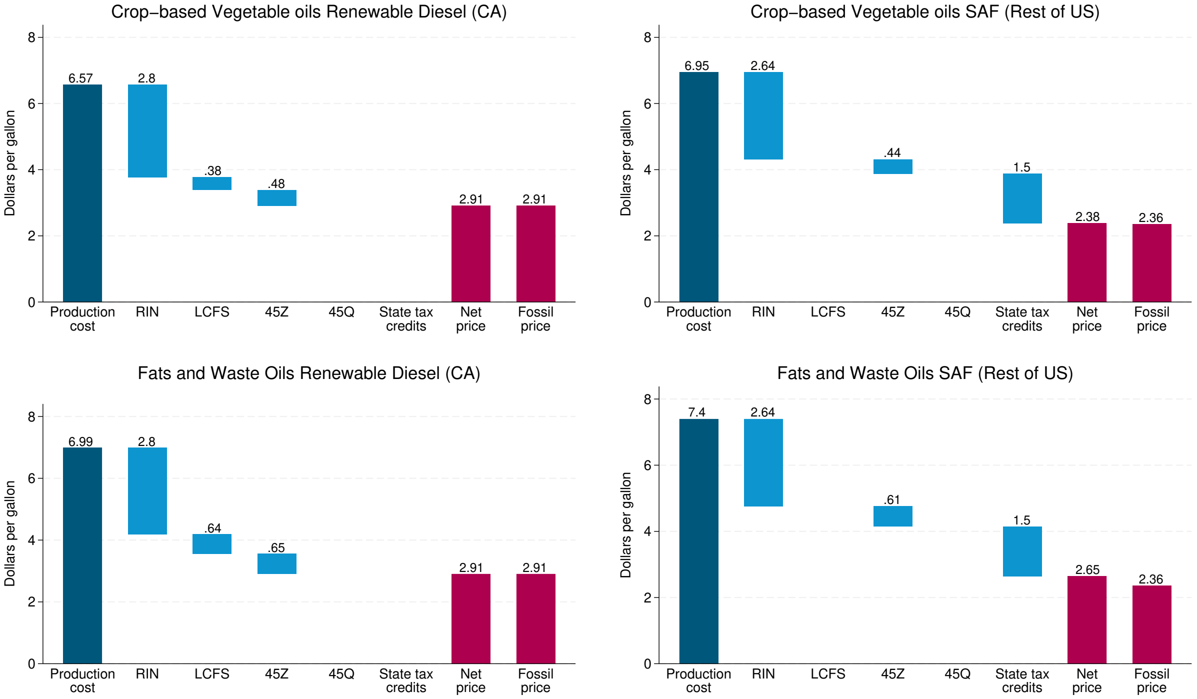

Figure 4: Costs and incentives in 2030 for SAF and Renewable Diesel under current policy

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.

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[19] 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. Results remain largely unchanged across alternative policy scenarios. For additional detail, see Online Appendix.

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

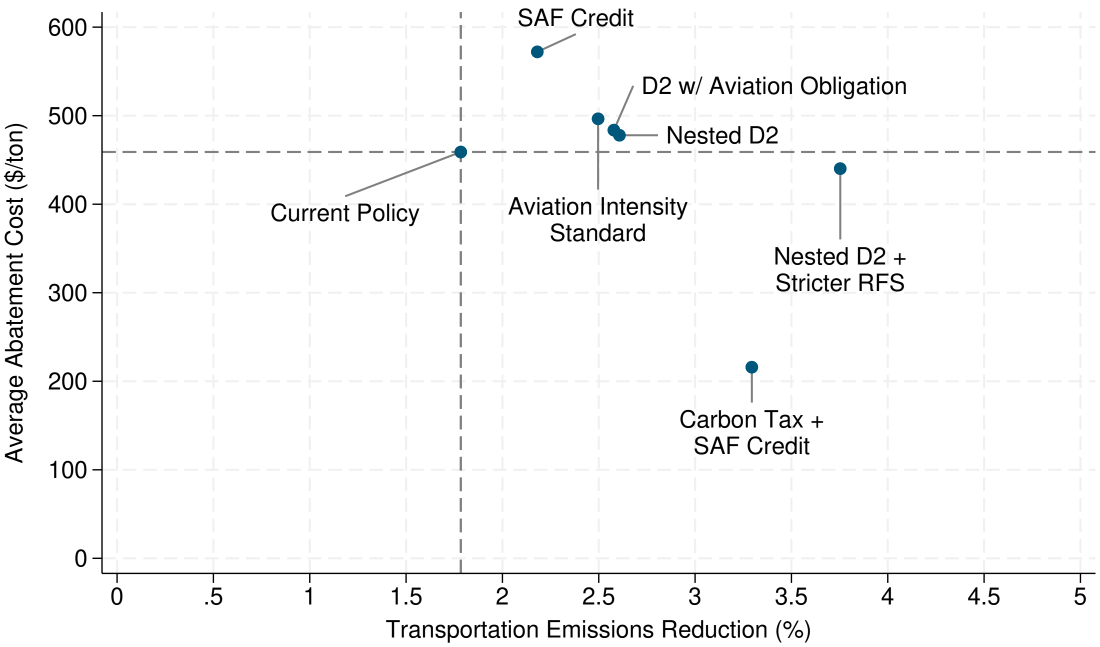

FIGURE 5: Emissions reduction and average abatement costs across policy scenarios

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 transportation emissions reductions, in dollars per ton.

4.1 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 the online Appendix.

The current policy mix represents costly emissions reductions at $459 per metric ton. Alternative policy scenarios that achieve the 3 Bgal target are also costly in terms of average abatement 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. 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 (122 to 210% of the emissions reduction achieved by current policy). In most cases in which additional SAF policies are put in place with existing policies, emissions reductions are limited by the interaction between overlapping policies intended to incentivize biofuel consumption. Because additional SAF production generates credits that can be used to comply with volumetric requirements for biomass-based diesel and ethanol under the RFS and the intensity target of the LCFS, policies that achieve the 3 Bgal target effectively 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 exploting the demand reduction channel.

The credit prices under each scenario are presented in Table 10. Under all scenarios where it is present, 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 bio-based diesel fuels under the LCFS. In contrast, when the stringency of the RFS is increased, greater federal support for bio-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, with the corresponding results presented in the online Appendix.

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 bio-based fuels. However, under one contrived policy scenario — a $15 per ton carbon tax with a SAF tax credit of $4.41 per gallon — greater emissions reductions as well as the SAF production target

Table 10: 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	-		1.65	1.34	122.31	-	-
SAF Credit	1.38	2.11	-	0.47	0.47	250.00	-	-
Nested D2	1.38	-	1.78	0.43	0.43	250.00	-	-
D2 + Aviation Ob.	1.38	-	1.73	0.44	0.44	250.00	-	-
D2 + Stricter RFS	1.38	-	2.59	1.97	1.97	75.77	-	-
C Tax + SAF credit	-	4.41	-	-	-	-	-	15.00
Aviation Intensity Std	1.38	-	-	0.52	0.52	250.00	284.42	-

Notes: This table shows the marginal policy incentive value for 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.

could be achieved at a 53% lower average abatement cost than the current policy scenario ($216 per ton vs. $459 per ton).

Under this scenario, biomass-based diesel use in road transportation decreases by more than 80%. This scenario, in comparison with other policies that achieve the production SAF target, and the carbon tax alone, highlights the potential for more cost-effective emissions reductions; the objective of cost effectiveness is in many cases at odds with large 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 be expected to substantially alter national-level results. Nevertheless, the 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 face a compliance obligation under the cap, indirect interactions are possible. Specifically, if SAF consumption in California displaces renewable diesel in meeting LCFS compliance, fossil diesel use may increase to satisfy transportation demand. This dynamic would raise allowance demand from diesel under the emissions cap, which, if binding, could induce additional emissions reductions in other sectors covered by the emissions 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. 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.

4.2 Distribution of Costs

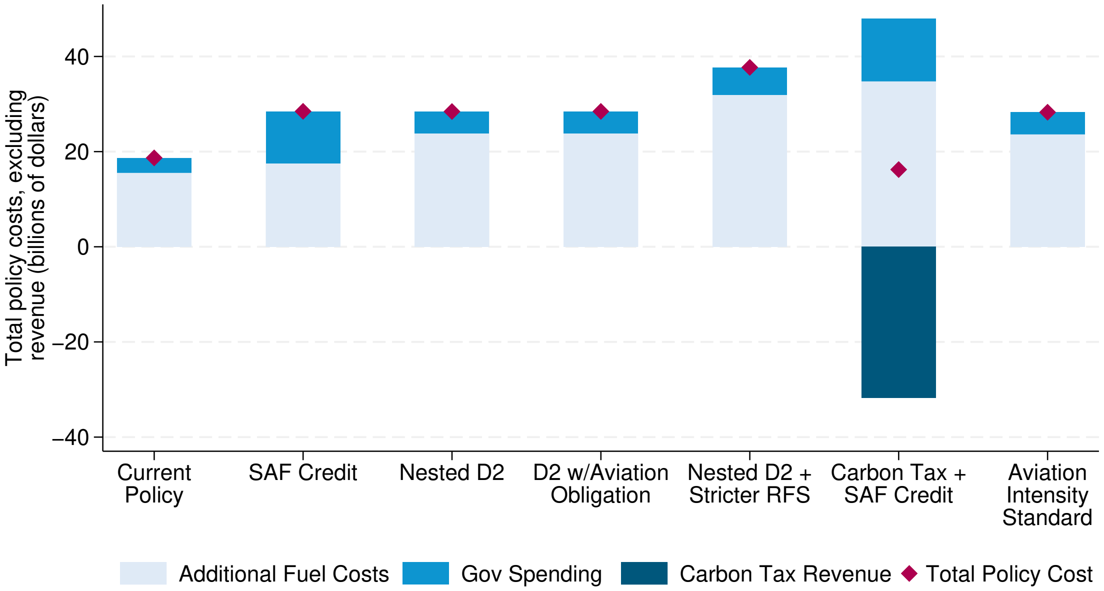

FIGURE 6: Policy cost breakdown across policy scenarios

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

The distribution of policy costs across drivers, air passengers, and taxpayers both within and outside of California depends importantly on the policy approach employed for achieving the SAF target (see Figure 6). The relative costs imposed on drivers, airline passengers, or taxpayers depends 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.

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 of the policies: the SAF tax credit policy because the burden falls on taxpayers, and the nested D2 policies that don't impose a compliance obligation on petroleum jet fuel, which place the burden on consumers of gasoline and diesel. For all policies capable of reaching 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 consumers of gasoline and diesel, even though they use only about 10% of the nation's gasoline and diesel. By comparison, California drivers bear approximately 21% of the on-road cost burden in the current policy scenario. This extra burden is due to additional incentives for SAF outside of California increasing competition for SAF and bio-based diesel feedstocks, resulting in higher credit prices under the LCFS needed to meet the standard

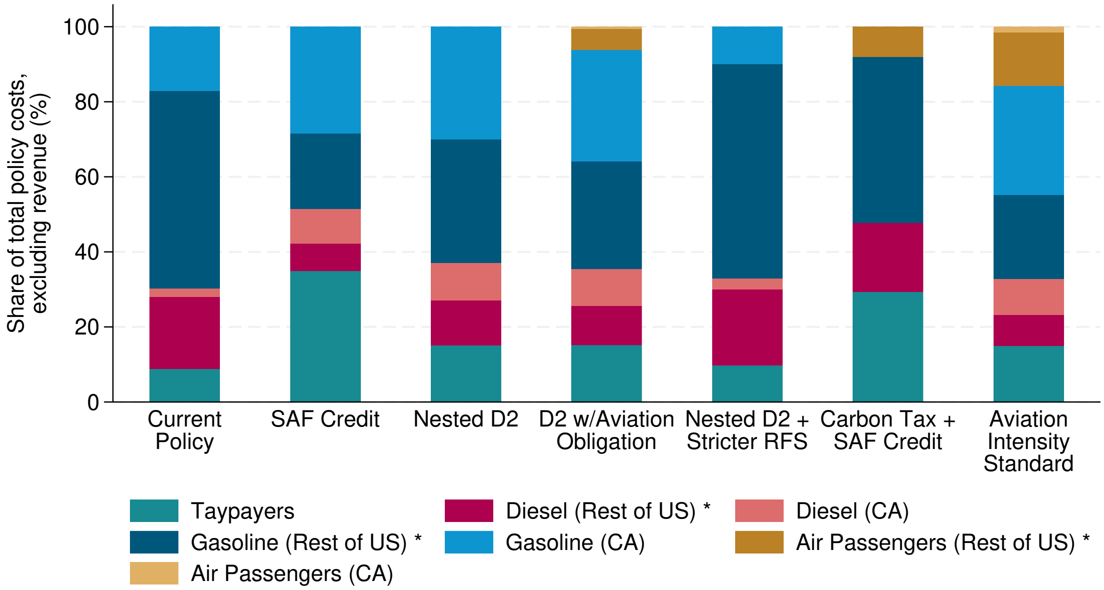

FIGURE 7: Policy cost distribution shares across policy scenarios (excluding tax revenue)

Notes: This figure shows the distribution of policy cost (excluding carbon tax revenue) under different policy scenarios. 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. 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 bio-based diesel that make it more costly to meet the California LCFS standard.

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 gasoline prices by $0.15 per gallon and jet fuel by $0.17 per gallon. However, scenarios with low impacts on blended fuel prices may simply be shifting policy costs from drivers to taxpayers, as illustrated in Figure 6.

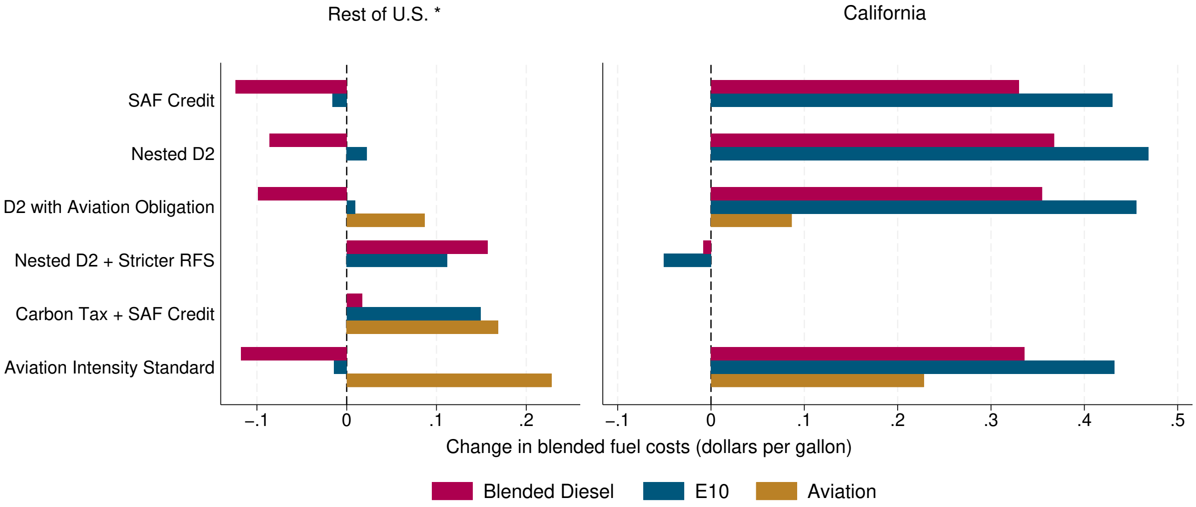

Figure 8: Blended fuel cost impacts relative to current policy

Notes: This figure shows changes in fuel cost relative to current policy scenario across fuel types resulting from each policy scenario. 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.

4.3 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 imported Brazilian 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, overall vegetable oil demand declines by 11%, demand for fats, oils, and greases falls by 18%, while corn demand rises by 9% and sugarcane demand increases by 80%. With a more stringent RFS, total feedstock demand increases by 29% 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 roughly 44% to 49% of SAF production across scenarios. However, when the RFS stringency is increased such that SAF production is additional to mandated road transport biofuel levels, ATJ corn + CCS makes up 88% of SAF production. Under current policy scenario, all SAF are produced through ATJ pathway. This illustrates how the structure of biofuel incentives and competition between feedstocks will have important implications for the SAF pathways that gain market share. Moreover, dramatically increasing biofuel mandate levels raises feedstock demand largely met by crops, which raises concerns around land-use

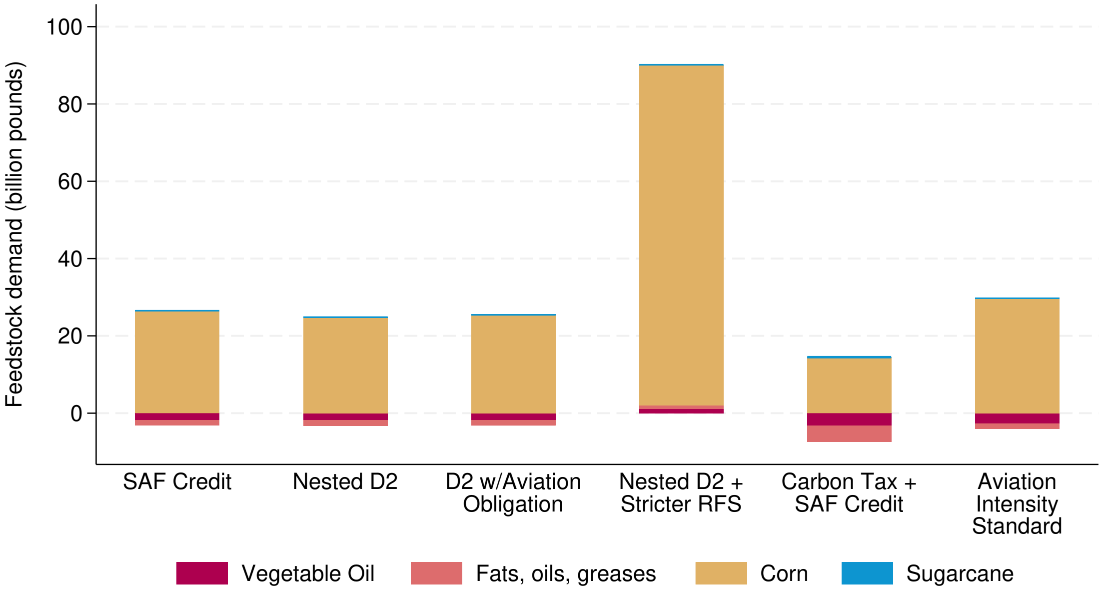

FIGURE 9: Changes in feedstock demand by scenario relative to current policy

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

change and interactions with food markets.

Only under the carbon tax policy scenario where existing biofuel support policies are replaced by a carbon tax and SAF tax credit do we see a decline in demand across feedstocks. This scenario drives emissions reductions from decreasing transportation demand to a greater extent than substituting lower-carbon fuels. The SAF target is met by the tax credit, and there is a 80% reduction in biomass-based diesel fuel consumption relative to current policy.

5 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 means 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. Reaching 3 Bgal of SAF by 2030 has significant costs, and the choice of policy approach adopted can have important effects on emissions, prices, cost and 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 RIN category for SAF, yield similar average abatement costs to current policy and a 40-46% increase in emissions reductions. Adding a federal SAF credit to existing policy yields 22% more emissions reductions than current policy at a 25% higher average abatement cost.

Combining the addition of a new RIN category for SAF with a stricter RFS yields a substantial increase in emissions reductions (110%) relative to current policy at a similar average abatement cost. The only scenario we examine that results in both an increase in emissions reductions and 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 85% increase in emissions reductions at an average abatement cost of $216 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. Recent research indicates that while learning rates for ethanol have been substantial, learning in biodiesel and renewable diesel has been comparatively lower (Scott, 2025). Whether bio-based aviation fuels or alternative fuel production pathways such as power-to-liquids can significantly decrease costs in the medium to long-term, 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. 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; some of the hypothetical policies we study that incentivize SAF production do not contribute to substantial near-term reductions in average abatement cost but may help lower future costs in a hard-to-decarbonize sector by promoting innovation.

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A1 Estimate Greenhouse Gas Emissions of Biofuels

Table A1: Carbon Intensity (CI) in gCO$_2$e/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	35.78	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	73.20	49.60	19.80	69.40	40.17	5.78	45.95	42.81	5.78	48.59
		Sugarcane	31.02	5.07	36.09	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 pathways and average estimates are unavailable for any ATJ pathways in CA-GREET.

Table A1 presents lifecycle analyses of greenhouse gas emissions using different Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) models. The well-to-wheel analysis is 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.[20] 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$_2$e/MJ.[21] For all other pathways, we use the mean carbon intensity values for "generally applicable pathways". Our lifecycle 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 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

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[20] 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.

[21] 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.

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.[22] 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 § 45Z, 2022).[23] 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 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.[24] 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 (Wang et al., 2023; Yoo, Lee, and Wang, 2022). However, the precise quantity of CO_2 that can be

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

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

[24] 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.

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, since 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. The main source of this divergence 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.

It is also important to note that recent revisions to the Clean Fuel Production Credit have removed ILUC from carbon intensity (CI) calculations (Pub. L. 119-21 § 70521, 2025). Accordingly, we apply the 45ZCF-GREET model—excluding ILUC emissions—when determining eligibility for the 45ZCF tax credit.

A2 Feedstock supply calibration

We calibrate the model to the years 2018-2023. For residual supply elasticities, we plug the actual values in Table A2 into equation 22 and solve for residual price elasticity relevant to biofuel production. We also compute supply curve parameters (α) for each feedstock type using equation 23.

$$\beta_s^{Biofuel} = \frac{Q_s^{All}}{Q_s^{Biofuel}} \beta_s^{All} - \frac{Q_s^{Other}}{Q_s^{Biofuel}} \beta_s^{OtherD} \tag{22}$$

$$\forall s: \quad Q_s^{Biofuel} = \alpha_s P_s^{\beta_s^{Biofuel}} \tag{23}$$

Table A2: 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).[25] We determine the volume-weighted average blended price for crop-based vegetable oils by utilizing supply and price information provided in Table 7 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 7. Feedstock quantities used in biofuel production are aggregated to the annual level using Monthly Biofuels Capacity and Deedstock Updates from the U.S. Energy Information Administration (EIA).[26]

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 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 (The White House, 2025b), followed by a further announcement on July 30, 2025, of an additional 40% ad valorem tariff specifically on certain Brazilian goods (The White House, 2025a). The impact of these new duties is incorporated into equation 3.

With six years of historical data available, we estimate six separate sets of feedstock supply curve parameters, as presented in Table A3. 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,

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[25] Data are available at: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/documentation.

[26] Data are available at: https://www.eia.gov/biofuels/biomass/.

our model does not explicitly account for these fluctuations.

Table A3: Estimated feedstock supply curve parameters (2018-2023)

	Crop-based veg oils		**Corn**		**Tallow and waste oils**		**Sugarcane**	
Year	$\boldsymbol{\beta_{biofuel}}$	$\boldsymbol{\alpha}$	$\boldsymbol{\beta_{biofuel}}$	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$	$\boldsymbol{\alpha}$
2018	0.91	32.26	1.03	1.42	2	30.24	1.1	0.000135
2019	0.93	30.09	1.12	1.18		23.74		0.000321
2020	0.89	17.38	1.17	0.79		16.51		0.000331
2021	0.80	15.90	1.10	0.70		14.19		0.000069
2022	0.64	20.02	1.03	0.75		11.04		0.000107
2023	0.63	31.85	1.07	1.00		22.87		0.000023

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 –.

A3 Fuel demand

A3.1 Travel demand estimates

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 data are obtained from the Federal Reserve Bank of St. Louis.[27]

$$ln(Travel\_Demand) = \alpha + \beta ln(GDP) \tag{24}$$

We obtain U.S. total vehicle-miles traveled (VMT) data from the Federal Highway Administration (FHWA).[28] The FHWA classifies vehicles into light-duty vehicles (short wheelbase and long wheelbase),[29] 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 Energy Information Administration Annual Energy Outlook, 2025 and by the California Air Resources Board (CARB) in the 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 A4 provides a mapping of FHWA vehicle types to those used by EIA and CARB.

There exists 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

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[27] 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.

[28] Data available at https://www.bts.gov/content/us-vehicle-miles.

[29] 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.

trucks and all combination trucks are heavy-duty trucks.

TABLE A4: 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.[30] 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' foregin 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.[31] With a few country-level 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.[32] 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 A5 presents the results from estimating the regression of travel demand variables on real GDP, as specified in equation 24.

TABLE A5: 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	2.18	0.53

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

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[30] Data were downloaded from https://www.transtats.bts.gov/Data_Elements.aspx.

[31] Data is obtained from https://www.icao.int/CORSIA/CCR.

[32] Data retrieved from https://www.transtats.bts.gov/traffic/.

presented in Table 7.

A3.2 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.[33] For light-duty ICE vehicles, fuel efficiency is adjusted to account for a 1.24% penetration of battery electric vehicles.[34] 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.[35]

For U.S. passenger and cargo-only airlines, we estimate fuel economy using monthly data on airline fuel consumption and revenue passenger/ton miles.[36] An annual fuel economy improvement rate of 1.5% is assumed for the aviation sector.[37]

Table A6 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 A6: 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[38]	
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[39]	0.73
HDV	Diesel	mpg diesel equiv	6.68	1.0%	7.16	7.03
	Electric	mpg kw equiv	0.42		0.50[40]	0.38
	Hydrogen	mpg kg equiv			9.30[41]	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	

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[33] 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.

[34] Data on electric vehicle share in the total light-duty vehicle fleet are published by the Alternative Fuels Data Center: https://afdc.energy.gov/vehicle-registration.

[35] Increase in average fuel economy is calculated from historical data (2000–2022).

[36] Data for airline fuel cost and consumption sourced from https://www.transtats.bts.gov/fuel.asp.

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

[38] Average fuel economy for battery electric vehicle is 3.6 mi/kWh in year 2019, shown in https://afdc.energy.gov/vehicles/electric-emissions-sources. We used the estimate in the ICCT report, shown in https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

[39] We used data from ford E-transit and REE automotive P7. These companies are several prototypes that develop medium electric vans based in US.

[40] 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

[41] We used estimate in the ICCT report, shown in https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/.

A3.3 Fuel demand calibration

We assume that on-road and aviation travel demand in California constitutes a constant proportion of the total U.S. travel demand. California's share of vehicle miles traveled (VMT) is determined using its actual 2023 figures from Table PS-1 of the Federal Highway Administration Highway Statistics Series, with the state representing about 9.63% of light-duty VMT and 10.79% of medium- and heavy-duty VMT. For aviation, California's share is estimated at 17% of total U.S. jet fuel consumption, based on 2023 data from Table F2 of the Energy Information Administration State Energy Data System.

We project fleet composition in California using the 2022 Scoping Plan Scenario. For regions outside California, we apply the AEO 2025 projections. As AEO includes hydrogen and other alternative technologies, we adopt an 11.5% light-duty battery electric vehicle penetration rate for the U.S. in 2030, as reported by Woody, Keoleian, and Vaishnav, 2023. The composition of vehicle types in California and in the rest of the U.S. is summarized in Table 8.

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

By combining the fuel economy values for on-road ICE vehicles, electric vehicles, and hydrogen trucks from Table A6 with the projected travel demand by region and vehicle type (as shown in Tables 7 and 8), 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 A7. 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 A7: Projected 2030 Fuel, Transportation Electricity, and Hydrogen Demand (in Billions)

Series	**Region**	**Mean**	**90% coverage**	**67% coverage**
Gasoline (gallons)	CA	11.15	(11.02,11.27)	(11.09 ,11.21)
Diesel (gallons)		4.10	(4.02,4.19)	(4.06, 4.15)
Jet fuel (gallons)		4.24	(4.11,4.36)	(4.18, 4.30)
Electricity_LDV (kWh)		14.30	(14.16,14.44)	(14.23, 14.38)
Electricity_MDV (kWh)		1.12	(1.10,14.80)	(1.11, 1.14)
Electricity_HDV(kWh)		1.60	(1.57,1.15)	(1.58, 1.61)
Hydrogen_HDV (kg)		0.08	(0.07,0.08)	(0.07 0.08)
Gasoline (gallons)	Rest of U.S.	112.09	(110.87,113.28)	(111.51, 112.75)
Diesel (gallons)		37.35	(36.56,38.12)	(36.97, 37.77)
Jet fuel (gallons)		20.69	(20.09,21.28)	(20.40, 21.01)
Electricity_LDV (kWh)		81.60	(80.76,82.41)	(81.20, 82.04)
Electricity_MDV(kWh)		1.73	(1.69,1.78)	(1.71, 1.76)

We calibrate the fuel demand curves in equation 57 by using the projected fuel demand values from Table A7 and fuel demand elasticities reported in the literature, as summarized in Table 6. 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 A8.

TABLE A8: Esimtated 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)

A4 Policy constraints

A4.1 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) 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 25. Specifically, the percentage standard for the D2 pool is calculated as follows:

$$\phi_{D2} = \frac{1.6RFV_{D2}}{\text{TotalFF}} \tag{25}$$

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:

$$\text{PolicyCost}_{FF}^{RFS} = \phi_{D2}P_{D2} + (\phi_{D4} - \phi_{D2})P_{D4} + (\phi_{D6} - \phi_{D4})P_{D6} \tag{26}$$

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 billion gallons.

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:

$$\text{PolicyCost}^{RFS}FF = \phi_{D2}P_{D2} + \phi_{D4}P_{D4} + (\phi_{D6} - \phi_{D2} - \phi_{D4})P_{D6} \tag{27}$$

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

A4.2 Tax incentives

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 total shown in Table A7.

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.

Based on maxium eligible fuel quantity shown in Table A9, we get the step-wise state tax credit structure shown in Table A10. 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

Table A9: Announced SAF production capacity and maxium 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

into our model as a step function, as described in equation 18.

Table A10: 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

A4.3 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 A11. 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 production and consumption of SAF to qualify for these incentives.

Table A11: Step-wise state-level tax function if LCFS and state tax credit interacts

(a) Case 1: LCFS for per gallon SAF exceed 1.5 dollars and CA LCFS can take in all IA/NE 0.0406 volume

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 for per gallon SAF exceed 1.5 dollars and CA LCFS can not take in all IA/NE 0.0406 volume

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

A5 Model implementation

A5.1 Equations to solve:

A5.1.1 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:

$$\max_{Q^j_{f,s}} \text{Profit}(Q) = \max_{Q^j_{f,s}} \sum_j \sum_{f,s} [P^j_f Q^j_{f,s} - C^j_{f,s} Q^j_{f,s} - \text{PolicyCost}^j_{f,s} \cdot Q^j_{f,s}],$$

$$\begin{aligned} s.t. \quad & Q^j_{f,s} \geq 0, \quad \forall \{f,s,j\} \\ & \sum_s Q^j_{f,s} \leq \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j}, \quad \forall \{f,j\} \\ & \sum_j Q^j_{SAF,s} \leq \frac{0.55}{0.25} \sum_j Q^j_{RD,s} \quad \text{for all } s \in \{vegoil, fatsgreases\} \end{aligned}$$

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 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 the optimization problem are:

Stationarity conditions (totaling 24 equations):

$$\forall\{f,s,j\} : P_f^j = \text{PolicyCost}_{f,s}^j + C_{f,s}^j - \mu_{f,s}^j + \nu_f^j + \text{HEFA}_{s \in \{vegoil, fatsgreases\}} \tag{28}$$

where $\mu_{f,s}^j$, ν_f^j, 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):

$$\forall\{f,s,j\} : \mu_{f,s}^j Q_{f,s}^j = 0 \tag{29}$$

$$\forall\{f,j\} : \nu_f^j \Big(\sum_s Q_{f,s}^j - \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j} \Big) = 0 \tag{30}$$

$$\text{for all } s \in \{vegoil, fatsgreases\} : \text{HEFA}_s \Big(\sum_j Q_{SAF,s}^j - \frac{0.55}{0.25} \sum_j Q_{RD,s}^j \Big) = 0 \tag{31}$$

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

$$\forall\{f,s,j\} : Q_{f,s}^j \geq 0 \tag{32}$$

$$\forall\{f,j\} : \sum_s Q_{f,s}^j \leq \overline{BL_{f,j}} \cdot Q_{\mathcal{F},j} \tag{33}$$

$$\text{for all } s \in \{vegoil, fatsgreases\} : \sum_j Q_{SAF,s}^j \leq \frac{0.55}{0.25} \sum_j Q_{RD,s}^j \tag{34}$$

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

$$\forall\{f,s,j\}: \mu^j_{f,s} \geq 0 \tag{35}$$

$$\forall\{f,s,j\}: \nu^j_f \geq 0 \tag{36}$$

$$\text{for all } s \in \{vegoil, fatsgreases\}: \text{HEFA}_s \geq 0 \tag{37}$$

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:

$$\forall\mathcal{F}: \quad P^j_{\mathcal{F}0} = \overline{PC_{\mathcal{F}0}} + \text{PolicyCost}^j_{\mathcal{F}0}. \tag{38}$$

Feedstock supply is modeled using a constant elasticity supply function. Residual supply elasticities specific to biofuel production are calculated as described in Section A2. The relevant equations, totaling 4, are provided below::

$$\forall s: \quad Q^{Biofuel}_s = \alpha_s P_s^{\beta_s^{Biofuel}} \tag{39}$$

A5.1.2 Fuel demand

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

$$\forall\{\mathcal{F},j\}: \quad Q_{\mathcal{F},j} = \alpha^D_{\mathcal{F},j} P_{\mathcal{F},j}^{\beta^D_{\mathcal{F}}} \tag{40}$$

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).

$$\forall\{\mathcal{F},j\}: \quad P_{\mathcal{F},j} = \frac{Q^j_{\mathcal{F}0} \cdot P^j_{\mathcal{F}0} + \sum_{f\in\mathcal{F}} Q^j_{f,s} \cdot P^j_f}{Q^j_{\mathcal{F}0} + \sum_{f\in\mathcal{F}} Q^j_{f,s}} \tag{41}$$

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

$$\forall f \in \{B100, RD, SAF\} : P_f^j = \phi_f P_{\mathcal{F}0}^j \tag{42}$$

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):

$$\forall j, \quad P_{E100}^j = \theta P_{\mathcal{G}0}^j \Big[1 - \mathbb{1}\Big(\frac{\sum Q_{E100,s}^j}{\sum Q_{E100,s}^j + Q_{\mathcal{G}0}^j} \geq 0.1 \Big) \Big(e^{\Big(\frac{\frac{\sum Q_{E100,s}^j}{\sum Q_{E100,s}^j + Q_{\mathcal{G}0}^j} - 0.01}{0.02} \ln 2 \Big)} - 1 \Big) \Big] \tag{43}$$

where P_{E100}^j is the price of ethanol in region j and $Q_{E100,s}^j$ 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.

A5.1.3 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:

$$\sum_{f \in (B100, RD, SAF), s} Q_{f,s}^j \geq RFV_{D4} \tag{44}$$

$$\sum_{f,s} \kappa_f Q_{f,s}^j \geq RFV_{D6} \tag{45}$$

$$P_{D4} \geq P_{D6} \tag{46}$$

$$P_{D6} \geq 0 \tag{47}$$

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):

$$P_{D6}(\sum_{f,s} \kappa_f Q^j_{f,s} - RFV_{D6}) = 0 \tag{48}$$

$$(P_{D4} - P_{D6})(\sum_{f \in (B100,RD,SAF),s} Q^j_{f,s} - RFV_{D4}) = 0 \tag{49}$$

The LCFS constraint is formulated as the following inequality:

$$\sum CI_{decifits} \leq \sum CI_{credits} \tag{50}$$

$$P_{LCFS} \leq \overline{P_{Cap}} \tag{51}$$

$$P_{LCFS} \geq 0 \tag{52}$$

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 3.3.3 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):

$$P_{LCFS} \cdot (P_{LCFS} - \overline{P_{Cap}}) \cdot (\sum CI_{decifits} - \sum CI_{credits}) = 0 \tag{53}$$

$$P_{LCFS} \cdot (\sum CI_{decifits} - \sum CI_{credits}) \geq 0 \tag{54}$$

$$(P_{LCFS} - \overline{P_{Cap}}) \cdot (\sum CI_{decifits} - \sum CI_{credits}) \geq 0 \tag{55}$$

A5.1.4 Market clearing conditions:

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

$$\forall s: \quad Q_s = \sum_j \sum_{f \in \{f:\ f\text{-}s\ is\ feasible\}} \theta_{f,s} Q^j_{f,s} \tag{56}$$

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

$$\forall\{\mathcal{F}, j\}: \sum_{f\in\mathcal{F},s} Q^j_{f,s} + Q^j_{\mathcal{F}0} = \overline{Q^j_{\mathcal{F}}} \tag{57}$$

A5.1.5 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 3.3. 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.

A5.2 Numerical solver

A5.2.1 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:

$$a \leq M_a y$$

$$b \leq M_b(1 - y)$$

$$a \geq 0$$

$$b \geq 0$$

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:

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

A5.2.2 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.