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Forecasting Credit Supply Demand Balance for the Low-Carbon Fuel Standard Program

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A Research Report from the University of California Davis Energy Economics Program

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Glossary

BAU	business as usual
BBD	biomass-based diesel
CARB	California Air Resources Board
CARBOB	California reformulated blendstock for oxygenate blending
CaRFG	California reformulated gasoline
CCS	carbon capture and sequestration
CI	carbon intensity
EIA	Energy Information Administration
EMFAC	EMission FACtors (EMFAC): a model to calculate statewide or regional emissions inventories
EER	energy economy ratio
EV	electric vehicle
GSP	gross state product
LCFS	low carbon fuel standard
ULSD	ultra-low sulfur diesel
VEC	vector error correction
VMT	vehicle miles traveled
ZEV	zero-emission vehicle

Executive Summary

In this report, we present our projections for the expected supply of and demand for Low Carbon Fuel Standard (LCFS credits) through 2030, as well as through 2035, based on potential changes to program stringency. Our main approach is to apply time-series forecasting methods to project the expected demand for transportation fuels and combine that with the expected evolution of fuel prices and carbon intensities as well as complementary policies' impact on the fuel mix.

The prospects for success in achieving more aggressive LCFS targets by 2030 will also be highly dependent on several factors for which historic trends provide less insight. These factors include the following.

- The pace of adoption and usage of both light-duty and heavy-duty ZEV vehicles.
- The future role played by biomethane supplied from farms and other sources.
- The pace of adoption of technologies such as Carbon Capture.
- The ability of suppliers to supply and distribute extremely high amounts of renewable diesel (RD) into California's diesel pool.

Our results provide statistically valid distributions of LCFS demand drivers and of credit balances given the assumptions used for a specific scenario on factors such as ZEV usage and carbon intensities. We also examine how those distributions change under a range of alternative assumptions regarding these factors. The credit balance distributions across those scenarios are what conveys the truly broad range of possible outcomes for the LCFS. The range of these distributions grows substantially after 2030, illustrating the fact that there is massive uncertainty about the program beyond the next half decade.

Our results imply that the program can accommodate a relatively aggressive target of a 43% reduction by 2035, but only if everything breaks right and many best-case outcomes arise toward the middle of the next decade. By contrast, if ZEV penetration falls well below targets, the program could reach cumulative deficits of 60 to 100 MMT by 2035. Our median forecast of our baseline scenario, targeting 30% carbon intensity reduction by 2030 and 43% by 2035, forecasts a small but significant cumulative deficit by 2035.

Under such circumstances, the role of cost-containment mechanisms will be critical for determining LCFS prices, and likely the overall viability of the program. We have assumed that LCFS prices will hit the containment price currently in place, now roughly $239/ton in 2022 Dollars. However current policy is designed to contain prices only during transitory credit shortages not chronic shortages that result in compounding deficits accumulating over multiple years. In this sense, our price forecasts represent a lower bound on pricing outcomes in scenarios where there are no compliance options viable at a cost of $239 or lower.

1 Introduction

State and local policy makers in the U.S. and beyond are looking to low carbon fuel standards (LCFSs) as a policy instrument for reducing greenhouse gas emissions in the transportation sector. California implemented its LCFS in 2011, setting a target of a 10% reduction in carbon intensity (CI) values for transport fuels used in the state by 2020 from 2011 levels, as part of its climate policy. The target has since been updated to a 20% reduction below 2011 levels by 2030. British Columbia has had an LCFS in effect since 2011, extended from 10% CI reduction from 2010 levels in 2020, to 20% in 2030, and an update for targets to 2030 and their extension into the 2030s were brought under consideration in a stakeholder process starting in early 2023, with suggestions for targets bracketing a highlighted case of 30% in 2030, 43% in 2035, and 65% in 2040, all converging to 90% in 2045. Oregon fully implemented its LCFS, the Clean Fuels Program (CFP), in 2016, seeking to reduce CI values of Oregon transportation fuels by 10% from 2015 to 2025. In 2022, Oregon extended its targets to 20% reduction below 2015 levels by 2030, and 37% by 2035. [1,2] Washington State passed legislation to implement a Clean Fuel Standard (CFS) in 2021 after several prior attempts had failed. The CFS began in 2023, and targeted a 10% reduction in CI values of state transportation fuels below 2017 levels by 2031, and 20% by 2034 (maintaining that level through 2038).[3] Canada also has an LCFS-like program, and began a phased implementation of its Clean Fuels Regulations (CFR) in 2022. The CFR targets an approximately 15% reduction in the CI score of transportation fuels by 2030.[4] Brazil also has a transportation CI reduction program, RenovaBio, which includes many features of an LCFS and began in 2020.[5] Other U.S. states have also investigated or continue to have legislative efforts for LCFS-like programs.[6]

The history of the LCFS regulation to date includes legal challenges linked to the way it differentiates fuels originating in different locations and extensive debates about the life-cycle calculations used to establish the carbon intensity scores assigned to the different fuels used for compliance. How to assess and address indirect land use effects caused by biofuels, in particular, have remained controversial in LCFS regulations. In the late 2010s especially,

[1] See https://www.oregon.gov/deq/aq/programs/Pages/Clean-Fuels.aspx for more information on the Oregon CFP.

[2] See also Witcover and Murphy 2021.

[3] See https://washingtonstatewire.com/whats-next-for-a-low-carbon-fuel-standard/ for the legislative history, and https://ecology.wa.gov/Air-Climate/Reducing-Emissions/Clean-Fuel-Standard for more information on the Washington CFS.

[4] See https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/clean-fuel-regulations.html for details on the Canada program, https://decarbonisation.uqam.ca/wp-content/uploads/sites/10/2022/10/WitcoverEtAl_JCCTRP_WG5_2022_Final_6oct2022.pdf for a comparison of the regulation in Canada with those in California, Oregon, and British Columbia.

[5] For more on RenovaBio implementation to date, see https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_BR2022-0047.pdf and https://www.bloomberglinea.com/english/doubts-surround-renovabio-brazils-top-market-for-carbon-credits/.

[6] For a summary as of 2022, see https://www.spglobal.com/commodityinsights/en/ci/research-analysis/policies-that-create-incentives-for-biofuels.html.

increasing costs of compliance in California raised concerns about both the efficiency of the regulation and its potential impact on fuel prices. Such concerns, combined more recently with fuel price increases associated with the war in Ukraine, contributed to the rejection of the LCFS mechanism in some states.

In the 2010s, partly in response to concerns over compliance costs, and partly in an effort to spur more innovation, new dimensions were added to the LCFS. They included, among other steps, expanded use "book-and-claim," an accounting mechanism that allows fuels transported by common carrier, like bio-methane and electricity from low carbon sources, to be physically consumed in one location and allowed to generate LCFS credits used for compliance elsewhere via a paper contract.[7]

Since 2020, however, the California LCFS compliance credit price underwent a significant price decline from near-highs to levels not seen for several years. The credit price drop accompanied increased volumes in several alternative fuels, including book-and-claim fuels biomethane and electricity, especially those receiving very low carbon intensity scores, as well as renewable diesel, a drop-in fossil diesel alternative made from lipid feedstocks with rapidly expanding production capacity.[8] Amid the credit price decline, the California Air Resources Board (CARB),the regulatory authority for the LCFS, signaled interest in tightening existing LCFS annual CI reduction targets through 2030 to reach more than 20% CI reduction, in addition to plans to extend targets past 2030 to align with the state's ambitious climate targets by mid-century. A stakeholder process began in late 2021 and continued through 2022, in which CARB aired several ideas for consideration and development in a planned 2023 regulatory amendment process. In addition to the extended/expanded targets, ideas on the table going into 2023 included (in no particular order):

- Tightening 2030 targets to between 25% and 35% CI reduction, extending to 2035 targets between 39% and 51% (and between 60% and 70% CI reduction targets in 2040, to align with state plans to meet targets);
- Placing limits on crop-based fuels in the diesel pool (over concerns about potential impacts on land use change and food prices from expanding use of soy for renewable diesel);
- Adding deliverability requirements for biogas use of book-and-claim eligibility and phasing out credit for avoided methane emissions behind the currently highly negative CI scores for biogas from animal manure sources (to better align with state plan priorities for biomethane use outside transportation);

[7]Additional expansions in California include allowing off-road fueling equipment using electricity or hydrogen, and alternative jet fuel to generate LCFS credits, as well as awarding LCFS credits for new infrastructure capacity for electric vehicle (EV) charging and hydrogen fueling, decoupling credit generation from fuel consumed within the state for the first time. These new credit generation sources could affect both the long run credit price and its transmission through to various types of fuels, if sufficient credits are generated to alter the long-run marginal options for compliance.
[8]Travel decreases due to the onset of the COVID pandemic likely also eased LCFS compliance due to lower petroleum fuel use, especially for gasoline, responsible for most emissions tallied in California's program.

- Extending the fast-charging and hydrogen fueling capacity credits to include medium- and heavy-duty infrastructure beyond the current light-duty crediting (to promote a shift to ZEV technologies in all on-road sectors, in line with recent CARB regulatory efforts);
- Adjusting crediting for electricity used offroad in lighter forklifts (less than 12,000lbs) in light of rapid electrification of this use and impending regulatory changes that would require ZE technologies for this application before 2030;
- Phasing out petroleum-based crediting for projects other than carbon capture and sequestration (CCS);
- Limiting crediting of direct air carbon capture and sequestration to within the U.S.; and
- Incorporating intrastate fossil jet fuel as an obligated fuel under the LCFS (to promote state goals to decarbonize aviation).

In this report, we assess if and how California is likely to achieve the central proposed value of 30% reduction in CI values by 2030 (and 43% by 2035), and summarize evaluations of other alternative 2030 targets from 25% through 35% (each with a higher associated 2035 target). We present results for the regulation largely as is, that is, without the changes listed above, to anchor the rulemaking discussion. We follow a general methodology similar to that used in Borenstein et al. (2019) for the California cap-and-trade program, extending and modifying its application to the LCFS from earlier work,[9] which evaluated the original 20% CI reduction targets for 2030 using data available through 2018. We apply time-series econometric methods to account for uncertainty in demand under "business-as-usual" (BAU) as indicated by historical data on a range of key variables. We begin by projecting a distribution of demand for fuel and vehicle miles under BAU economic and policy variation, which we define as continuation of the trends and correlations since 1987. We then transform those projections into a distribution of LCFS net deficits for the entire period from 2022 through 2035, assuming a steady drawdown of accumulated credit "bank" going into 2022. The distribution of net deficits illustrates a range of possibilities of demand for LCFS credits based on historical trends. Next, we generate LCFS credit supply scenarios that consider a variety of assumptions about inputs, technology, and the efficacy of complementary policies. By interacting projections of demand and various supply scenarios for LCFS credits, we can characterize the equilibrium number of credits generated under varying policy conditions and, furthermore, illustrate changes in the fuel mix that would be necessary to achieve compliance assuming that, as now, renewable diesel remains the marginal compliance fuel.

For sources of credit generation not yet prevalent in the policy, we base decisions on California Air Resource Board (CARB) modeling used in its 2022 Scoping Plan. In particular we use Scoping Plan projected penetration of electric battery and hydrogen fuel cell vehicles into the heavy-duty fleet, which incorporates assumptions about implementation of California's primary regulations to encourage ZEVs in this duty sector, namely Advanced Clean Trucks and Advanced Clean Fleets regulations, the latter of which is still in process. State policies impacting the

[9] See, https://escholarship.org/uc/item/7sk9628s.

demand side such as vehicle efficiency standards and target reductions in vehicle miles traveled are not explicitly modeled, although the modeled uncertainty in the BAU scenario takes account of past trends in these variables and allows for considerable variability. Targeted scenario modeling of demand side policies and additional supply side policies is a possible area for future research.

The remainder of this report is structured as follows. Section 2 describes the background of the California LCFS, including the history of the policy, recent trends, and the economic mechanisms through which CI standards influence markets. In section 3, we describe our data and econometric model used to forecast BAU demand for LCFS credits and discuss the projected demand-related outcomes. In section 4, we describe our compliance scenario methods and assumptions used to translate our forecast variables into LCFS credit and deficit projections, showcasing a baseline run that reaches 30% CI reduction in 2030 (and 43% in 2035). In section 5 we present results of this baseline scenario. We first discuss projected credit and deficit values under our baseline assumptions, and then translate those projections into projected LCFS credit prices. In section 6, we provide results for alternative scenarios, including alternate targets. Finally, in section 7, we conclude by discussing the implications of our analysis and highlighting opportunities for future research.

2 Background: the California LCFS

The California LCFS was initially implemented in 2011, amended in 2013, re-adopted in 2015, extended in 2019 to set targets through 2030, and in 2023 began rulemaking for tightening targets for the remainder of the 2020s and extend them well into the 2030s. The LCFS is a standard whereby providers of transportation fuel (e.g., oil companies and refiners) are required to reduce the carbon intensity (CI) of their fuel mix each year. Each year, the average CI score of fuels reported used in the state must be reduced further below the CI of a petroleum-based reference fuel (e.g., 0.25% below the reference fuel in 2011 to 20% below in 2030). The reference fuels are diesel, E10 gasoline (CaRFG in California), and, from 2019 forward, jet fuel. The LCFS falls within a general regulatory framework known as intensity standards. It regulates the carbon intensity of transportation fuels measured in CO_2e per megajoule of energy, rather than the total amount of CO_2 released from a fuel.

As with all intensity standard mechanisms, the LCFS implicitly subsidizes the sales of fuels that are 'cleaner'—that is, lower in carbon intensity—than the standard, and pays for the subsidy through charges imposed on fuel that is 'dirtier' than the standard (CI rating above the standard). Sales of individual fuels rated at a CI below the standard generate credits, and sales of fuels rated at a CI above the standard generate deficits, in amounts proportionate to volumes. The LCFS requires annual compliance by regulated entities; all incurred deficits must be met by credits generated by production of low-carbon fuels or purchased from creditholders. The units of LCFS credits are dollars per metric ton of CO_2e. LCFS credits can be banked without limit, allowing overcompliance under less stringent standards to help cover increased obligations as the standard grows more stringent, and they are fungible—meaning credits generated in any fuel pool, that is, used rather than each of the reference fuels listed above, are treated equivalently.

One of the attractions of policies like the LCFS to the policy community is that these subsidies and charges work to partially offset each other and, along with allowing carbon emissions up to the level of the standard without penalty, dilute the pass-through of the implied carbon cost to retail fuel prices. This 'feature' of the LCFS has also been criticized by environmental economists, who note that the dilution of the carbon cost works to encourage more fuel consumption than would arise under alternative instruments such as a carbon tax.[10] In an extreme case, the subsidy of 'cleaner' fuel could spur consumption growth to the point where the quantity of fuel that is consumed overwhelms the reduction in the carbon intensity of the fuel, and carbon emissions can increase. This extreme case is unlikely as it would require very price-elastic fuel demand. However, the overall point that, relative to other regulations, the LCFS can encourage consumption of fuels has continued to raise concerns in some circles.

CARB set annual standards for the CI of fuels in both the diesel and gasoline pools, and, from 2019, the jet pool, currently through 2030. These annual mandates are shown in the Appendix in Table 10 and Table 11. Since LCFS credits are awarded to fuels with a reported CI rating below the standard, and LCFS deficits to those above the standard, the number of credits or deficits per unit of fuel depends on the CI rating of that fuel. The LCFS is energy-based and thus the number of credits per unit of fuel also depends on factors relating to the energy output of the fuel, namely its energy density.[11] In the case of new alternative fuel/vehicle combinations (such as EVs, methane, and hydrogen), credit generation also depends the powertrain efficiency relative to the reference petroleum fuel used in an internal combustion engine**.**

2.1 LCFS Credit Generation Beyond Liquid Alternative Fuels for On-Road Conventional Vehicles

Early policy development and academic research on the LCFS focused on its characteristic as an intensity standard targeting the marginal costs of fuels. As described above, per unit costs of cleaner fuels would be reduced through the subsidy effect and the costs of dirtier fuels would reflect the cost of acquiring credits. Revisions to California's LCFS program during the 2010s increased options for generating credits beyond direct fueling of non-petroleum fuels into vehicles. Fuels transported in common carrier systems alongside higher carbon fuels, like biomethane (natural gas pipeline) and lower carbon electricity (grid), could be credited via indirect accounting mechanisms, so-called "book-and-claim," that permits credit generation via contracting for low carbon fuel as long as the fuel quantity can be tied to actual fueling from the common carrier network. Off-road applications that use petroleum fuels, like light rail,

[10] See Holland, Hughes, and Knittel 2009.

[11] See Holland, Hughes, and Knittel 2009 for more information regarding energy-based LCFS relative to other types of LCFS. The "energy economy ratio" (EER) policy parameter increases credit generation for a given amount of energy if the fuel/vehicle type is more efficient. In California's LCFS, for example, light-duty EVs and hydrogen fuel cell Table 10Table 10Table 10are credited as displacing additional petroleum fuel (3.4 and 1.9 times, respectively) due to engine efficiency. Other fuel/vehicle combinations have their own parameters. For more on EERs especially in the context of LCFS treatment of EVs and, see https://haas.berkeley.edu/wp-content/uploads/WP318.pdf.

forklifts, cargo equipment, and truck refrigeration, can generate credits for using electricity or hydrogen instead. From 2019, alternative jet fuels with CI scores below the jet standard can also generate credits if onloaded instate (while fossil jet fuel carries no obligation). Steps taken to lower petroleum fuel production – either of crude or refinery improvements – if deemed substantial or innovative enough can earn credits for carbon savings compared to a 'baseline' norm for the operation (so-called petroleum projects), as opposed to with the annual CI standard, as is the case for most fuels. Unused public capacity for electricity fast charging and hydrogen fueling for light-duty vehicles can earn "infrastructure capacity" credits at levels based upon the fueling that would occur if the stations were in complete operation, aiming to support state goals for ZEV infrastructure and vehicle rollout. This last category was the first significant departure of crediting from actual flows of fuel.[12]

2.2 Cost Containment

Initially, there were no formal limits on how high LCFS credit prices could rise, although legal challenges to the regulation effectively delayed implementation, freezing the standard from 2013 through 2015, and effectively limited demand for credits and their pass-through to fuel prices. In its 2015 re-adoption rule, CARB introduced the credit clearance market, which is a cost-containment mechanism that would in theory limit price increases under some scenarios, and set a maximum price for trades in that market. As the lawsuits were resolved in favor of continued implementation of the LCFS and the standard declined steadily in the late 2010s,[13] credit prices rose to close to the price ceiling set by the clearance market through much of 2019 and 2020. Additional cost containment provisions were added in 2020, before credit prices declined from close to its peak in January 2021 to under $90 in the last few months of 2022 into early 2023.[14]

Entities in need of LCFS credits for purposes of immediate compliance can purchase credits in the credit clearance market held at the end of the compliance year at a price no higher than the prescribed maximum of $200 per ton in 2016 and adjusted for inflation thereafter (currently around $240 per ton). If these entities are unable to purchase sufficient credits in this market to reach compliance, then they may carry over their deficits to future periods. Carryover deficits grow by 5% per year, meaning that firms pay an 'interest' penalty for deferring compliance. However, firms that hold credits are not required to sell in the credit clearance market, and they would not do so if they believed that they may be able to sell their credits at a higher price in the future. Thus, the credit clearance market provides only a soft cap.

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[12] The LCFS also allows for credits of direct air carbon capture and sequestration, anywhere, regardless of whether the project has any link to California or its transportation fuels, although credits in this category have yet to be generated.

[13] There was also a court-ruled freeze for the diesel pool standard in 2017-2018; it resumed its trajectory in 2019.

[14] These figures are from regulatory program data tracking reported trades; historical LCFS credit prices can be accessed via the Data Dashboard at the ARB LCFS website: https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard (Figure 4). Trade media sources (Argus and OPIS, depicted in ARB's Figure 4) have recent prices somewhat lower, between $60 and $70, based on partial transaction data gathered through their sourcing. Platts data are displayed on the Neste website: https://www.neste.com/investors/market-data/lcfs-credit-price.

In 2020, CARB imposed a hard price cap of $200 per ton in 2016 dollars for LCFS credit transactions. To help facilitate compliance under this cap, it instituted a mechanism to 'borrow credits' from future residential EV charging if insufficient credits are offered for sale in the credit clearance market to result in compliance. Under this mechanism, utilities earning residential credits must borrow credits to sell to obligated entities that need them for compliance at up to the credit price ceiling. Borrowing can total up to 10 million credits cumulatively (systemwide), and must take place within a six-year window, after which time a predetermined payback schedule begins during which requisite credits are taken from the utilities from those earned for contemporaneous fueling. For example, if credit borrowing were needed in 2025, a window would open that allowed borrowing through 2031, with advanced credit payback occurring 2032—2036. The advanced credit provision essentially shores up the credit ceiling price set for the clearance market.

These cost-containment mechanisms are suited for dealing with a transient disruption in clean fuel supply or some other cause of a short- to medium-term supply-demand imbalance of LCFS credits. Because of the requirement that deficits deferred after the credit clearance market be restored with interest, that mechanism, if needed, would not be effective at containing costs in an environment of chronic, long-term credit supply-demand imbalance. The 10 million "advanced" EV credits thus provide a considerable backstop to the credit price ceiling. Because those credits must be repaid later when the standard is presumably tighter, the potential supply and demand balance may just be deferred, although enough additional EV charging in the future could offset this difficulty. A circumstance where compliance is only feasible through high-cost fuels or sharp reductions in fuel consumption would push credit prices to the maximum credit price for the credit clearance market with a 10 million credit buffer, after which the maximum credit price would be expected to rise further. One objective of this paper is to assess the potential likelihood of outcomes that draw significantly on the advanced credit mechanisms or move beyond that, considering the tighter 2030 (and 2030s) CI targets currently under consideration.

3 Fuel Demand Data and Methodology

This section outlines data and methods used to project business-as-usual (BAU) for LCFS deficit generation as well as credit generation to 2035. In this paper we use the term business-as-usual (BAU) frequently, and take it to mean, regarding LCFS credit demand, the continuation of historical trends through the compliance period. LCFS credit supply, on the other hand, is based on a list of assumptions on current alternative fuel mix trends to 2035. Therefore, the uncertainty in the projections stems from the estimation of BAU demand, which against an assumed state of supply, yields a distribution of net deficits accumulated over the period 2022 to 2035, on which we base subsequent analysis.

3.1 Model of BAU Demand

We are interested in forecasting demand for fuel and vehicle miles under BAU economic conditions. Demand for fuel and vehicle miles are highly dependent on other economic variables. Demand for both fuel and vehicle miles will be influenced by general economic activity and oil prices. In a booming economy, consumers travel more and purchase more fuel. We aim to fit an econometric model that characterizes past trends in key credit demand variables, such as fuel consumption and key input prices for the gasoline and diesel fuel "pools," namely oil price and soybean prices, vehicle miles traveled, and an indicator of the state economy.[15] The estimates from that model are then used to simulate relationships moving forward to project potential credit demand.

Let $X_t = (X_{1t}, X_{2t}, \ldots, X_{6t})'$ denote the vector composed of the six variables included in our model used to characterize the BAU environment, where t is at the quarterly level. The six components of X_t are

X_{1t} = California Reformulated Gasoline Consumption
X_{2t} = California Diesel Fuel Consumption
X_{3t} = U.S. Soybean Prices
X_{4t} = California Vehicle Miles Traveled (VMT)
X_{5t} = Brent Oil Price
X_{6t} = California Gross State Product (GSP)

Define $Y_{it} = ln(X_{it})$ for $i = 1, \ldots, 6$ and $Y\_t = (Y_{1t}, Y_{2t}, \ldots, Y_{6t})'$. We fit a cointegrated vector error correction (VEC) model to Y_{it}. Cointegration allows the variables to have one or more stable long-run relationships. We specify three cointegration relationships:

$$Y_{1t} = \beta_{10} + \beta_{11}Y_{4t} + \beta_{12}Y_{5t} + \beta_{13}Y_{6t} + z_{1t} \quad (1)$$
$$Y_{2t} = \beta_{20} + \beta_{21}Y_{4t} + \beta_{22}Y_{5t} + \beta_{23}Y_{6t} + z_{2t} \quad (2)$$
$$Y_{3t} = \beta_{30} + \beta_{32}Y_{5t} + z_{3t} \quad (3)$$

The first equation represents the demand for gasoline and the second represents the demand for diesel. The third equation implies that soybean and crude oil prices are tied together in the long run. We impose zero coefficients on VMT and GSP in the third equation because we have no rationale for these California variables to be tied to the soybean price.[16] The Z_{it} terms represent the deviations from the cointegration relationship, also known as the error correction terms.

The VEC model to estimate the interrelationships among the six credit demand variables is:

$$\Delta Y_t = \alpha z_{t-1} + \Sigma_{j=1}^{p-1} \Gamma_j \Delta Y_{t-j} + \Sigma_{k=1}^{4} \omega_k s_k + \varepsilon_t \, , \quad (4)$$

[15] The list includes soybean prices to capture trends in commodity prices. It may also improve the model's ability to project trends in use of biomass-based diesel within the diesel pool.
[16] The purpose of this third equation is to model the marginal cost of producing biomass-based diesel, which can then be used to model the LCFS credit price under the assumption that biomass-based diesel is the marginal compliance fuel.

where Δ is the first-difference operator, s_k are seasonal indicators for the quarter of the year, $p = 4$ so that three quarterly lags of Y_t are included in the model, and ε_t is a vector of idiosyncratic disturbances. The 6×3 matrix α represents how the six variables respond to deviations from the cointegration relationship. Putting equations 1-3 together with equation 4, we can write the model as:

$$\Delta Y_t = \alpha\beta_0 + \alpha\beta' Y_{t-1} + \Sigma_{j=1}^{p-1}\Gamma_j \Delta Y_{t-j} + \Sigma_{k=1}^{4}\omega_k s_k + \varepsilon_t \qquad (5)$$

where

$$\beta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\beta_{11} & -\beta_{21} & 0 \\ -\beta_{12} & -\beta_{22} & -\beta_{32} \\ -\beta_{13} & -\beta_{23} & 0 \end{bmatrix}$$

and $\beta_0 = (-\beta_{10}, -\beta_{20}, -\beta_{30})'$.

3.2 Data

The dataset used in this analysis is constructed by six dependent variables available from 1987 to 2021. We only use data from 1987 to 2019 to fit the VEC model to exclude the distortion from the COVID-19 pandemic. Because our data are measured at the quarterly level, we have a total of 140 observations for each variable.[17] California GSP was collected from the Bureau of Economic Analysis.[18] The oil prices used in our model are Europe Brent spot prices FOB collected from the Energy Information Administration (EIA) at the monthly level and aggregated to quarterly averages.[19] We chose to use Brent oil prices rather than West Texas Intermediate prices because Brent prices are more relevant to California markets. Historical vehicle miles traveled (VMT) on California highways are reported by the Office of Highway Policy Information at the monthly level.[20] On-highway VMT data are reported in the aggregate and not divided into gasoline and diesel vehicles. Our model also requires soybean prices, which we collect from the Agricultural Marketing Service at the United States Department of Agriculture (USDA).[21] We aggregate monthly spot prices in Central Illinois to quarterly averages to be used in the model.

The main variables of interest in our model are gasoline and diesel consumption and VMT in California, as we need to forecast BAU fuel demand in order to construct a distribution of LCFS

[17] All variables are measured at the quarterly level except CA GSP. The Bureau of Economic Analysis (BEA) reports quarterly data only since the year 2003. Therefore, we use annual data for CA GSP, which is available for the entire sample 1987-2021.
[18] Available at https://apps.bea.gov/regional/downloadzip.cfm
[19] Historical Brent oil prices can be found at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.
[20] Available at https://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm
[21] The soybean prices used in this study can be accessed by creating a custom report in the Market News Portal at https://www.ams.usda.gov/market-news/custom-reports and querying Central Illinois soybean under grains.

deficits. We collect monthly prime supplier sales volumes for California reformulated gasoline (CaRFG) from the EIA.[22] This measure captures all finished gasoline that is consumed in California, including imports to the state. We assume all gasoline is consumed in the transportation sector.

Measuring diesel fuel consumption is more nuanced. The EIA reports monthly sales volumes for refiners at each step in the supply chain. We aggregate wholesale and retail sales volumes for No.2 distillate to construct a measure of consumption of No.2 distillate. According to data from the EIA, 99% of No.2 distillate is used for diesel fuel in California. Therefore, we calculate sales volumes of CARB diesel, which is ultra-low sulfur diesel (ULSD) sold in California, as 99% of No.2 distillate sales. The diesel pool, however, comprises biomass-based diesel (BBD), which includes biodiesel and renewable diesel, as well as petroleum diesel. BBD demand was negligible prior to 2011 but has been increasing since then. Therefore, we construct the measure for diesel fuel consumption as the sum of BBD and ULSD. The EIA does not report sales of BBD, so we use volumes reported by CARB in the LCFS quarterly summary since the years of substantial BBD demand occurred in that time period.[23] We aggregate monthly CARB diesel sales from the EIA to quarterly totals and add quarterly volumes of BBD from CARB.

The LCFS regulates fuel used in the California transportation sector. Therefore, to accurately estimate the number of deficits generated from CARB diesel using our data, we need to measure the amount of diesel fuel consumed in California that is allocated to the transportation sector. Since 1992, approximately 70% of distillate consumed in California has been used on-highway in the transportation sector.[24] For the post-2012 time frame, we use the volumes reported in the LCFS quarterly summary as the most direct measure of both ULSD and BBD coming under the program. We then calibrate our pre-2012 diesel volume data taking the fraction of volumes reported in the EIA data that is also reported under the LCFS post 2012 and adjusting pre 2012 volumes by this percentage. Importantly, scaling diesel by a constant has no effect on the coefficient estimates in the VEC model that we use to generate our BAU simulations.

3.3 Coefficient Estimates from the VEC Model

The long-run coefficient estimates from the VEC cointegration model appear in Table 1. Collectively, the coefficient estimates presented here make up the $\hat{\beta}$ matrix, therefore characterizing the long-run, cointegrating relationships between the variables in our model using 1987–2019 data. The three columns in Table 1 correspond to the three cointegrating equations specified in equations 1, 2, and 3, and the rows, to their long-run relationships with VMT, the oil price, and GSP.

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[22] The EIA classifies a prime supplier as "a firm that produces, imports, or transports selected petroleum products across State boundaries and local marketing areas, and sells the product to local distributors, local retailers, or end users."

[23] The LCFS quarterly summary can be accessed at https://ww3.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm

[24] Historical distillate sales in California by end-use sector can be accessed at https://www.eia.gov/dnav/pet/pet_cons_821usea_dcu_nus_a.htm

Table 1. Long-Run Coefficient Estimates of the Co-Integrating Equations

	ln(**CaRFG**)	*ln*(**Diesel**)	*ln*(**Soybean Price**)
ln(**VMT**)	-1.102**	-3.050***	0
	(0.437)	(0.774)	(0)
ln(**Oil Price**)	-0.173*	0.0426	0.913***
	(0.0984)	(0.127)	(0.201)
ln(**GSP**)	0.0460	1.185***	0
	(0.221)	(0.391)	(0)
Constant	28.49	18.10	-4.437
Observations	127	127	127

Standard errors in parentheses. *** p<0.01, ** p<0.05

In the first two equations (columns) of Table 1, gasoline and diesel demand in California, the coefficients on the oil price capture the price responsiveness of demand for each fuel. The coefficient on VMT captures fuel economy improvements as more VMT per gallon implies fewer gallons. Because the VMT measure is not reported by vehicle type, implied fuel efficiency gains in each of the two fuel pools are not discernible. The price elasticity for gasoline has the expected sign. The elasticity for diesel, on the other hand, is positive. This may reflect the fact that diesel demand is very inelastic. The coefficients on GSP reflect the income effect. Gasoline and diesel fuel are normal goods and thus should be expected to be positively correlated with income in the state. In the next section, we use the long-run coefficient estimates from Table 1, along with the short-run estimates located in the Appendix in Table 8 and random shocks, to project a range of forecasts for gasoline, diesel, and vehicle miles demand out to 2035.

3.4 BAU Demand Simulations

We use the coefficient estimates from the VEC model to predict the distribution for each variable through the compliance period under study, 2022–2035. Specifically, we simulate 1000 potential values for each variable in each quarter during the compliance period. To this end, we assume that the potential shocks ε_t that may occur in the compliance period have the same distribution as the shocks during our estimation sample period, 1987–2019. Using this assumption, we simulate potential future shocks by sampling randomly with replacements from the 1987–2019 shocks. For each random draw, we use the VEC model to generate a hypothetical path for the six variables. We repeat this exercise 1000 times to give a distribution of potential paths.

Specifically, for each simulation $k = 1,2,\ldots,1000$, we generate hypothetical future values for the six variables by iterating on the following equation for t from 2022 through 2035:

$$\hat{Y}_{kt} = \hat{Y}_{k,t-1} + \hat{\alpha}\hat{\beta}_0 + \hat{\alpha}\hat{\beta}'\hat{Y}_{k,t-1} + \Sigma_{j=1}^{p-1}\hat{\Gamma}_j\Delta\hat{Y}_{k,t-j} + \Sigma_{k=1}^{4}\widehat{\omega}_k s_k + \hat{\varepsilon}_{kt}^{*} , \tag{6}$$

where $\hat{\varepsilon}_{kt}^{*}$ is the k^{th} random draw from the estimation-sample residuals. For observations in the sample period, we use $Y_{kt} = Y_t$ and $\hat{\varepsilon}_{kt}^{*} = \hat{\varepsilon}_t$, which means that the simulation replicates observed data until the end of 2021 and then simulates a hypothetical path after 2021. We back out the projected levels of each variable for each simulation k as $\hat{X}_{ikt} = \exp(\hat{Y}_{ikt})$ for $i = 1,2, \dots ,6$.

The hypothetical paths for blended gasoline, diesel, VMT, GSP, oil price and soybean price simulated using equation 6 are described in Figure 1, with the median draw from each year (solid line) and a 90% pointwise confidence interval (dashed lines). The blended gasoline and diesel projections provide an indication of demand by fuel "pool" relevant to the light-duty and medium-/heavy-duty sectors, respectively.

For each variable in our VEC model, the level of uncertainty grows as we move further into the future. In Figure 1, 90% of the draws from our sample fall between 11.76 and 16.08 billion gallons of CaRFG being consumed in 2035—a 14.53% decrease and 16.86% increase, respectively, from 2021 levels of 13.76 billion gallons. By similar calculations, the 90% confidence interval for consumption of diesel falls between a 7.84% reduction and 70.54% increase from 2021 levels by 2035. Despite being greatly affected by Covid-19, VMT in California is projected to increase at a similar rate as the pre-pandemic's during the compliance period. VMT has also been far less volatile than gasoline and diesel consumption in California and therefore we see a tighter range of uncertainty around future VMT projections.

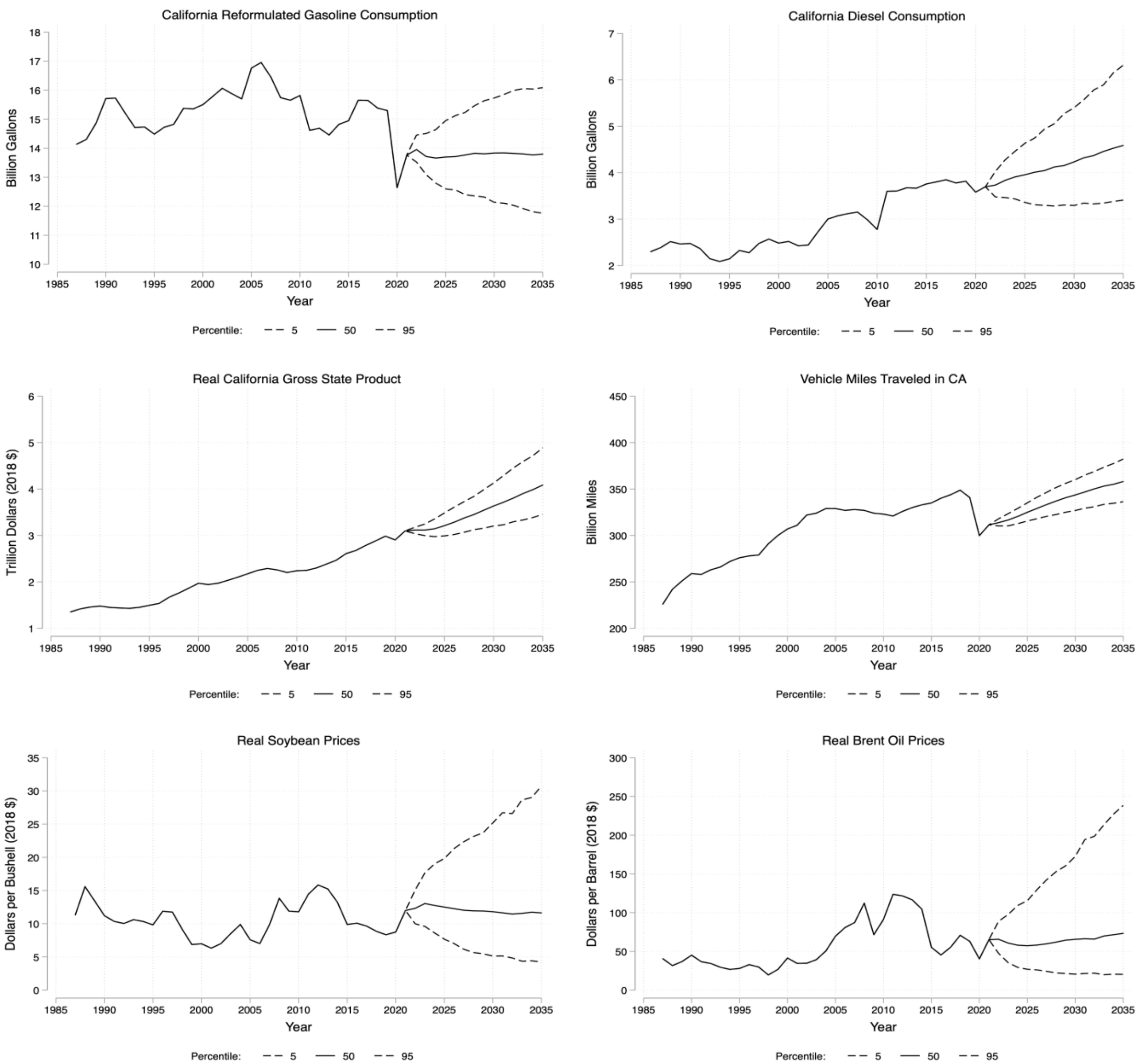

Figure 1: Variable Forecasts Under Baseline Assumptions

4 Baseline Scenario Assumptions and Methods

Our projection of the demand for fuels and other variables such as VMT provides the foundation for a projection of the demand for, and supply of, LCFS credits. In this section we describe the assumptions we make in mapping our forecasts of fuels demand to the supply and demand of credits. We begin with a baseline scenario that incorporates many of the policies and goals of the 2022 Scoping Plan. For this scenario we assume that the LCFS targets are a 30% reduction by 2030 and a 43% reduction by 2035. In section 5 we present results for this scenario, and in section 6 we present results based upon variations of our baseline scenario that consider different assumptions or policy alternatives, such as LCFS targets of 25% or 35% by 2030.

Throughout, we assume that biomass-based diesel (BBD) will be the marginal price-responsive option for compliance under the LCFS. In other words, the cost and ability to blend additional BBD will form the basis for LCFS credit prices. This is not the same as assuming that BBD will be the most significant, or the lowest (or highest) cost compliance pathway. Some compliance pathways, such as ethanol, may very well be lower cost but will be constrained by blending or other availability constraints. As we describe below, under the assumptions of the Scoping Plan alternative fuels such as electricity, bio-methane, and hydrogen will play an increasingly large role in the LCFS. However, the availability and cost of credits from these sources will be dominated by the success or failure of policies beyond the LCFS itself. Thus, we take the provision of these alternative fuels credits to be “infra-marginal,” or available at or below our forecast credit prices.

Under these assumptions, BBD will be the most significant “swing fuel” for compliance. As we discuss below, the cost of blending BBD will be heavily influenced by Federal policies including the renewable fuel standard (RFS), and targeted production tax credits. These policies will heavily subsidize the cost of blending BBD for LCFS compliance, and as a result we project relatively modest credit prices as long as BBD is a viable compliance option. However, we also project scenarios where the option to blend BBD is exhausted, and in those circumstances, we assume that credit prices reach the levels set by the cost containment policies.

4.1 Baseline Scenario Assumptions for Deficit Generation

Each gallon of CaRFG contains reformulated blendstock for oxygenate blending (CARBOB) and ethanol. Due to the “blend wall” for ethanol, CaRFG, as well as all reformulated gasoline in the U.S., is often referred to as E10. The average gallon of ethanol earns LCFS credits since the volume-weighted CI rating of ethanol used in the program falls below the standard. Therefore, each gallon of CaRFG consumed in California will generate both LCFS deficits and credits. We calculate total CARBOB consumption as 90% of CaRFG, with the remaining 10% being ethanol. Therefore, the baseline projection assumes that the E10 blend wall persists through 2035. For generating a baseline demand for credits, the currently observed BBD blend rate in the liquid diesel pool persists through 2035 as well. That is, we assume that 43.8% of liquid diesel fuel used in the transportation sector is BBD. Our baseline projection assumes a steady decline in the CI value of ethanol, assuming a continuation of the rate of decline observed over the previous decade. For BBD, we assume an increase in the CI value to 48 in order reflect an anticipated reliance upon higher CI feedstocks, most notably soy-oil.[25] We assume CARBOB and diesel remain at the full CI value applied in 2022, including the impact of increases in CI value for crude oil used for refining California fuels, throughout the modeling timeframe.[26] These assumptions are summarized in Table 2.

Table 2. Baseline Assumptions for Deficit-Generating Fuels (30% Target by 2030)

		Gasoline Pool		
	Share of Total Fuel	**2022 CI**	**2030 CI**	**2035 CI**
CARBOB[26]	0.90	101.75	101.75	101.75
Ethanol	0.10	59.63	53.10	48.95
Gasoline Pool Target	NA	89.50	69.61	56.29
		Diesel Pool		
	Share of Total Fuel	**2022 CI**	**2030 CI**	**2035 CI**
CARB Diesel[26]	0.562	101.38	101.38	101.38
Bio-based Diesel	0.438	48[27]	48	48
Diesel Pool Target	NA	90.41	70.32	56.86

In addition to fuel assumptions for the baseline scenario, we also make hypotheses on zero-emission vehicles (ZEVs). We make assumptions regarding the penetration of ZEVs in order to forecast credit generation from electricity and hydrogen as well as to forecast the level of fossil fuel displacement. ZEV penetration is difficult to predict, and its trends have been evolving. We assume that the recently approved Advanced Clean Cars II rule, the Advanced Clean Trucks rule, as well as the proposed Advanced Clean Fleets (ACF) rules are in place.[28] These programs form the basis for our assumptions regarding the ZEV shares of the light-, medium-, and heavy-duty fleets. The total number of on-road vehicles is taken from EMFAC,[29] but not the breakdown of vehicles by engine type (ICEs vs. ZEVs).

[25] The unit for CI score, here and throughout, is grams of CO2-equivalent per megajoule (gCO2e/MJ). More on how the program assesses this rating, an estimate of lifecycle GHG emissions for each fuel, is available on the LCFS website.

[26] The LCFS tallies the impact of the higher crude CI score relative to the 2010 baseline used to calculate the annual CI targets as "incremental deficits," with all petroleum gallons rated at the average level. We assume these CI scores hold throughout the modeling timeframe. California alone among LCFS jurisdictions evaluates and includes additional emissions due to increases in petroleum fuel CI score from its base(line) year levels. The provision is triggered if a threshold level increase is surpassed based on a three-year rolling average CI value for crude oil inputs to California fuels. It was first assessed in 2019, and has been annually since.

[27] The BBD CI score reflects an assumed blend of lower CI alternative feedstocks and higher CI soy-based BBD.

[28] See https://ww2.arb.ca.gov/news/california-moves-accelerate-100-new-zero-emission-vehicle-sales-2035, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks, and https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets.

[29] See https://arb.ca.gov/emfac/project-analysis

For light-duty vehicles we assume 5 million BEVs in 2030 and roughly 10.5 million in 2035. Although the ACC II regulation requires all new LDVs sold in California be ZEVs by 2035, our assumptions reflect the expectation that this requirement will both increase the number of used ICE vehicles brought into California from other states and delay the scrappage (prolong the use) of incumbent ICE vehicles in the state.[30]

For medium- and heavy-duty vehicles, we draw on the fleet composition projections from the 2022 Scoping Plan Scenario.[31] These projections imply only modest growth in freight ZEVs before 2030, but a rapid expansion between 2030 and 2035. Although these markets might experience the same secondary effects in terms of ICE vehicle lifetimes and out-of-state imports as the LDV market, we do not make adjustments for such an outcome and instead take the Scoping Plan projections as our baseline.

Table 3 summarizes our assumptions for light-duty, medium-duty, and heavy-duty vehicles in terms of absolute numbers and fleet shares of ZEV vehicles. Table 3 also shows our baseline assumptions regarding the CI ratings of electricity and hydrogen (adjusted – divided – by energy economy ratios (EERs) as used by CARB to better reflect basis for credit generation).[32]

Table 3. Baseline EV Assumptions by Vehicle Type[33]

	2022			2030			2035		
ZEV Type	**# of ZEVs (mil.)**	**Share of Vehicle Class**	**EER-adjusted CI score**	**# of ZEVs (mil.)**	**Share of Vehicle Class**	**EER-adjusted CI score**	**# of ZEVs (mil.)**	**Share of Vehicle Class**	**EER-adjusted CI score**
LDV-EV	1.50	5.91%	10.71	5	19.16%	4.43	10.49	39.37%	0.31
MDV-EV	0	0%	10.71	0.13	8%	4.43	0.38	22.9%	0.31
HDV-EV	0	0%	7.29	0.017	5%	3.01	0.046	11%	0.21
HDV-H_2	0	0%	21.48	0.015	4%	21.48	0.056	13%	21.48

The declining CI rating of EVs reflects recent trends, and policies in place to reduce the CI rating of the grid through increasing use of renewables or accelerated penetration of EVs. More rapid

[30] That said, our assumptions on LDV fleet composition are very similar to those made by California ARB in its Scoping Plan.

[31] These assumptions are summarized in https://ww2.arb.ca.gov/sites/default/files/2022-11/2022-sp-PATHWAYS-data-E3.xlsx.

[32] We hold hydrogen CI scores constant at recent values for the projection. For EV CI scores, we apply a linear decline from recent values (used for 2022) to zero around 2035. CARB uses EERs to adjust for relative efficiency of fuel/engine combination for alternative vehicles compared to internal combustion engine vehicles (ICEVs), reflecting relative differences in distance per MJ of energy spent. Here and throughout this paper, recent CI scores, fuel volumes, and credits generated are from California LCFS quarterly program data from the ARB available at the time of analysis; https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries. Note that some retroactive updates occur with new data releases, so there may be small discrepancies between values used here and those in newer releases.

[33] See footnote above for an explanation of EER-adjusted CI score assumptions.

declines of EV CI score to zero are considered in alternative scenarios to the BAU and sensitivity analyses on the results.

In addition to the assumptions in Table 3, we assume in the baseline scenario that future EVs will only partially replace internal combustion engine vehicles (ICEV) on the light-duty side or be driven fewer miles than the remaining ICE vehicles. Research examining trends in the 2010s supports this assumption (Davis 2019), but there is great uncertainty about the projected relationship of EVs and ICE vehicles within household portfolios. Since EVs are assumed to partially replace average fuel economy ICEVS, gasoline demand declines in proportion to the share of EVs in the vehicle pool. Specifically, we calculate the number of kilowatt-hours for light-duty EVs according to the following equation:

$$kWh_t = s_t \times (0.8 \times X_{4t}) \times 0.32 , \tag{7}$$

where s_t is the share of EVs of LDV vehicles in year t, X_{4t} is vehicle mile demand from the VEC model, and the 0.32 scale factor translates miles into kilowatt-hours.[34] Then, credits from electricity can be calculated by plugging in the number of kilowatt-hours into equation 18 a (in the Appendix.

We can apply similar assumptions to calculate the amount of gasoline that would be displaced by the LDV fleet. Under the assumption that each additional EV displaces 0.8 miles of each mile traveled by ICE, the deficit reduction equals the share of VMT being replaced by light-duty EV times the forecast gasoline demand (equation 18 b, Appendix).

We have no information on how VMT for the heavy-duty sector may change with increasing EV penetration. While vehicles deployed may be well used, as is currently the case, fleets and loads may also shift in unexpected ways. On the one hand mileage in ZEVS may be lower due to range or convenience limitations. On the other hand, ZEV mileage might be higher if operating costs are significantly lower than for ICEVs. For this exercise, we assume that the average freight ZEVs will be driven 75% of the miles as the average ICE MDV or HDV.[35] An assumption is made that ZEVs will be driven the same miles as an average ICE HDV, but only 75% of the targets envisioned as being met due to the Advanced Clean Trucks and Advanced Clean Fleets regulations. In both cases, the displacement of diesel reflects the share of ZEVs in the MDV and HDV fleet, discounted by 25%.

With these assumptions, we can calculate the amount of gasoline and diesel fuel that would be displaced by the expansion of ZEV fleets (Table 4).

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[34] The AFDC reports this: https://afdc.energy.gov/vehicles/electric_emissions_sources.html

[35] These simplifying assumptions do not appreciably impact results given the low assumed HDV penetration levels during the period. At higher penetration levels, assumptions about and implementation of HDV fuel displacement could be important to volumes of biofuels required for compliance, and the treatment used here for simplicity would no longer suffice.

Table 4. Baseline Displacement Assumptions by Fuel (Billion Gallons)

	2022	2030	2035
Gasoline			
LDV - Electricity	0.50	1.78	3.81
MDV - Electricity	0	0	0.10
Diesel			
HDV - Electricity	0	0.15	0.39
HDV - Hydrogen	0	0.13	0.47

4.2 Other Baseline Scenario Assumptions

Until this point, we have described BAU forecasts for LCFS deficits and baseline assumptions for credit generation from BBD, ethanol, on-road electricity, and hydrogen. However, there are other pathways to credit generation that must be considered before estimating an overall credit/deficit balance. As shown in Figure 2, BBD, ethanol, and on-road electricity make up 90% of the credits that were generated in 2021. For most of the remaining pathways, like off-road electricity, alternative jet fuel, and projects such as innovative crude production or refinery efficiency investments, we assume that credit generation under BAU remains constant at 2021 Q4 levels. The "forklift,…" category in Figure 2 includes these sources, plus fast-charging and hydrogen-refueling infrastructure capacity credits ("infrastructure credits").

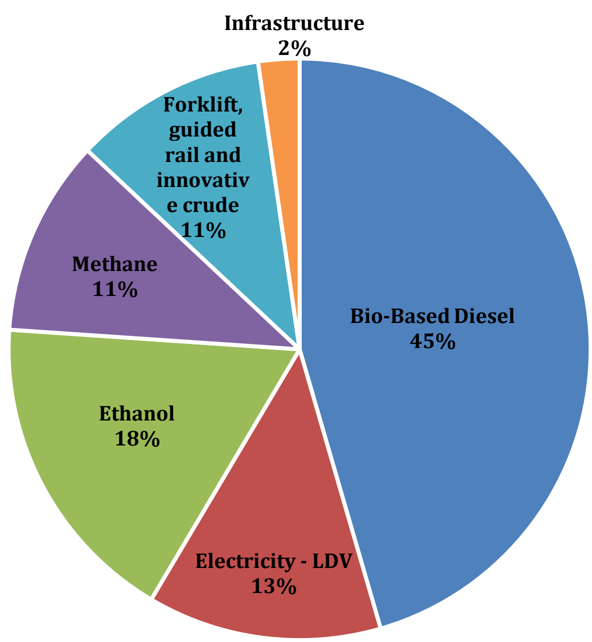

Figure 2. LCFS Credit Generation by Pathway in 2021

The assumptions we make about credit categories not detailed above are summarized below.

- **Total Bank Credit**: 9,450,000 in 2022 (acquired from 2021 cumulative credit bank). Distributed evenly between 2022 and 2035 (0.68 MMT – million MT -- per year).
- **Forklifts, guided rails, other off-road electricity categories, innovative crude, and refinery investment credits**: remain at 2021 Q4 total of 0.515 MMT per quarter.
- **Alternative jet fuel:** assume to be 0.025 MMT per year.
- **Methane Credits:** start at 2021 Q4 value and grow linearly at the linear growth rate from 2012 - 2022. The result is a rough doubling of methane-related credits, including from renewable natural gas, such as from landfills and dairy, by 2030. (Note: we are attributing growth in all methane-related credits – not just as an end-use fuel but as an input to other fuels such as electricity – to this category.)
- **Infrastructure Credits**: EV fast-charging and hydrogen fuel station operational (unused) capacity each receive credits equal to 2.5% of deficits from the prior quarter, resulting in 5% combined.

4.3 Deriving Implied BBD Blend Rates Required for Compliance

Above, we described how we would generate a distribution of credit shortages, assuming that the BBD blend rate remains at 2022 levels. In this section we relax this assumption and answer the question of how much BBD would be necessary to reach annual compliance under particular assumptions about the LCFS. We take this approach to evaluating the difficulty of compliance because BBD is the marginal fuel for compliance.

Holding the BBD blend rate at 2022 levels implies that annual net credits in the program are:

$$NC_t^{2022} \equiv BBD_t^{2022} - D_t^{2022} + LDelec_t^{on} + HDelec_t^{on} + MDelec_t^{on} + HDhydro_t^{on}$$
$$+eth_t + meth_t + infra_t + other_t + bank_t - C_t \quad (8)$$

where BBD_t^{2022} denotes credits from BBD under the 2022 blend rate and D_t^{2022} denotes deficits from petroleum diesel under the 2022 BBD blend rate. The other variables are as follows: $LDelec_t^{on}$, $HDelec_t^{on}$, and $MDelec_t^{on}$ denote credits from light-, heavy-, and medium-duty electric vehicles, $HDhydro_t^{on}$ is credits from heavy-duty hydrogen vehicles, eth_t is credits from ethanol, $meth_t$ is credits from methane, $infra_t$ is infrastructure credits, $other_t$ is credits from other sources, $bank_t$ is credits from allocating the bank evenly across years, and C_t is CARBOB deficits.

Positive net credits imply that the program is more than achieving compliance in that year. These credits can be carried over to the next year. We compute accumulated net credits from year to year as long as they are positive. If accumulated net credits become negative, then *BBD* needs to be blended above the 2022 rate to achieve compliance. We define accumulated net credits under the 2022 *BBD* blend rate as:

$$ANC_t = \begin{cases} NC_t + ANC_{t-1} & if\ ANC_{t-1} \geq 0 \\ NC_t & if\ ANC_{t-1} < 0 \end{cases} \quad (9)$$

where $ANC_{2021} = 0$.

When $ANC_t < 0$, we replace petroleum diesel with BBD until either we reach compliance or the blend rate hits 100%. The number of gallons of diesel available to be substituted equals $\frac{D_t^{2022}}{Ddpg}$, where *Ddpg* equals the number of deficits per gallon of petroleum diesel. Each substituted gallon generates $(BBDcpg + Ddpg)$ additional net credits, where *BBDcpg* equals the number of credits per gallon of BBD. Thus, the number of gallons required to be substituted to achieve compliance equals $\frac{ANC_t}{BBDcpg+Ddpg}$ or zero, whichever is smaller. The number of gallons of BBD used in this compliance scenario is:

$$BBDgallons_t = \frac{BBD_t^{2022}}{BBDcpg} + min\left(\frac{min(ANC_t,0)}{BBDcpg+Ddpg}, \frac{D_t^{2022}}{Ddpg}\right) \qquad (9)$$

If the number of gallons required to achieve compliance exceeds the number of available gallons, then we set the blend rate at 100% and classify the program as not achieving compliance that year.

5 Baseline Scenario Results

In this section we apply the assumptions described above to translate our forecasts of economic conditions into projections of the supply-demand balance of LCFS credits. We first present results that assume the BBD blend rate remains at 2022 levels (around 44%) even if that results in a net deficit balance. We then examine the degree to which increasing the BBD blend rate can eliminate any projected net deficits under the various program assumptions in a baseline compliance scenario.

5.1 LCFS Credit Balance at 2022 BBD Blend Rates

Using the parameters from Table 2 and Table 3, we translate the forecasts of fuel demand, after accounting for gasoline and diesel displacement from alternative fuels, into forecasts of the deficit/credit balance over the compliance period subject to our baseline scenario assumptions. Using the predictions of CaRFG and diesel demand, we calculate CARBOB and CARB diesel deficits in each state of the world represented by our simulations.[36] The distributions of projected gasoline and diesel demand were presented in Figure 1 but are adjusted for the consumption offset by alternative fuels as described above. Figure 3 summarizes the median volumes of gasoline and diesel displaced by electricity and hydrogen (where electricity and hydrogen displace gallons of blended petroleum fuel)[37] projected under the ZEV use assumptions listed earlier in this section along with the remaining consumption of petroleum gasoline and diesel.

[36] See equation 18 in the Appendix for more details.

[37] For LDVs, E10 is the blended fuel displaced. For MDVs and HDVs, diesel at the 2022 blend rate of 43.8% BBD is the blended fuel displaced. All conversions for displacement use energy densities and EERs listed in the LCFS regulation.

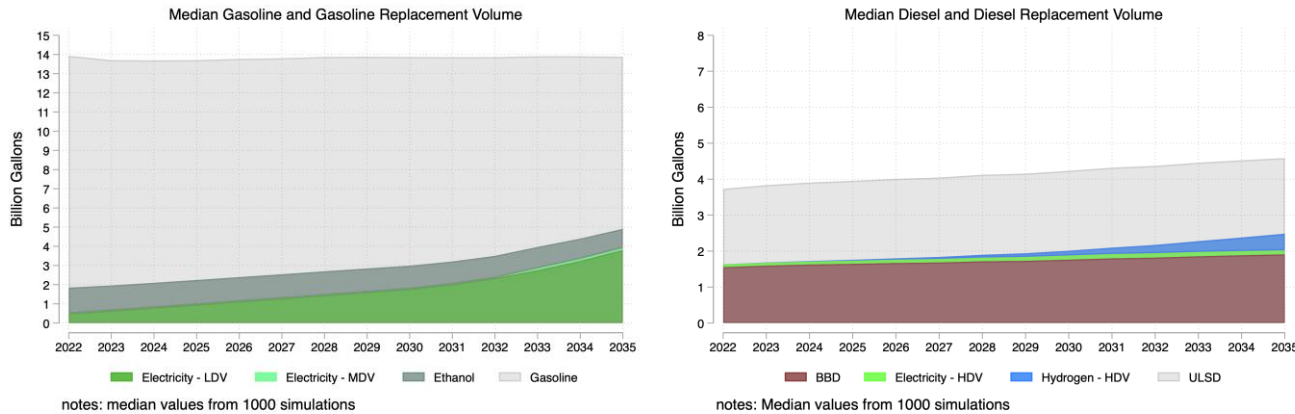

Figure 3. Fuel Volumes at Current Blend Rates

Although petroleum fuel consumption is projected to decline (once ZEV expansion is considered), the annual deficits produced by both fuels increase rapidly due to the tightening of the CI standard through 2035. For example, a projected 12 billion gallons of CARBOB yield 17.5 MMT of deficits in 2022, while roughly 7.5 billion gallons projected for 2035 generate a deficit of over 46 MMT. The distribution of cumulative deficit for CARBOB is centered around 483 MMT on average, with over half of that total generated between 2030 and 2035. Similarly, baseline ULSD deficits are projected to rise from just over 3 MMT per year in 2022 to over 12 MMT per year in 2035, again assuming a constant 44% BBD blend. If the BBD blend did not increase this would yield over 110 MMT in cumulative deficits through 2035.

We now combine these projected deficits with our projections of credits based upon the assumptions described above. The significant sources of credits include a declining contribution of ethanol, and a rapidly growing contribution of electricity and methane. The baseline projection also includes credits from all other sources producing credits in 2021, such as fixed guiderail and electric forklifts, unused ZEV infrastructure capacity, as well as the roughly 10 MMT bank of system-wide credits accumulated since the beginning of the LCFS. We combine all the cumulative sources of credits and deficits through 2035 in Figure 4, assuming 30% CI reduction in 2030 (highlighted in Figures), and 43% in 2035. Figure 4 illustrates the sources and quantities of credits and deficits drawn from different points of our forecast distribution. The left-hand bar represents the draw with the 5% lowest cumulative net deficit, while the right-hand bar represents the draw with the 95% highest projected deficit. The column marked 50 represents our median forecast. Assuming a 44% BBD blend rate for the period, our median forecast is for a cumulative deficit of roughly 120 MMT by 2035. Note that our approach is high-level, examining aggregate net deficits for the compliance period and abstracting away from annual compliance decisions and situations that could impact year-to-year credit availability.

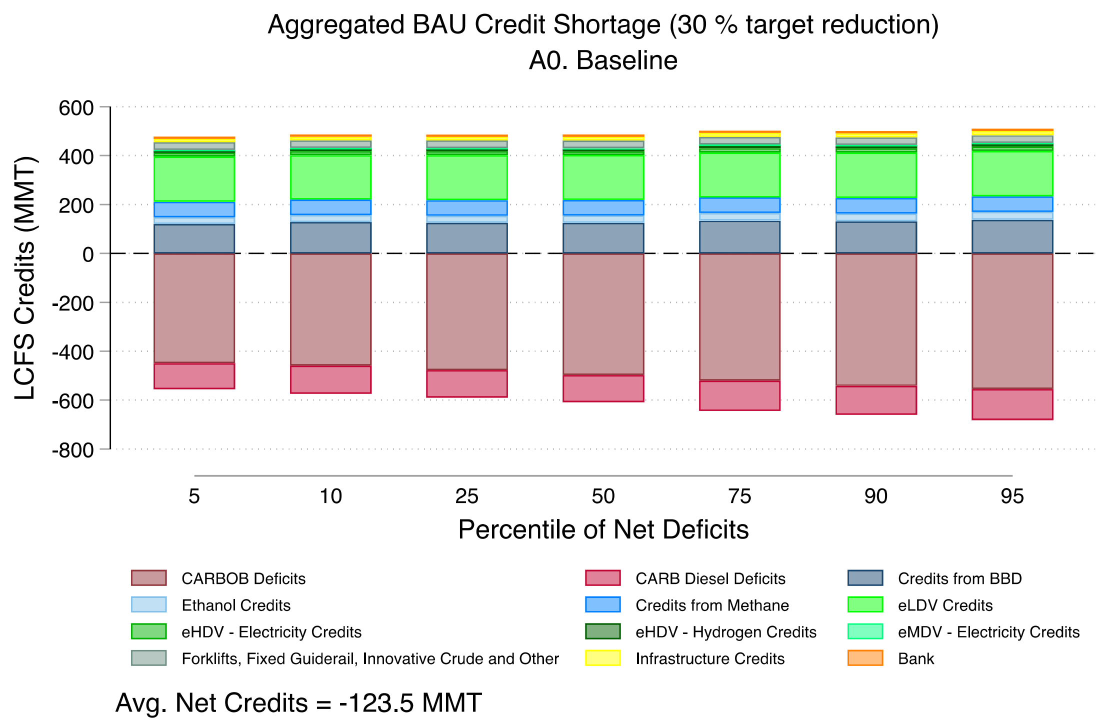

Figure 4: Breakdown of Net Credits through 2035

5.2 BBD Blending Under the Baseline Compliance Scenario

Having presented the range of credit deficits through 2035 under an assumption of a static BBD blend rate, we now relax the BBD blend rate assumptions. Recall that our approach is to increase the BBD blend rate from its "default" baseline level of 43.8% if such an increase is necessary to balance credit supply and demand in a given future year. We also assume that this additional BBD comes from a blended feedstock with a CI value of 48. If our forecast implies a credit surplus, as it does in early years, we maintain the blend rate at 43.8% and accrue a BBD blend-based credit bank.[38] This amount of banked BBD-blend credits is applied to the first year in which a deficit is projected. If a deficit remains even after applying these banked amounts, we then increase the BBD blend rate. We cap the blend rate at 100% of projected diesel demand and the model begins to accrue a deficit bank if there is an annual deficit even after blending diesel to 100% BBD.

Applying the above approach, Figure 5 shows the implied blend rate resulting from our baseline scenario, again assuming a target of 30% reduction by 2030 and 43% by 2035. As noted above, we assume blending is capped at 100% of projected diesel demand. The excess credits from existing blend levels accrue through 2024 under our median forecast, but are exhausted quickly after that. Our median forecast reaches a maximum blend rate of 100% around 2029, after which the system begins to accrue excess deficits. We assume that credit prices are set by the

[38] This BBD blend-based credit bank is distinct from the bank of credits that existed going into 2022. Recall that we distribute credits from this latter bank equally across all future model years.

cost-containment mechanism under these scenarios. During the years 2030 through 2033, almost all of our 1000 draws project that 100% blending would be insufficient to balance credits and deficits in those years. After 2033, the assumed, but uncertain, expansion of alternative fuels in the medium- and heavy-duty fleets, combined with the assumed acceleration of light-duty electrification brings down the deficit projections to the point where roughly half the draws can reach a credit/deficit balance with less than a 100% BBD blend.

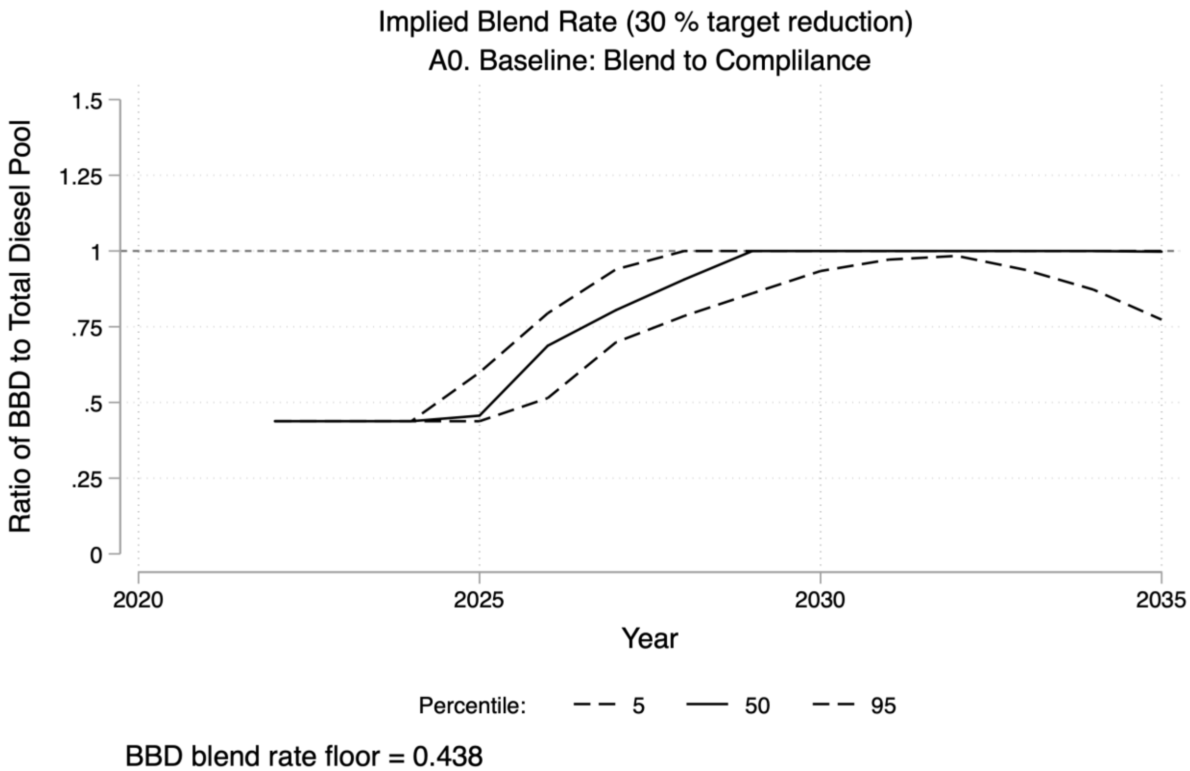

Figure 5: Projected BBD Blend Rate for Compliance

It is important to note that our method is not necessarily an equilibrium approach. If the market anticipated a credit deficit in later years, this could induce higher blend rates before actual annual deficits materialize. Due to the decreasing CI standards, shown in

Table 10, all else equal, BBD production in later years will earn fewer credits since the CI rating will be closer in magnitude to the standard, and the yet-to-be displaced diesel would earn more deficits as its CI rating falls farther above the standard. Therefore, it is possible that the scenarios depicted could induce higher BBD blending in earlier years, which would produce smaller deficits in later years due to the extra accrued BBD credits. On the other hand, it is likely that physical constraints on the production and distribution of BBD would constrain the rapid expansion of BBD to extremely high blend levels in the next several years. After accounting for increases in the BBD blend rate, we can calculate the annual amount of credits and deficits produced across the various categories. These values are summarized in Figure 6 of the mean forecast,[39] again assuming a target of a 30% reduction by 2030 and a 43% reduction by 2035. The values summarized in this figure are also presented in Table 13 in the Appendix. As can be seen in Figure 6, deficits outstrip credits from roughly 2029, creating an increasing aggregate deficit through 2035 for all draws on average.

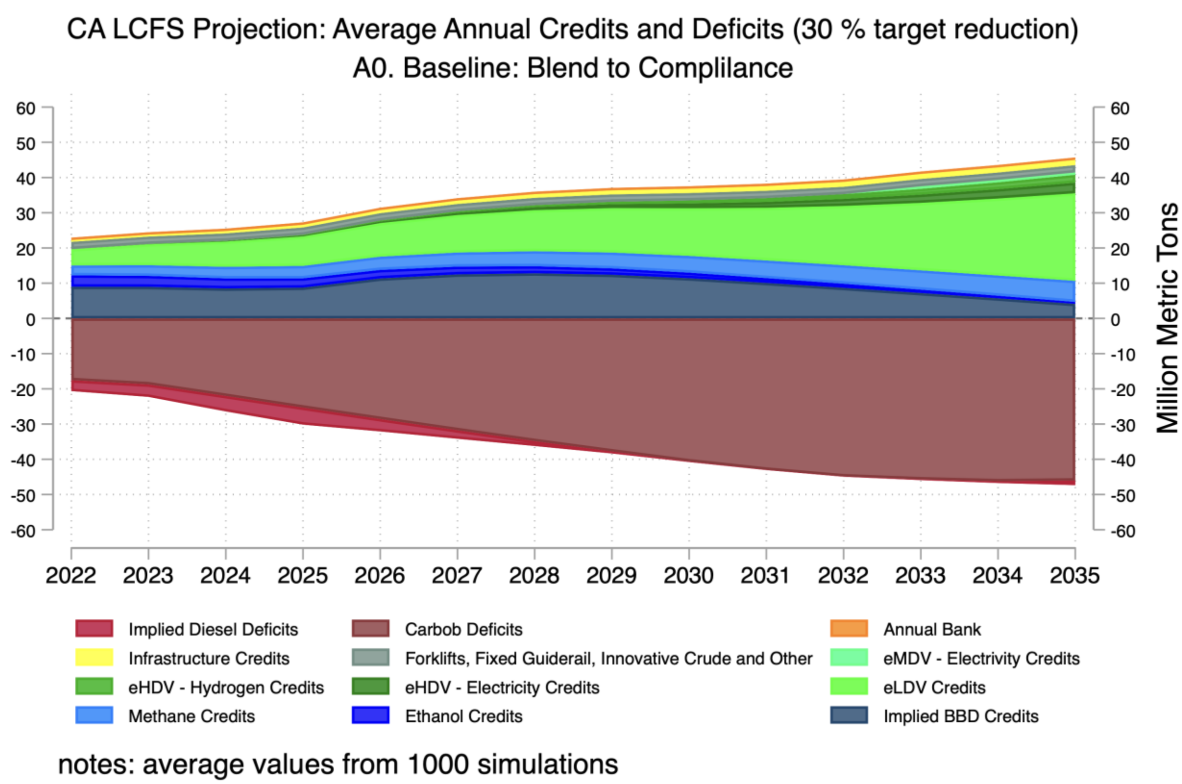

Figure 6: Average Annual Sources of Credits and Deficits

The assumed rapid increase in electric and hydrogen use in transportation allows for the market to return to balance by 2035 in just under 50% of our draws. The full distribution of the

[39] We use the average here to better capture the range of results across simulations (as opposed to the median result, which draws from a single simulation, used elsewhere in the paper).

projected credit deficits is summarized in Figure 7. Under our assumptions, BBD blending increases only if needed to balance credits and deficits in a specific year. Therefore, no bank of credits would arise unless the blend rate necessary for credit/deficit balance drops below our floor rate of 43.8%. This doesn't arise after 2029, so our lower emissions scenarios produce a balance of zero net credits by 2035. This is why the histogram in Figure 7 is left-skewed and has a large mass at zero.

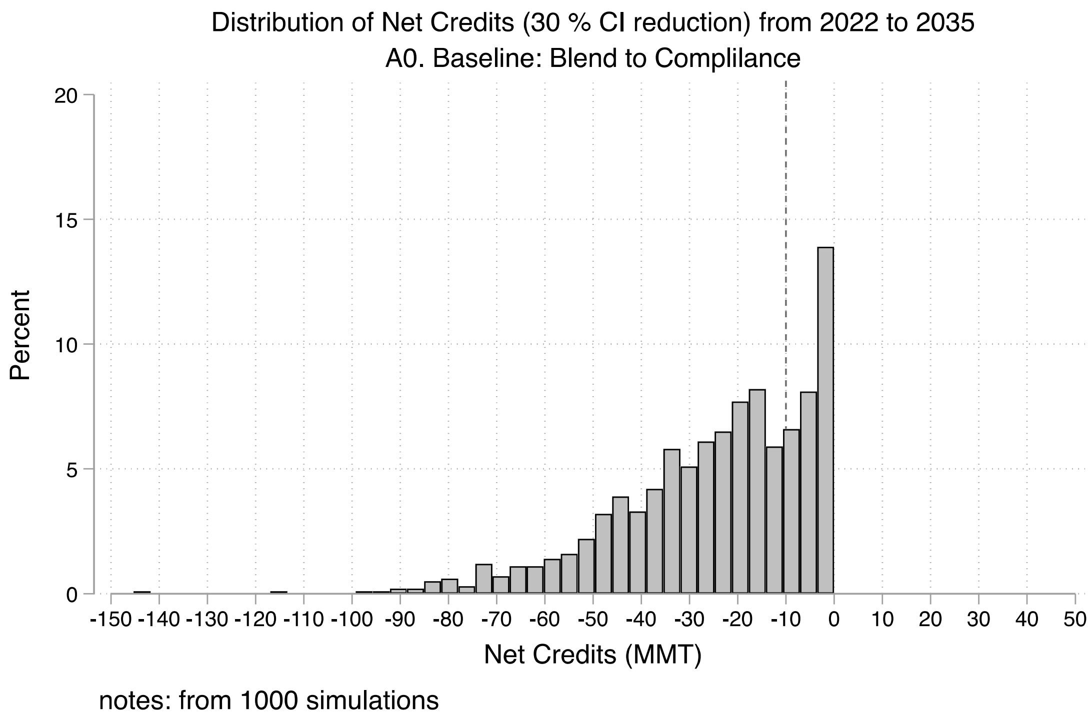

Figure 7: Distribution Net Credits Through 2035 Assuming Maximum 100% BBD Blend

5.3 Credit Price Impacts Under the Baseline Scenario

Given our projections of the balance of credits and deficits through the year 2035, we can examine the implications of these forecasts for LCFS credit prices. Below, we describe our assumptions regarding credit prices and present the projections.

As before, our operating assumption is that soy-based renewable diesel (RD) will comprise the marginal compliance fuel, at least for credit prices below the cost containment level of $239.18/ton in 2022.[40] When LCFS market balance can be reached by blending additional RD, then we assume the LCFS credit price will be based upon the cost of compliance via blending RD. The cost of BBD will depend upon many factors, including feedstock costs, production capacity, transportation costs, and federal subsidies. These components, however, determine

[40] We will express all of our prices in $2022 dollars so the 2022 price-cap is the relevant value for this exercise.

the cost of acquiring RD, not the *additional* cost of using RD to generate credits in the LCFS program. It is this latter concept that will be the basis for LCFS compliance costs.

We simplify our approach by assuming that CA LCFS compliance costs will be based upon the incremental cost of consuming RD in California, as opposed to a non-LCFS state. Based upon discussions with stakeholders and market analysts, we feel this is a reasonable assumption. Given that feedstock costs and federal incentives will be common across all RD markets, the incremental costs will be set by the cost of transporting RD to California, presumably from the U.S. Midwest. We assume this cost to be 30 cents per gallon of RD, based on discussion with industry stakeholders.

Renewable diesel transportation costs will therefore be the driver of LCFS credit prices as long as RD blending is a feasible compliance option. However, many of our scenarios exhaust this option by meeting 100% of diesel demand with RD or BD. We assume that LCFS credit prices will reach containment levels under those scenarios. This would be consistent with either a circumstance where compliance is reached via options whose marginal cost exceeds $239/ton (such as direct air capture), or with cost containment measures being applied to the LCFS market and either deficits accruing and/or advanced credits being drawn upon.

Therefore, our pricing results are based upon a weighted average of the two possible outcomes in this model: prices set by RD transportation costs or prices set by the cost containment mechanism. For any scenario where compliance is reached with a BBD blend below 100%, prices are set by the former and for any scenario where the BBD blend reaches 100%, prices are set by the latter.

In addition, since credits can be banked, we assume that future expectations of credit prices will feed back to the present day. Therefore, a scenario where credits reach the containment level in 2030, for example, is assumed to increase credit prices immediately. These assumptions are complicated by the fact that, as described above, some scenarios reach a blend ceiling in 2030 but blend below 100% by 2035. Since a surplus can be banked, but deficits only accrue when credit prices reach their maximum, we assume that 2030 prices drive previous prices under such scenarios, and the 2035 price impacts post-2030 prices. Further, it is important to recognize that uncertainty grows rapidly as we project farther into the future. For this reason, although we include forecasts based both upon both 2030 and 2035 projections, we believe the 2030 values are more robust.

With these assumptions in mind, the distribution of anticipated LCFS prices is summarized in Table 5. Each column of Table 5 represents a different 2030 LCFS reduction target (and associated 2035 target). For our baseline scenario assumption of a 30% reduction by 2030, roughly 75% of the draws reach the price cap in 2030, yielding an expected credit price of $212. This drops to roughly 50% of the draws in 2035, with an associated expected credit price of $145/ton.

Table 5: Baseline Model Credit Price Projections ($/ton)

Compliance Targets	**25%/35%**	**30%/44%**	**35%/51%**
End Year 2030	46	211	239
End Year 2035	43	145	239

6 Sensitivities and Alternative Scenarios

The results in section 5 assume that the LCFS reduction targets are 30% by 2030 and 43% by 2035. In this section we explore the sensitivity of our estimates to certain compliance assumptions and to the compliance targets that are adopted. We first briefly describe the alternative reduction targets and examine the impact of alternative compliance assumptions on our baseline 30% target, before presenting credit price results under the alternative assumptions.

6.1 Alternative Reduction Targets

As described above, we examine how the LCFS credit balance would evolve under alternative reduction targets, but maintaining our baseline assumptions about carbon intensities, ZEV adoption, methane, and infrastructure credits. We consider alternative 2030 targets of reductions of 25% and 35% in addition to the 30% evaluated in the previous section. These alternative 2030 targets are associated with 35% and 52% reductions by 2035, respectively.

6.2 Sensitivities

We also examine the impact of several important assumptions relating to the supply of LCFS credits. These scenarios are summarized in Table 1. First, we assume that ZEV credits achieve a CI score of zero immediately in 2022 in a "Low ZEV CI" scenario (SA1), rather than declining linearly to reach approximately a zero CI in 2035. Second, we assume biofuel CI scores below current levels in a "Lower Biofuel CI" scenario (SA2). Third, we examine a "Low ZEV" scenario (SA3), which assumes that ZEVs displace 65% of VMT per ZEV target, rather than the 80% in our baseline scenario. Fourth, we examine a "High ZEV" scenario (SA4), where 100% of ZEV goals are achieved (for both LDV and HDV) and each ZEV displaces the average amount of diesel or gasoline consumed by an ICE vehicle.

Table 6: Alternative Scenarios

Alternative Scenario	Description
SA1: Low ZEV CI	CIs for electricity and hydrogen assumed to equal zero starting 2022

SA2: Low Biofuel CIs	CI for blended BBD assumed to be 43, CI for ethanol assumed to be 35, based upon extensive CCS, from 2025 onward
SA3: Low ZEV	ZEV adoption reaches 65% of Scoping Plan targets, or equivalently ZEV adoption targets are met but each ZEV displaces 65% of ICE fuel consumption
SA4: High ZEV	ZEV adoption reaches 100% of Scoping Plan targets and each ZEV displaces 100% of the fuel of an average ICE vehicle

The scenarios on ZEV adoption assumptions, A3 and A4, are the most impactful to our forecasts. They influence the amount of gasoline and diesel fuel displaced before biofuel blending is considered. Figure 8 illustrates the impact of these assumptions on gasoline volumes through 2035. In the low ZEV scenario, petroleum gasoline demand is just under 10 billion gallons in 2035 and in the high ZEV scenario it is roughly 8 billion gallons in 2035. Diesel volumes are less sensitive to ZEV usage assumptions, given that the penetration of advanced clean trucks is assumed to accelerate only after 2030.

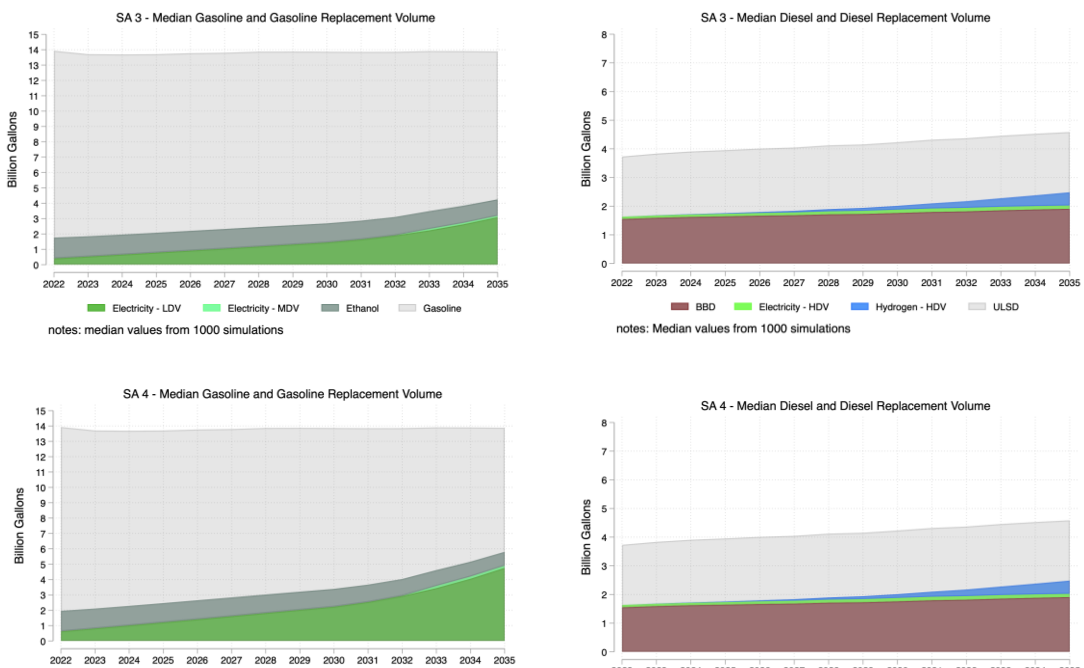

Figure 8. Alternative Scenario Fuel Volume Results

6.3 BBD Blending Under Alternative Scenarios

In this section we examine the impacts of ZEV penetration and usage on the implied BBD blend rate. Figure 9 is similar to Figure 5 in graphing the implied BBD blend rate by year for the 5%, 50%, and 95% highest blend rates amongst simulation draws. Here we plot these blend rates for the low ZEV usage and high ZEV usage scenarios (A3 and A4, respectively, described in terms of the VMT efficiency interpretation) in addition to our baseline scenario (A0). With low ZEV usage, all draws reach full blending by 2030, whereas with high ZEV usage the median draw is now able to reach compliance via BBD blending in every year through 2035.

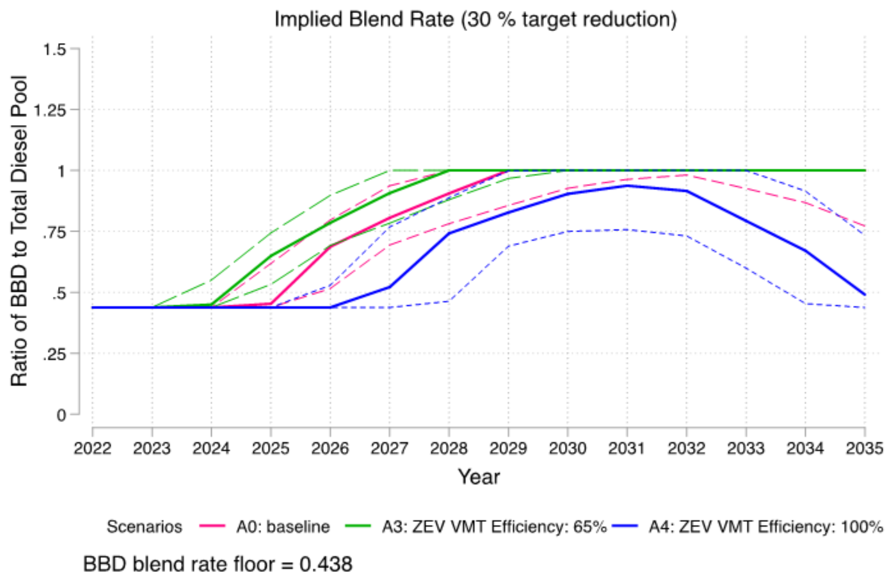

Figure 9. Implied Blend Rates by Scenario (median draw - solid; 5% and 95% draws - dashed)

To illustrate the implications of the blend ceiling on credit balances, we plot cumulative net credit or deficit balances by year for the same three scenarios, again assuming a 30% compliance target in 2030 in Figure 11. This figure captures the high degree of credit balance uncertainty created by the uncertainty of ZEV fleet targets and usage. The 5% draw on the low ZEV scenario results in a net deficit exceeding 100 MMT in credits by 2035, whereas the median draw of our baseline scenario has a cumulative deficit around 20 MMT and the “best case” draw from the high ZEV usage scenario achieves a small credit surplus by 2035. This latter result implies that BBD blending at our assumed floor of 43.8% is more than sufficient to reach credit balance in 2035 in this scenario.

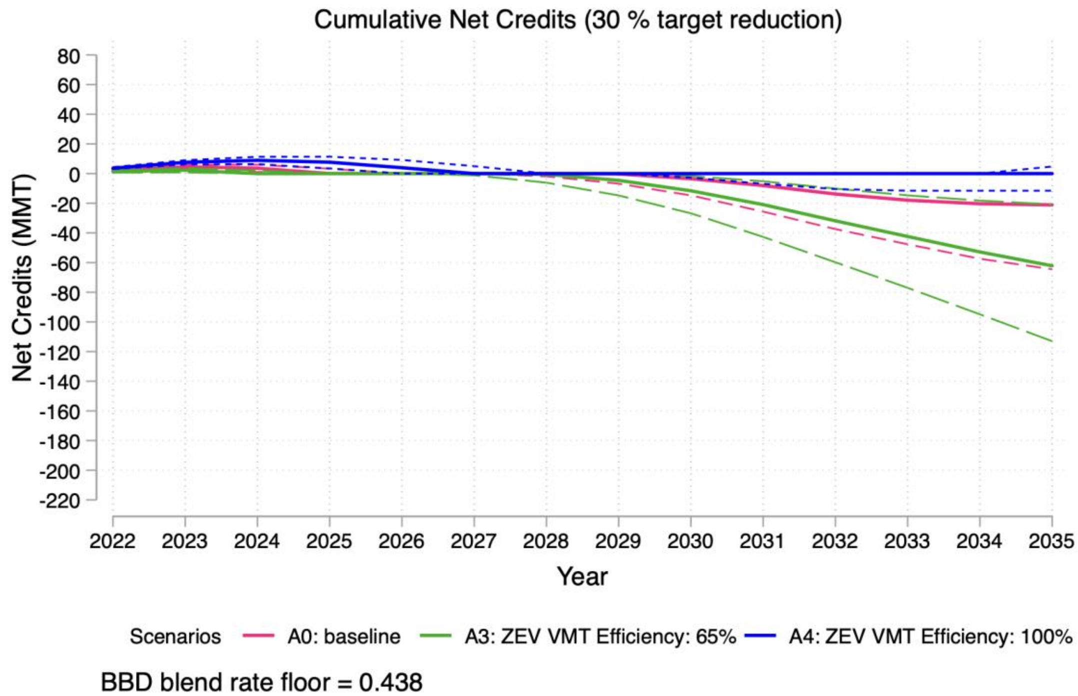

Figure 10. Cumulative Net Credits by Scenario (negative credits are deficits; median draw - solid; 5% and 95% draws - dashed)

We summarize the projected LCFS prices given net deficits for the median draw across all of our scenarios and for the three potential reduction targets in Table 7: Projected LCFS Prices by Target Year and Scenario ($/ton). All values are normalized to 2022 nominal $/ton. Recall that these pricing values reflect an average of two binary outcomes, $43 or $239 across our 1000 draws for each scenario and target.

Table 7: Projected LCFS Prices by Target Year and Scenario ($/ton)

Scenario	2030 Reduction Target			2035 Reduction Target		
	25%	30%	35%	35%	43%	51%
Baseline	43.00	211.36	239.00	43.00	144.72	239.00
A1: Low ZEV CI	43.98	182.36	239.00	43.00	114.74	239.00
A2: Low Biofuel CIs	43.59	154.13	239.00	43.00	99.45	239.00
A3: Low ZEV usage	70.83	236.26	239.00	46.72	236.65	239.00
A4: High ZEV usage	43.00	85.92	237.63	43.00	43.39	220.58

Forecast prices for the less ambitious (25% in 2030) and more ambitious (35% in 2030) reduction targets are not very sensitive to our scenario assumptions. However, biofuel CI assumptions and particularly the ZEV usage assumptions significantly impact projected prices for the 30% by 2030 reduction target.

7 Summary

The California Low Carbon Fuel Standard is entering a new phase of more ambitious and aggressive CO2 reduction. In this report, we present our projections for the expected supply of and demand for LCFS credits through 2030, as well as through 2035. Our main approach is to apply time-series forecasting methods to project the expected demand for transportation fuels and combine that with the expected evolution of fuel prices and carbon intensities as well as complementary policies' impact on the fuel mix.

While pre-existing trends and complementary policies imply that the carbon intensity of California's transportation fuels will steadily decrease over the next decade plus, the prospects for success in achieving more aggressive LCFS targets by 2030 will be highly dependent on several factors for which historic trends provide less insight. These factors include the following.

- The pace of adoption of both light-duty and heavy-duty ZEV vehicles and the amount of conventional fuel that is displaced by each additional ZEV.
- The future role played by biomethane supplied from farms and other sources.
- The pace of adoption of technologies such as Carbon Capture and Sequestration that could dramatically lower the carbon intensities of some existing fuels, particularly ethanol.
- The ability of suppliers to supply and distribute extremely high amounts of renewable diesel (RD) into California's diesel pool.

Many of our scenarios result in the market exhausting the ability to blend additional renewable diesel into the diesel pool (because diesel reaches 100% renewable share), leaving no obvious means of compliance for the LCFS in that given year.[41] In most scenarios this credit deficit arises shortly before or after 2030.

In many scenarios the credit imbalance improves towards the year 2035, leading to lower LCFS credit price projections when we consider 2035 as the end-year for our forecast, rather than 2030. However, there is considerable uncertainty in these later years.

[41] Alternative jet fuel, which can generate credits in the LCFS while petroleum jet fuel counterpart does not generate deficits, could provide an outlet for additional renewable fuel volumes, but would have to do so in sufficient volume to cover accumulated deficits (without causing a reduction in deficit generation, as RD displacement of on-road diesel does).

Our results provide statistically valid distributions of LCFS demand drivers and of credit balances given the assumptions used for a specific scenario on factors such as ZEV usage, carbon intensities, methane, and infrastructure credits. We also examine how those distributions change under a range of alternative assumptions regarding these factors. The credit balance distributions across those scenarios are what conveys the truly broad range of possible outcomes for the LCFS. The range of these distributions grows substantially after 2030, reflecting massive uncertainty about how the fuels market will evolve in California under the LCFS and other state policy, within and beyond the next half decade, and the implications for LCFS compliance.

Our results imply that the program can accommodate a relatively aggressive target of 43% by 2035, but only if everything breaks right and many best-case outcomes arise toward the middle of the next decade. By contrast, if ZEV penetration falls well below targets, the program could reach cumulative deficits of 60 to 100 MMT by 2035. Our median forecast of our baseline scenario, targeting 30% carbon intensity reduction by 2030 and 43% by 2035, forecasts a small but significant cumulative deficit by 2035.

Under such circumstances, the role of cost-containment mechanisms will be critical for determining LCFS prices, and likely the overall viability of the program. We have assumed that LCFS prices will hit the containment price currently in place, now roughly $239/ton in 2022 Dollars. However, current policy is designed to contain prices only during transitory credit shortages not chronic shortages that result in compounding deficits accumulating over multiple years.[42] In this sense, our price forecasts represent a lower bound on pricing outcomes in scenarios where there are no compliance options viable at a cost of $239 or lower.

[42] This is especially the case for scenarios that exhaust the 10 million ‘advanced credit’ reserve that allows borrowing from future residential charging activity to shore up the credit price ceiling (and which would need to be paid back under more stringent targets, beyond the timeframe under consideration here).

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Appendix A

This Appendix contains figures, tables, and equations that are referenced in the text and may be relevant to the reader.

A.1 Additional Output from Simulations and the VEC Model

The estimates of the β and Γ matrices from the VEC model in equation 5 appear in Table 8.

Table 8. Short-Run Coefficient Estimates from VEC Model

	ΔY_{1t}	ΔY_{2t}	ΔY_{3t}	ΔY_{4t}	ΔY_{5t}	ΔY_{6t}
Panel A: Estimates of α Matrix						
$Y_{1,t-1}$	-0.0524	0.537***	-0.287	-0.0312*	0.482	-0.0455
	(0.0582)	(0.171)	(0.235)	(0.0178)	(0.366)	(0.0295)
$Y_{2,t-1}$	0.0374	-0.285***	-0.0182	0.0129	0.0146	0.0477***
	(0.0308)	(0.0905)	(0.124)	(0.00942)	(0.194)	(0.0156)
$Y_{3,t-1}$	-1.30e-05	0.101**	-0.171***	-0.000946	0.242**	0.00406
	(0.0163)	(0.0480)	(0.0659)	(0.00500)	(0.103)	(0.00828)
Panel B: Estimates of Γ Matrix						
$\Delta Y_{1,t-1}$	-0.521***	-0.924***	0.433	0.0437	0.171	0.177***
	(0.110)	(0.323)	(0.443)	(0.0336)	(0.690)	(0.0556)
$\Delta Y_{1,t-2}$	-0.197*	-0.582*	0.0912	0.0659*	0.412	0.193***
	(0.114)	(0.334)	(0.458)	(0.0347)	(0.714)	(0.0575)
$\Delta Y_{1,t-3}$	0.00807	-0.784**	0.0888	0.0163	0.0556	0.0408
	(0.105)	(0.310)	(0.425)	(0.0322)	(0.663)	(0.0534)
$\Delta Y_{2,t-1}$	-0.00600	-0.442***	-0.0965	0.00603	-0.230	-0.0166
	(0.0373)	(0.110)	(0.150)	(0.0114)	(0.234)	(0.0189)
$\Delta Y_{2,t-2}$	0.00507	-0.293***	-0.0277	0.00396	-0.0139	-0.00602
	(0.0371)	(0.109)	(0.150)	(0.0114)	(0.234)	(0.0188)
$\Delta Y_{2,t-3}$	-0.00171	-0.0353	-0.184	-0.00665	0.0813	-0.00891
	(0.0310)	(0.0911)	(0.125)	(0.00948)	(0.195)	(0.0157)
$\Delta Y_{3,t-1}$	-0.0288	-0.130*	0.413***	0.000863	0.0634	0.00776
	(0.0257)	(0.0755)	(0.104)	(0.00785)	(0.161)	(0.0130)
$\Delta Y_{3,t-2}$	-0.0458*	-0.0967	-0.0881	0.0115	0.137	-0.00312
	(0.0259)	(0.0762)	(0.105)	(0.00793)	(0.163)	(0.0131)
$\Delta Y_{3,t-3}$	-0.0242	0.0273	-0.000206	0.00163	-0.299*	0.0192

	ΔY_{1t}	ΔY_{2t}	ΔY_{3t}	ΔY_{4t}	ΔY_{5t}	ΔY_{6t}
	(0.0265)	(0.0779)	(0.107)	(0.00810)	(0.167)	(0.0134)
$\Delta Y_{4,t-1}$	-0.0431	-0.0682	1.067	-0.150*	-0.0675	-0.142
	(0.273)	(0.804)	(1.103)	(0.0836)	(1.720)	(0.138)
$\Delta Y_{4,t-2}$	0.119	0.379	0.926	-0.127	0.191	-0.122
	(0.269)	(0.792)	(1.086)	(0.0823)	(1.694)	(0.136)
$\Delta Y_{4,t-3}$	-0.0618	0.806	-0.905	-0.131	-0.200	-0.0755
	(0.269)	(0.792)	(1.086)	(0.0823)	(1.694)	(0.136)
$\Delta Y_{5,t-1}$	-0.0115	0.0386	-0.0671	0.00646	0.254**	0.0202**
	(0.0158)	(0.0466)	(0.0639)	(0.00484)	(0.0996)	(0.00802)
$\Delta Y_{5,t-2}$	0.0118	-0.00318	-0.0839	-0.00420	-0.0779	0.00642
	(0.0163)	(0.0478)	(0.0657)	(0.00498)	(0.102)	(0.00824)
$\Delta Y_{5,t-3}$	0.0283*	-0.0565	-0.0478	-0.000578	0.187*	0.00985
	(0.0165)	(0.0486)	(0.0667)	(0.00506)	(0.104)	(0.00837)
$\Delta Y_{6,t-1}$	-0.115	0.688	-0.00799	0.0106	-1.879	-0.0395
	(0.190)	(0.558)	(0.766)	(0.0581)	(1.195)	(0.0962)
$\Delta Y_{6,t-2}$	0.146	0.835	-0.876	0.0210	-0.131	0.00548
	(0.184)	(0.543)	(0.744)	(0.0564)	(1.161)	(0.0935)
$\Delta Y_{6,t-3}$	0.169	0.587	1.583**	-0.0174	1.136	-0.0852
	(0.184)	(0.542)	(0.743)	(0.0563)	(1.159)	(0.0933)
Constant	-0.0190	-0.00442	-0.0121	-0.0266***	-0.00670	-0.00691
	(0.0224)	(0.0658)	(0.0903)	(0.00685)	(0.141)	(0.0113)
Observations	127	127	127	127	127	127

Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

In Table 9, we summarize the annual mean of the forecast for the 6 variables coming out of the simulations over the compliance period.

Table 9. Summary Statistics for Baseline Variables across Random Samples

	CaRFG (Billion gal.)	**Diesel** (Billion gal.)	**VMT** (Billion mi.)	**Real Brent Oil Price** (2018 $)	**Real Soy Price** (2018 $)	**Real CA GSP** (Tri. 2018 $)
2022	13.942	3.74	313.898	66.537	12.406	3.114
2023	13.724	3.858	317.043	62.175	13.325	3.114
2024	13.708	3.919	321.18	61.229	13.171	3.161
2025	13.754	3.984	325.482	63.289	12.961	3.237
2026	13.821	4.042	329.646	65.323	12.906	3.318
2027	13.875	4.116	333.658	67.343	12.753	3.4
2028	13.919	4.186	337.298	71.446	12.689	3.485
2029	13.93	4.252	340.735	74.103	12.769	3.574
2030	13.957	4.323	344.158	77.204	12.894	3.663
2031	13.964	4.395	347.29	81.267	12.958	3.754
2032	13.955	4.474	350.293	84.987	13.118	3.845
2033	13.955	4.558	353.052	88.624	13.236	3.938
2034	13.94	4.64	355.817	91.939	13.576	4.032
2035	13.926	4.728	358.374	95.753	13.675	4.127

A.2 LCFS Credit Implementation Details

In this subsection of the Appendix, we provide details regarding how credits are generated under the LCFS. To illustrate how quantities of fuel translate into credits or deficits, we adopt the notation of the LCFS regulation and define the following terms.

- I is the set of credit-generating fuels.
- $XD \in \{gasoline, diesel\}$ represents the fuel being displaced.
- $EER_i^{XD}$the dimensionless Energy Economy Ratio (EER) of fuel i relative to gasoline or diesel. The EER is fuel and vehicle specific.
- ED_i is the energy density of fuel i.
- $CI_{standard,t}^{XD}$ is the CI requirement for fuel XD in the year of quarter t. The standard for each year is presented in Table 10 and Table 11.
- $CI_{reported,i,t}^{XD}$ is the EER-adjusted CI for fuel i, displacing fuel XD in quarter t.
- $E_{displaced,i,t}^{XD}$ is the total amount of fuel energy for fuel XD that is displaced by alternative fuel i in quarter t.
- E_it is the quantity of energy of fuel i in quarter t.
- Q_it is the quantity of fuel i used in quarter t.
- $C = 1 \times 10^{-6} \frac{MT}{gCO_2e}$ converts credits into metric tons.

Let $i \in I$ denote the fuel type (i.e., i= biodiesel, ethanol, electricity, etc.). LCFS credits or deficits for each fuel or blendstock for which a fuel reporting entity is the credit or deficit generator will be calculated according to the following equation in quarter t.

$$Credits_{i,t}^{XD}\ (MT) = \left(CI_{standard,t}^{XD} \& -\ CI_{reported,i,t}^{XD}\right) \times E_{displaced,i,t}^{XD} \times C \tag{14}$$

where

$$CI_{reported,i,t}^{XD} = \frac{CI_{it}}{EER_i^{XD}} \tag{15}$$

and

$$E_{displaced,i,t}^{XD} = E_{it} \times EER_i^{XD} \tag{16}$$

and

$$E_{it} = ED_i \times Q_{it} \tag{17}$$

Substituting equations 15, 16, and 17 into equation 14, we can then express credits as:

$$Credits_{it}^{XD}(MT) = \left(CI_{standard,t}^{XD} - \frac{CI_{it}}{EER_i^{XD}}\right) \times ED_i \times Q_{it} \times EER_i^{XD} \times C \tag{18 a}$$

Deficits reduction due to fuel displacement :

$$Deficit\ Reduction_{it}^{XD}(MT) = -\left(CI_{standard,t}^{XD} - \frac{CI_{it}}{EER_i^{XD}}\right) \times ED_i \times Q_{it} \times EER_i^{XD} \times C\ \times\ Share_{it} \tag{18 b}$$

Aggregating fuels and quarters over the compliance period, the total quantity of credits supplied over the compliance period will be

$$Aggregate\ LCFS\ Credits = \Sigma_{i \in I} \Sigma_{t=0}^{T} Credits_{it}^{XD} \tag{19}$$

In the calculations above, deficits are equivalent to negative credits. The compliance period is characterized by T, which for our purpose is the fourth quarter of 2035 and $t = 0$ corresponds to the first quarter of 2022.

Table 10. LCFS CI Standards for Gasoline

year	Gasoline Baseline (2010)	Gasoline Standard		
2011	95.85	95.61	95.61	95.61
2012	95.85	95.37	95.37	95.37
2013	98.95	97.96	97.96	97.96
2014	98.95	97.96	97.96	97.96
2015	98.95	97.96	97.96	97.96
2016	98.47	96.5	96.5	96.5
2017	98.47	95.02	95.02	95.02
2018	98.47	93.55	93.55	93.55
2019	99.45	93.23	93.23	93.23
2020	99.44	91.98	91.98	91.98
2021	99.44	90.74	90.74	90.74
2022	99.44	89.5	89.5	89.5
2023	99.44	88.25	88.25	88.25
2024	99.44	86.3	85.59	84.88
2025	99.44	84.35	82.93	81.51
2026	99.44	82.39	80.26	78.13
2027	99.44	80.44	77.6	74.76
2028	99.44	78.49	74.94	71.39
2029	99.45	76.54	72.28	68.01
2030	99.44	74.58	69.61	64.63
2031	99.44	72.62	66.94	61.26
2032	99.44	70.67	64.28	57.89
2033	99.44	68.72	61.62	54.51
2034	99.44	66.77	58.95	51.14
2035	99.44	64.81	56.29	47.77
	% Reduction in 2030	**25%**	**30%**	**35%**
	% Reduction in 2035	**35%**	**43%**	**52%**

Table 11. LCFS CI Standards for Diesel

year	Diesel Baseline (2010)	Diesel Standard		
2011	94.71	94.47	94.47	94.47
2012	94.71	94.24	94.24	94.24
2013	98.02	97.04	97.04	97.04
2014	98.02	97.04	97.04	97.04
2015	98.02	97.04	97.04	97.04
2016	101.97	99.93	99.93	99.93
2017	101.84	98.28	98.28	98.28
2018	101.76	96.67	96.67	96.67
2019	100.06	93.80	93.80	93.80
2020	99.89	92.40	92.40	92.40
2021	99.68	90.96	90.96	90.96
2022	100.45	90.41	90.41	90.41
2023	100.45	89.15	89.15	89.15
2024	100.45	87.18	86.46	85.74
2025	100.45	85.20	83.77	82.33
2026	100.45	83.23	81.08	78.93
2027	100.45	81.26	78.39	75.52
2028	100.45	79.28	75.70	72.11
2029	100.45	77.31	73.01	68.70
2030	100.45	75.34	70.32	65.29
2031	100.45	73.37	67.63	61.88
2032	100.45	71.39	64.93	58.48
2033	100.45	69.42	62.24	55.07
2034	100.45	67.45	59.55	51.66
2035	100.45	65.47	56.86	48.25
	% Reduction in 2030	**25%**	**30%**	**35%**
	% Reduction in 2035	**35%**	**43%**	**52%**

A.3 Additional Tables

Table 12. 2022-2035 Average Annual Credits/Deficits by Source (Baseline)

2022-2035 Average Annual Credits and Deficits 30% (2030) Target - 1000 simulations													
year	**CARBOB**	**ULSD**	**BBD**	**Ethanol**	**Methane**	**LDV Electricity**	**HDV Electricity**	**HDV Hydrogen**	**MDV Electricity**	**Forklift, Guiderail and Other**	**Annual Bank**	**Infrastructure**	**SUM**
2022	-17.50	-3.10	11.56	3.24	2.80	4.61	0.00	0.00	0.00	2.09	0.68	0.52	**4.88**
2023	-18.72	-3.56	11.63	3.10	3.04	5.94	0.05	0.04	0.00	2.09	0.68	0.56	**4.85**
2024	-22.05	-4.39	11.17	2.86	3.29	7.19	0.13	0.10	0.00	2.09	0.68	0.66	**1.71**
2025	-25.40	-5.24	10.69	2.64	3.53	8.40	0.27	0.19	0.00	2.09	0.68	0.77	**-1.40**
2026	-28.71	-6.08	10.15	2.42	3.78	9.55	0.43	0.29	0.00	2.09	0.68	0.87	**-4.54**
2027	-31.92	-6.94	9.63	2.21	4.03	10.64	0.64	0.43	0.00	2.09	0.68	0.97	**-7.57**
2028	-35.03	-7.80	9.07	2.00	4.27	11.67	0.85	0.57	0.00	2.09	0.68	1.07	**-10.57**
2029	-37.96	-8.64	8.48	1.78	4.52	12.63	1.10	0.71	0.00	2.09	0.68	1.17	**-13.46**
2030	-40.86	-9.48	7.88	1.58	4.76	13.54	1.38	0.87	0.00	2.09	0.68	1.26	**-16.31**
2031	-43.26	-10.27	7.24	1.37	5.01	14.96	1.68	1.10	0.00	2.09	0.68	1.34	**-18.07**
2032	-45.08	-11.03	6.59	1.15	5.26	16.85	2.01	1.36	0.00	2.09	0.68	1.40	**-18.72**
2033	-45.94	-11.74	5.93	0.94	5.50	19.16	2.34	1.66	0.72	2.09	0.68	1.44	**-17.23**
2034	-46.47	-12.39	5.25	0.74	5.75	21.86	2.67	1.96	0.70	2.09	0.68	1.47	**-15.70**
2035	-46.26	-12.97	4.58	0.55	5.99	24.88	3.03	2.26	0.68	2.09	0.68	1.48	**-13.03**

Table 13. 2022-2035 Average Annual Credits/Deficits by Source (Post-Blend)

2022-2035 Average Annual Credits and Deficits 30% (2030) Target (Blend to Compliance) - 1000 simulations													
year	**CARBOB**	**ULSD**	**BBD**	**Ethanol**	**Methane**	**LDV Electricity**	**HDV Electricity**	**HDV Hydrogen**	**MDV Electricity**	**Forklift, Guiderail and Other**	**Annual Bank**	**Infrastructure**	**SUM**
2022	-17.50	-3.10	9.01	3.24	2.80	4.61	0.00	0.00	0.00	2.09	0.68	0.52	**2.33**
2023	-18.72	-3.56	9.00	3.10	3.04	5.94	0.05	0.04	0.00	2.09	0.68	0.56	**2.21**
2024	-22.05	-4.39	8.52	2.86	3.29	7.19	0.13	0.10	0.00	2.09	0.68	0.66	**-0.94**
2025	-25.40	-4.83	8.79	2.64	3.53	8.40	0.27	0.19	0.00	2.09	0.68	0.77	**-2.89**
2026	-28.71	-3.53	11.45	2.42	3.78	9.55	0.43	0.29	0.00	2.09	0.68	0.87	**-0.70**
2027	-31.92	-2.43	12.65	2.21	4.03	10.64	0.64	0.43	0.00	2.09	0.68	0.97	**-0.03**
2028	-35.03	-1.39	12.99	2.00	4.27	11.67	0.85	0.57	0.00	2.09	0.68	1.07	**-0.25**
2029	-37.96	-0.58	12.58	1.78	4.52	12.63	1.10	0.71	0.00	2.09	0.68	1.17	**-1.29**
2030	-40.86	-0.18	11.56	1.58	4.76	13.54	1.38	0.87	0.00	2.09	0.68	1.26	**-3.34**
2031	-43.26	-0.10	10.19	1.37	5.01	14.96	1.68	1.10	0.00	2.09	0.68	1.34	**-4.95**
2032	-45.08	-0.08	8.76	1.15	5.26	16.85	2.01	1.36	0.00	2.09	0.68	1.40	**-5.60**
2033	-45.94	-0.21	7.26	0.94	5.50	19.16	2.34	1.66	0.72	2.09	0.68	1.44	**-4.37**
2034	-46.47	-0.51	5.74	0.74	5.75	21.86	2.67	1.96	0.70	2.09	0.68	1.47	**-3.33**
2035	-46.26	-1.34	4.17	0.55	5.99	24.88	3.03	2.26	0.68	2.09	0.68	1.48	**-1.80**

Table 14. Probability of the implied BBD Blend Rate $\geq$ 100%

Scenario	**Baseline**			**A1: Low ZEV CI**			**A2: Low Biofuel Cis**			**A3: Low ZEV usage**			**A4: High ZEV usage**		
Target by 2030	**25%**	**30%**	**35%**	**25%**	**30%**	**35%**	**25%**	**30%**	**35%**	**25%**	**30%**	**35%**	**25%**	**30%**	**35%**
2022	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2023	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2024	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2025	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2026	0%	0%	3%	0%	0%	1%	0%	0%	0%	0%	0%	26%	0%	0%	0%
2027	0%	1%	61%	0%	0%	40%	0%	0%	6%	0%	15%	92%	0%	0%	9%
2028	0%	19%	98%	0%	9%	93%	0%	1%	58%	1%	62%	100%	0%	0%	59%
2029	0%	56%	100%	0%	38%	100%	0%	10%	94%	5%	93%	100%	0%	7%	94%
2030	1%	86%	100%	0%	71%	100%	0%	39%	100%	14%	99%	100%	0%	22%	99%
2031	1%	93%	100%	1%	86%	100%	0%	59%	100%	22%	100%	100%	0%	32%	100%
2032	2%	94%	100%	1%	88%	100%	0%	66%	100%	24%	100%	100%	0%	27%	100%
2033	0%	87%	100%	0%	76%	100%	0%	55%	100%	12%	100%	100%	0%	8%	100%
2034	0%	77%	100%	0%	63%	100%	0%	42%	100%	6%	100%	100%	0%	2%	99%
2035	0%	52%	100%	0%	37%	100%	0%	22%	100%	2%	99%	100%	0%	0%	91%

A.4 Additional Figures

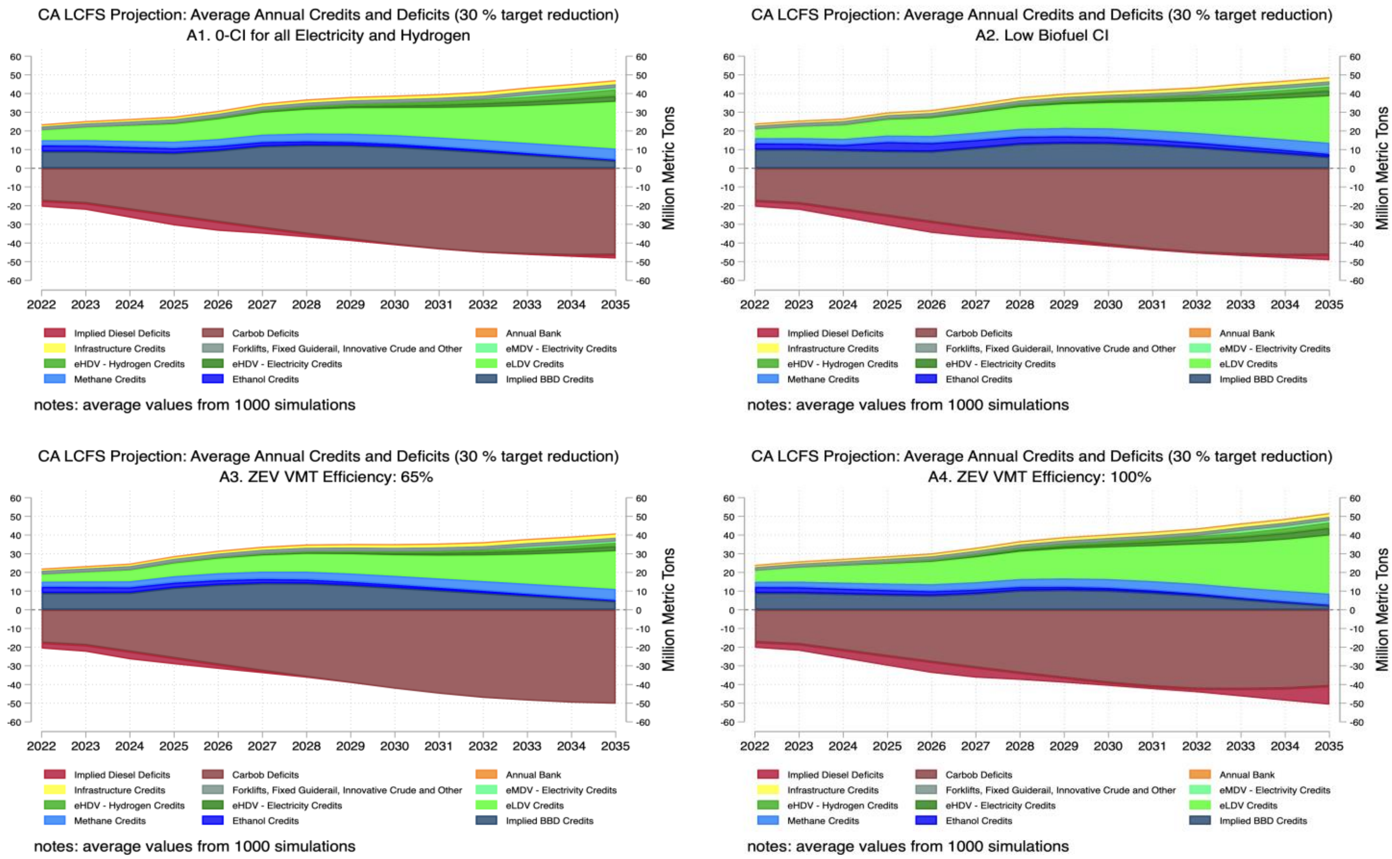

Figure 11: Annual Sources of Credits and Deficits by Scenario Post-Blend