Title: A Model of State and Federal Biofuel Policy:
Feasibility Assessment of the California Low Carbon Fuel Standard

Authors:

Adam Christensen (corresponding author)
Johns Hopkins University
Department of Geography and Environmental Engineering
3400 N Charles St
Ames Hall 313
Baltimore, MD 21218
847.331.8788
adam.christensen@gmail.com

Benjamin Hobbs
Johns Hopkins University
Department of Geography and Environmental Engineering
3400 N Charles St
Ames Hall 313
Baltimore, MD 21218
410.516.4681
bhobbs@jhu.edu

Keywords: biofuel, market model, policy, renewable fuel, tax credits, fuel prices, low carbon fuel standard, renewable fuel standard

Abstract

Biofuel policy is under near constant review at both the federal and state level. For example, as part of on-going implementation of the California Low Carbon Fuel Standard (LCFS), the California Air Resources Board has recently designed and is implementing a new cost containment mechanism as part of the compliance credit market embedded within the LCFS. This mechanism was born out of concerns that there may be a shortage of LCFS credits, which could lead to an unpredictable rise in the credit price. In general, it is important to develop appropriate mathematical tools with which to estimate the impact of policy changes on biofuel markets. Motivated by the need for such analyses, a novel regional market model is developed that quantifies several categories of impacts across different regional markets. These market impacts include policy-specific effects of California's LCFS as well as the federal level Renewable Fuel Standard (RFS). Several scenarios are developed to highlight issues of long term LCFS feasibility; in particular, this work highlights the role that biodiesel/renewable diesel might need to play in order for the goals of the LCFS to be met. We find that biodiesel blending will need to increase dramatically within a short period of time (i.e., by 2016 all diesel fuel would need to be 20% blends) in order to generate enough LCFS credits. Additionally, this model highlights the indirect market linkages between the LCFS/RFS credit markets; certain biofuels can register under both programs and generate both credits. As a result, if attempts in the US Congressional to fully repeal the RFS are successful, it is possible that

the LCFS credit price could increase more than 50%. Symmetrically, it is also true that if the LCFS program were eliminated, certain RFS credit markets would also be impacted, but to a lesser extent.

1. Introduction

1.1 Problem Statement

Understanding how biofuels are produced and consumed in the transportation fuel market is challenging for three fundamental reasons. First, there is little demand for pure biofuels in transportation applications. This is because there are very few vehicles in the United States fleet that can burn high percentage blends of biofuel. For 2014, the Energy Information Administration (EIA) estimates that 6% of the light truck and car market can consume ethanol in blends up to 85% (E85), but only a smaller proportion of these vehicles actually burn E85 due to fuel availability issues [1]. B100 (100% biodiesel) can, theoretically be burned in many diesel engines on the road today, but engine manufacturers often only warranty engines up to B20 (20% biodiesel, 80% petroleum diesel) [2].

As a consequence, the second challenge is that biofuel must compete on a cost basis with many other liquid fuels that are mixed together to create a final transportation fuel. Fuel blenders are those entities in the supply chain that mix final transportation fuels (i.e., gasoline and diesel); their final products must meet relevant ASTM standards as well as fuel quality standards enforced by the Environmental Protection Agency (EPA) [3]. Other than these constraints, the fuel blender has discretion in how to blend the final product. This puts biofuel producers in direct economic competition with market entities that rely entirely on fossil fuel feedstocks (crude oil refiners, natural gas liquid producers, and other chemical manufacturers).

Third, there are many policies at the state and federal levels that encourage the production/consumption of biofuels. However, variations and inconsistencies among these policies creates a complex system of market distortions with unintended consequences [4]. Beyond the special tax treatment and minimum blending requirements that biofuels receive, policy makers are working to incentivize the consumption of biofuel with lower lifecycle greenhouse gas (GHG) emissions. Examples of these policies are the national Renewable Fuel Standard (RFS) and the California Low Carbon Fuel Standard (LCFS) [5]–[7]. More recently, Oregon has introduced regulations to establish their own Clean Fuel Standard [8]. Despite the fact that California and Oregon share a border, there are serious inconsistencies in the two program's carbon accounting; furthermore, carbon credits generated within each program cannot be traded between the two states. The state of Washington is also considering developing a LCFS of its own, but at the time of writing only a basic framework/feasibility study had been released by Governor Inslee [9]. Despite these differences, the model formulation presented here is general enough to allow for the inclusion of other states' LCFS policies. Regulating lifecycle GHG emissions poses some unique challenges and results in market distortions since the carbon emissions are a function of all upstream processing rather than a pure intrinsic property of the biofuel [10], [11].

As a result of the interwoven network of policies and markets, it can be difficult for policy makers to understand the impacts of potential policy changes; it can also be difficult for obligated parties (e.g., fuel suppliers) to untangle a least-cost compliance strategy.

This work focuses on presenting the rationale and mathematical structure of a model of the US biofuel market with state-level policy detail. The formulation is designed to be computationally efficient and is motivated by a desire to inform federal and state regulators of the impacts of their decisions on market behavior. This model also includes policy details of the RFS and the embedded renewable identification number (RIN) compliance credit markets as well as California's LCFS credit market. Previous models that have not include all pertinent details of RIN markets or have been developed within a framework that does not explicitly consider the behaviors of all the various liquid fuel market players [12]–[15]. The proposed model includes all immediately relevant sub-mandates (biomass-based diesel, advanced, and renewable) as well as potentially strategic details of RIN/LCFS credit banking. The model structure is general enough to allow for additional policies to be considered; for example, future work could include influences of the California cap and trade system (AB32) [16].¹

This paper is motivated by the need to develop a concise mathematical representation of the biofuel market, including state and federal level policies. Others have modeled the biofuel market before, but a single model that includes the LCFS, RFS, along with a state-level description of the US has not been proposed in literature [17]–[19]. Beyond the need to develop the mathematical model, this paper is motivated by two primary research questions:

- 1) Is the LCFS, as current written, feasible? If not, what might need to change in the biofuel marketplace to ensure feasibility? and
- 2) How do the RFS and LCFS policies impact each other?

Specifically, we are interested in how might RIN and LCFS credit prices influence each other in the event that either of the policies be eliminated. These two policies have not been controversy-free, many proposals for their elimination being promoted at the state and federal levels. This analysis would help highlight any unintended consequences should any of these proposals get implemented.

In the rest of Section 1 contains a discussion of state level biofuel policy, including the CA LCFS. Additional policy background, including challenges faced by regulators in charge of implementing the Renewable Fuel Standard program are included in a detailed appendix. The appendix also briefly describes the programmatic requirements associated with the RFS. Section 2 is devoted to documenting, in detail, the model structure, solution methodology as well as underlying assumptions and data sources. Specific model parameters are also tabulated in an appendix. Section 3 develops scenarios that

¹ Beginning on January 1, 2015 the suppliers of gasoline blendstocks and diesel fuel oils in California will have a compliance obligation for all GHG emissions that would result from combustion of all such fuels (17 California Code of Regulations §95852).

will help to answer key questions posed in the previous paragraph regarding the feasibility of the LCFS; results from these scenarios will be discussed in Section 4. Section 5 will conclude with policy implications and suggestions for further research.

1.2 State-Level Policy and the California Low Carbon Fuel Standard (LCFS)

State-level fuel tax policies vary widely throughout the US. For example as of July 1, 2014, the state of New York taxes gasoline at a rate of 50.5 cents/gallon while Alaska only taxes gasoline at 18.4 cents/gallon [20], [21]. At the time of writing there were no state-level tax credits that were available for biofuels (although should they become available, their effect would be easy to account for in our modeling framework).

Of particular note with regard to state biofuel policy is the California LCFS. California fuel consumption represents approximately 11% of all gasoline and 8% of all diesel fuel in the US; California is thus the largest state consumer of transportation fuels in the US. An often-touted policy outcome of low carbon fuel standards is to stimulate investment in second- or third-generation fuel production facilities; it is necessary that the market be large enough to spark the interest in these capital-intensive projects. Therefore, encouraging California to adopt a LCFS was a strategic decision for proponents of biofuel consumption.

As mentioned above, the LCFS program regulates an average carbon intensity of the fuel produced in/imported to California. Therefore, the regulated parties under the LCFS are all fuel producers. To track the average carbon intensity of fuels in California, the state uses a credit/deficit accounting system. LCFS credits (units: metric ton of emissions reduced) are generated when a fuel producer/(importer) produces/(imports) a fuel that is below the carbon intensity listed in the regulation, while deficits (in metric tons) are generated when a fuel is produced/(imported) that has a higher carbon intensity. LCFS credit prices are typically reported in units of \$/metric ton. This structure implies that a carbon-intensive biofuel producer can generate deficits and would therefore be responsible for acquiring credits to offset those deficits. This behavior does happen, but deficits generated by biofuel producers are small compared to those generated by oil refiners. So for modeling purposes, we assume that oil refiners and importers of petroleum blendstocks are the only entities that generate deficits.

The performance-based LCFS policy structure allows for a wide variety of other compliance pathways to exist, and in theory, should ease the burden of compliance. To date, compliance has been achieved through five primary fuels: biodiesel, renewable diesel, ethanol, natural gas, and bio-methane; the evolution of compliance since 2011 for these fuels is shown in Figure 1. The “Other” category in Figure 1 includes LCFS credits generated by electrification and by changes to oil refiner operations, which generated only a small number of credits. From the second subplot in Figure 1, it can be seen that in all years, over-compliance has been a key strategy (i.e., # credits generated > # deficits generated).

Figure 1: Percent of LCFS credit generation by fuel and the ratio of the credits to deficits generated.

There are a number of other incentives in California and other states designed to target other parts of the biofuel supply chain (tax benefits for pumping infrastructure, rebates, etc.). These are not modeled in this work due to unavailability of public data. It is not expected that the omission of these infrastructure-related incentives will affect the primary conclusions of this paper. The model presented here makes the assumption that if renewable fuel is available it can be consumed, regardless of existing infrastructure challenges; in this way our results might actually under-predict the LCFS credit shortage.

2. Methods

The model is formulated as a multi-period competitive equilibrium model among producers, refineries, distributors, and consumers of transport fuels in the US with a state-level granularity. In a competitive equilibrium, each market participant maximizes its profit subject to prices that it believe it cannot alter, and the prices are set at levels that clear all markets. To model such a market, we can formulate a mixed complementarity problem (MCP) which consists of the first-order (Kuhn Tucker) conditions of each party's profit maximization problem plus market clearing (supply = demand), which is what we previously proposed for the national liquid fuel markets [22].

In the situation we model here, because we model demand as fixed (perfectly inelastic) and because technical relationships and costs are represented by linear functions, the equilibrium problem can also be formulated as a linear optimization problem (linear program, LP) whose solution is the market equilibrium [23]. The LP was written in GAMS and solved using the CPLEX package, with the default solver options resulting in a solution time on the order of 10 seconds for a model with 32,000 equations and 250,000 variables. Due to the high efficiency of LP solvers, solution times for LPs are typically much faster when compared to similarly sized MCPs. This efficiency allowed the LP model to incorporate much more detail than our liquid fuels MCP model [22], in particular state-level data over multiple time periods for several market players. While the LP formulation allows for further refinements, the MCP formulation does

provide some additional flexibility to model elastic demand and to generalize to other interesting bi-level problem formulations at the expense of a more computationally complicated model [23], [24].

The following subsections are dedicated to describing data inputs and formulations for the commodities and market participants that we model. In particular, notation and basic model structure are summarized in Section 2.1, while Section 2.2 summarizes the model objective function, constraints, and data inputs.

2.1 Model Considerations and Notation

2.1.1 Notation/Set Definitions

All notation for model decision variables (all of which are constrained to be nonnegative) as well as sets are detailed in the appendix.

2.1.2 Overall Market Structure

EPA publishes public RIN data on a monthly basis for each type of RIN [25]. RINs are assigned a code (commonly referred to as a “D” code) based on the type of biofuel generated as described in section 1.2. We assume that cellulosic fuels do not influence the operating RIN market; to date less than 1% of all generated RINs are cellulosic RINs (D3 and D7). Based on this background, we approximate the biofuel production market by defining four groups of market players who are the sources of fuel in the US market: ethanol producers, biodiesel producers, sugarcane ethanol importers and renewable diesel importers. The other participants that make up the downstream parts of the US supply chain are crude oil refiners, fuel blenders, fuel traders and RIN traders, and finally the consumer. Consumers of transportation fuel are considered to have perfectly inelastic demand, and the magnitude of this demand is estimated from EIA’s Annual Energy Outlook 2013 [26]. It is possible to model elastic demand using the LP framework presented here through successive linear programming or a Gauss-Seidel style algorithm [27], [28].

This model is formulated at the state level. Prices and quantities of each commodity modeled are determined endogenously within the model. Each market player (producers, refiners, and blenders) is located within a state, assuming there is physical production/import capacity available. Fuel traders and RIN traders operate between regions and can profit from arbitraging these products. It is assumed that renewable diesel only enters into California (CA) and is consumed in CA. To explicitly track shipments of fuel into CA for compliance use in the LCFS the set l is created to explicitly separate quantities of fuels produced for the CA market and those that are not. The model does allow additional shipments of biofuels into CA without generating deficits if the biofuel is not registered under the LCFS; petroleum blendstocks produced or imported into CA generate deficits that must be offset. This means that each state has a local market for ethanol/LCFS-ethanol, sugarcane ethanol/LCFS-sugarcane ethanol, biodiesel/LCFS-biodiesel, LCFS-renewable diesel, blendstock for oxygenate blending (BOB)/LCFS-BOB, unblended diesel/LCFS-unblended diesel, finished gasoline, finished diesel, and D4/D5/D6 RINs. The model was developed with state level RIN markets in order to

investigate aspects of RIN trading among obligated parties; however, since RINs are traded electronically without additional transaction costs, all state prices will be the same in a competitive equilibrium. This is not the case with LCFS credit markets because those credits cannot be traded with other states.

A simplified schematic of the market model is shown in Figure 2. For simplicity, the network that describes the LCFS program has been omitted. All solid circles are market players, while open circles indicate where an endogenous price can be calculated. This basic structure is repeated in all regions. Regions trade only unblended fuel products; finished fuels are supplied to the region by a fuel blender player within that region

Figure 2: Market diagram.

2.1.3 What is Not Modeled

The model developed in this research is not coupled with agricultural markets nor does it attempt to explicitly capture land use changes. These are important dynamics to consider when assessing lifecycle GHG emissions for fuel production pathways, and for understanding how biofuel supply depends, for instance, on agricultural policies. However, because this model only includes approved fuels under the RFS, therefore land use change effects and GHG impacts are only implicitly considered through definition of the model's GHG coefficients. Supplies of all of these fuels is assumed to be inelastic.

All market players in the model are considered to be competitive, risk-neutral profit maximizers who have perfect information on market prices. Because of the risk neutrality and information assumptions, financial contracts and speculation are not considered. Within each region the biofuel market participants are each represented as an aggregate industry player. It is assumed that US gasoline and diesel markets are workably competitive, so that prices reflect marginal costs. There is however evidence of market power as measured by the Herfindahl-Hirschman Index (HHI), but the markets we consider are significantly concentrated only in the case of the refining market in the East

Coast region. It has increasing from an HHI of 1136 in 1990 to a level of 1819 in 2000; other regions were considered to be unconcentrated or only moderately concentrated [29].

The model assumes perfect foresight and its time periods are defined on a calendar year basis. Results from this model are presented through 2022. As a result of the annual rulemaking cycle that EPA engages in, future applications would need to update and re-run the model to fully consider programmatic adjustments.

2.1.4 Blending Finished Fuels for Consumption

In this formulation, the blender has the option to produce three finished fuel products in order to meet consumer demand. The blender can sell: finished E10 gasoline; finished E85 fuel; and diesel/biodiesel/renewable diesel blends at any levels (unless mentioned specifically). Since an upper limit on the blending of biodiesel is not included, the model will likely require blending beyond what is seen in actual market operation; however, limited public data exists on state level diesel/biodiesel blends. It is assumed that E85 would be valued on an energy-content basis relative to standard finished gasoline (E10). There is some initial evidence in Brazil that consumers will arbitrage their fuel preferences based on the energy content of the fuel [30], causing fuel prices to move towards convergence on a \$/megajoule basis. Following this, it is assumed that consumers in the US would make similar decisions. There are a number of other unique technical constraints that US consumers face when adopting E85 (i.e., number of flex-fuel vehicles); these constraints will affect the actual adoption of E85. However, these details are not explicitly included in our model at this time. There are a number of studies that focus on the intersection of consumer behavior, E85 adoption, infrastructure challenges and pricing [31]–[37]. As a result of the simplifications, this particular model is expected to over produce/consume E85.

2.2 Cost Minimization and Data Inputs

Below we present the overall objective function (total cost) that the market LP minimizes. Then subsections describe each category of constraints and data sources for the various market players.

$$\begin{aligned}
 TotalCost = & \sum_{\substack{p \in P(b), s \in S(b) \\ c \in C(b), l, y}} \left(\sum_{\text{inputs}} \alpha_i E_i q_{p,c,s,y}^l - \sum_{\text{coprod}} \beta_j E_j q_{p,c,s,y}^l - (TotTaxCred_{p,c,s,y} + ImportTariff_{c,y}) q_{p,c,s,y}^l \right) \\
 & + \sum_{\substack{p=blender \\ c,l,s,y}} (TotTaxRate_{s,c,y} - TotTaxCred_{p,c,s,y}) q_{p,c,s,y}^l \\
 & + \sum_{\substack{p=refiner \\ c \in C(bl), l, s \in S(bl), y}} E_{c,s,y} q_{p,c,s,y}^l \\
 & + \sum_{\substack{p=transporter \\ c,l,s,y}} DistMarkup_{c,s,y} purch_{p,c,s,y}^l \\
 & + 1 \times 10^6 S_y
 \end{aligned} \tag{1}$$

Here, the notation p represents elements in a set of players, $P(x)$, that are necessary for a product x to be in the market. For example, $P(b)$ represents all players that are required to produce biofuels in the set b ; similarly, $S(b)$ represents the set of states where those biofuel producers are located. The first summation in the above objective represents all costs associated with the production of the biofuel. Biofuel producers are modeled with a simple input-output production function. In these production functions, α_i is a yield parameter for process inputs for fuel type I , β_j is a yield parameter that describes the generation of a valuable co-product of type j , and E_j represents an exogenous (assumed) price of the input/co-product. The parameters $TotTaxRate_{s,c,y}$ and $TotTaxCred_{p,c,s,y}$ represent the sum of both federal and state policies in units of \$/gal. As an example, the process inputs to make biodiesel would be all elements of a set $i \in I(biodiesel)$ *{electricity, natural gas, methanol, oils}*. The second term would represent the revenues obtained from selling valuable co-products produced and sold at an exogenous price E_j ; for biodiesel, it is assumed that there are no co-products.

The second summation of the total cost function represents costs incurred by the fuel blender. It is assumed that the blender is the entity that is responsible for paying federal and state fuel taxes, as specified by the parameter $TotTaxRate_{s,c,y}$ (\$/gal). The third summation represents the costs borne by the refiner in producing BOB and unblended diesel fuel, the two elements in the set bl ; these costs are considered exogenous. The final summation represents costs generated by the fuel transporter. It is assumed that finished fuels are not transported explicitly; only their blend components are transported to demand areas.

In the following subsections, we provide more detail on the data inputs to this model. For clarity, the constraints in the model will be detailed under each market player's subsection. These constraints will describe both physical (capacity) constraints as well as policy limits.

2.2.1 Renewable Diesel Importer

Unlike fatty acid methyl ester (FAME)-based biodiesel that must meet ASTM standard specification D6751, renewable diesel is a hydrocarbon drop-in fuel that meets the diesel ASTM standard D975, which is the primary standard that governs all petroleum-based diesel fuel. Some other common names for renewable diesel are green diesel, hydrotreated renewable diesel (HRD), second-generation diesel, and hydroprocessed esters and fatty acids (HEFA). For this study, we will simply use the term renewable diesel for simplicity. Renewable diesel is produced from waste oils (animal fat, vegetable oils) that have been processed in a refinery to produce a diesel transportation fuel. The interested reader is directed to Knothe (2010) for a detailed explanation of processing and physical properties.

The primary benefit of renewable diesel, which is of key importance to this analysis, is that California considers renewable diesel to have a lifecycle carbon intensity as low as 16.21 gCO₂e/MJ produced from used cooking oil (Neste Oil-Singapore). This carbon intensity represents an 85% reduction in carbon emissions over traditional petroleum based diesel; the magnitude of the emissions reductions also makes this a valuable fuel

for achieving LCFS compliance. The market has responded to this incentive, and in Q4 of 2014, renewable diesel represented approximately 9% of LCFS credits generated. At the time of writing, there were just two entities that were registered under the LCFS to generate credits for the use of renewable diesel: Kern Oil & Refining Company in Bakersfield, CA and Neste Oil based in Singapore. Kern Oil produces a co-processed renewable diesel/petroleum diesel while Neste Oil is producing a 100% bio-based diesel fuel [38]. With a few exceptions, all shipments of renewable diesel were shipped to a California port [39]. It is logical to infer that these shipments were then consumed in CA to capture the value of the LCFS credit and avoid further transportation costs.

While public data exists on quantities shipped, there is very little public information regarding the cost of production of renewable diesel, and even the consumer price of renewable diesel is difficult to obtain. By some accounts, renewable diesel is sold to the consumer at a price that is competitive with petroleum diesel [40]. It is unclear if the cost curve for petroleum diesel and renewable diesel can safely be assumed to be the same. In light of this lack of public data, we rely on a previously obtained production cost function with yield parameters derived using the Aspen-Plus bio-refinery model [41], [42].

The yield parameters detailed in Equation (1) are tabulated in Table 5. Yield coefficients are in rough agreement with those that correspond to the tallow-to-renewable diesel pathway application submitted by Neste Oil as part of the California LCFS [43].

For modeling purposes, we assume that there is zero production of renewable diesel in the US and all imported renewable diesel enters into the CA market from Singapore. While these are simplifying assumptions, we know from EIA company-level import data and LCFS program documents that Neste Oil's renewable diesel product generated 100% of the renewable diesel LCFS credits in 2014. In prior years, Neste Oil generated the vast majority (2011 – 57%, 2012 – 97%, 2013 – 77%) of the renewable diesel LCFS credits. In 2014, renewable diesel imports from Finland and Bahrain represented 37% of all Neste Oil's imports (41.6 Mgals), while the rest originated from Singapore (112 Mgals). Shipments from Bahrain and Finland were brought into Texas ports and the additional transportation costs prevented most of those shipments from being consumed in CA under the LCFS. EIA does track refinery/terminal stocks of renewable diesel, but not production of US-based renewable diesel [44].

Knowing that the most policy relevant renewable diesel is generated overseas in Singapore poses difficult data challenges as there is no publicly accessible data for prices of finished fuel, shipping costs, or chemical input costs. To reconstruct the cost of production, we had to use proxy prices based upon US data. Proxy data sources are tabulated in

Table 5 in the appendix.

Renewable diesel qualifies under the same tax credit as biodiesel, and while the tax credit has expired at the time of writing, historically, this credit was available in 2011 and 2013 at the rate of \$1/gal. Capital costs associated with Neste's Singapore plant are

approximated using a simple financing model that makes the following assumptions: 15 year project life, 200 million gallon nameplate capacity, \$0.90/gal of production capacity, \$30M in working capital (labor costs, maintenance, etc.), 80/20 debt/equity, 8.25% interest, 10 year loan, and straight-line depreciation with zero salvage value. These assumptions yield an estimate of \$0.24/gal for capital costs. Many of the parameters used in this model were taken from Pearlson et al. (2011, 2013).

2.2.1.2 Constraints

There are two constraints applied to the renewable diesel market player: 1) a capacity constraint (Equation (2)) and 2) an LCFS credit generation constraint (Equation (3)).

$$\sum_l q_{p,b,s,y}^l \leq \bar{q}_{p,b,s,y}$$

$$\forall l, b, s, y$$

$$p \in \{Producer, Importer, Refiner\}$$
(2)

$$cr_{p,b,s,y} = q_{p,b,s,y}^l \rho_b \left(CI_{f(b),y}^{std} - CI_{b,s} \right)$$

$$\forall b, f, s, y$$

$$l \in \{LCFS\}$$

$$p \in \{Producer, Importer\}$$
(3)

A capacity constraint for an importer of fuels should be interpreted as a limitation on the infrastructure/scheduling at a port to accept delivery of fuels rather than the nameplate capacity of the plant. In this case, company level imports were tracked from EIA data for Neste Oil – Singapore, and the maximum of these historical quantities were used as the annual capacity constraint; the parameter $\bar{q}_{p,b,s,y}$ describes this capacity constraint [39]. Import capacity assumptions for future years will be discussed later in the section on scenario development (Section 3). LCFS credits (in metric tons) generated from imported renewable diesel are constrained by Equation (3); ρ_b is the volumetric energy density of the fuel and is taken from the LCFS regulations shown in Table 4 [5].

2.2.2 Biodiesel Producer

National averages for biodiesel/diesel blends have recently hovered around 2% [45]. Minnesota, however, requires a minimum of 10% biodiesel to be blended into their diesel fuel; if specific conditions are met, Minnesota could increase the blend to 20% by 2018. A simple input-output production model was used again for biodiesel, with input data sources tabulated in Table 6 in the appendix. Yield parameters are taken from a National Biodiesel Board survey of the industry considering all feedstock types (virgin or waste oils) [46]. A capital cost model was not developed for a biodiesel plant; instead, we approximated fixed costs as \$0.25/gallon [45].

As with the renewable diesel producer, their optimization is subject to a capacity constraint as well as an LCFS credit generation constraint. The production capacity by state is available from EIA reports [47]. LCFS credit generation is described through Equation (3), above.

2.2.3 Sugar Ethanol Importer

In 2012-2104 Brazilian shipments exceeded 70% of all U.S. ethanol imports [48]. Importers are interested in Brazilian ethanol because it qualifies as an advanced biofuel under the RFS and is eligible to generate RINs as well as LCFS credits, while Brazil is the largest foreign producers of low-carbon ethanol [49]. Therefore, we only consider shipments of Brazilian ethanol to US ports. The cost function for the sugar ethanol importer does not contain any yield parameters because the foreign price of ethanol is taken as exogenous. Brazilian pricing data is available from UNICA [50]. Producer prices available from UNICA do not include shipping charges from Sao Paulo to the US; this cost was assumed to be a fixed \$0.22/gallon which has been adapted from [51]. The ethanol blenders tax credit of \$0.45/gallon was available in 2011; however, in 2011 a tariff for imported ethanol (\$0.54/gallon) was also applied.

As with the previous two categories of producers/importers, the sugar ethanol importer is subject to a capacity constraint as in Equation (2). The import capacity for each state was assumed to be twice the maximum import volume from 2011-2014 and carried forward, unchanged, until 2022 [39]. This methodology could result in ~1 billion gallons of sugar ethanol to be imported in a given year. Equation (3) describes how LCFS credits are generated from sugar ethanol.

2.2.4 Corn Ethanol Producer

The production of ethanol from corn represents the largest pool of biofuel in the US, so there is a lot known about the production inputs and co-product yields. For more information, the interested reader is directed to Wu (2008). Exogenous prices for feedstocks and co-products are tabulated in Table 7 (in the appendix) in the Data Source column.

Fixed costs are approximated using a simple investment cost model assuming the following: 15 year project life, 100 million gallon nameplate capacity, \$2.11/gal of production capacity, \$30M in working capital (labor costs, maintenance, etc.), 40/60 debt/equity, 8.25% interest, 10 year loan, and straight-line depreciation with zero salvage value. These assumptions yield an estimate of \$0.43/gal for fixed costs. Historical production capacities by state were gathered from the Nebraska Energy Office [52]. Equation (3) also governs the number of LCFS credits generated by corn ethanol imported into CA.

2.2.5 Fuel Blender

2.2.5.1 General Considerations

Fuel blenders are located within each state and are responsible for blending finished fuel and delivering it to the consumer. It is assumed that the blender simply purchases other blendstocks from producers, mixing a finished fuel and then delivering that finished fuel to consumers. It is also assumed that the blender is the main point in the supply chain where state and federal fuel taxes are levied while some tax credits are also available directly to blenders. Therefore, taxes (net of credits) are the primary costs that the blender is exposed to. This assumption ignores capital costs associated with

storing/blending fuels, but at this time the authors are unaware of any public data that would guide further model refinement.

2.2.5.2 Constraints

Unlike fuel producers, blenders are responsible for generating RINs that are then sold to refiners for compliance. The following equality constraints represent the generation of D4, D5, and D6 RINs. The notation $B(k)$ is used to indicate that the sum is over a subset of biofuels that are eligible to produce each type of RIN. For completeness, D4 RINs can be produced from biodiesel or renewable diesel, D5 RINs are produced from sugar ethanol, and D6 RINs are produced from corn ethanol.

$$\begin{aligned} rin_{p,s,y}^k &= \sum_{l,b \in B(k)} EV_b q_{p,b,s,y}^l \\ \forall l, k, s, y \\ p &\in \{Blender\} \end{aligned} \quad (4)$$

In addition to the RIN generation constraints, blenders must also comply with fuel blending limitations for both ethanol and biodiesel. It is assumed the renewable diesel is a perfect substitute for petroleum diesel and therefore does not carry any blending restrictions. The E10 and E85 blend constraints are formulated in Equations (5) and (6). It is noted that the term “E85” is a bit of a misnomer in that any fuel with >15% ethanol can be labeled as E85. The annual average ethanol blend in E85 is closer to 74%, which explains the coefficient in Equation (6).

$$\begin{aligned} \sum_b q_{p,b,s,y}^{E10} &= 0.10 \sum_c q_{p,c,s,y}^{E10} \\ \forall s, y, p &\in \{Blender\}, b \in \{Ethanol, SugarEthanol\}, c \in \{BOB, Ethanol, SugarEthanol\} \end{aligned} \quad (5)$$

$$\begin{aligned} \sum_b q_{p,b,s,y}^{E85} &= 0.74 \sum_c q_{p,c,s,y}^{E85} \\ \forall s, y, p &\in \{Blender\}, b \in \{Ethanol, SugarEthanol\}, c \in \{BOB, Ethanol, SugarEthanol\} \end{aligned} \quad (6)$$

In this model, we have assumed that the average biodiesel blend has to be no higher than 5% (B5) unless the state has a specific policy of higher blends, in those cases, the upper limit is assumed to be 15% (B15). The B5 blend constraint is shown in Equation (7); the B15 constraint is formulated in a similar way, but operates on only a subset of the states.

$$\begin{aligned} \sum_{b,l} q_{p,b,s,y}^l &= 0.05 \sum_{c,l} q_{p,c,s,y}^l \\ \forall l, s, y, p &\in \{Blender\}, b \in \{Biodiesel\}, c \in \{UnblendedDiesel, Biodiesel, RenewableDiesel\} \end{aligned} \quad (7)$$

2.2.6 Refiner Player

2.2.6.1 General Considerations

Complicated internal refinery operations make a simple linear input-output model ineffective at capturing the costs associated with refining crude oil into a gasoline blendstock or diesel fuel. In lieu of this, BOB and unblended diesel prices were considered exogenous and were taken from EIA databases of refiner product prices [53]. The prices included in this database include transport costs, which need to be removed because our model applies transportation costs endogenously. Transportation markups are also estimated from EIA and are included in the Liquid Fuel Market Module (LFMM), which is sub-module in the larger National Energy Modeling System (NEMS) software package [54]. More elaborate refinery models could be incorporated into a framework in later research.

2.2.6.2 Constraints

The refiner, as the main regulated entity under both the RFS as well as the LCFS, is subject to a number of policy constraints. These policy constraints are detailed here. Further discussion of these two programs can be found elsewhere [5], [55].

Taken together the following equations are used to model the RFS imposed upon each state's refiner:

$$\begin{aligned} rin_{p,s,y}^k - bnkrin_{p,s,y}^k + bnkrin_{p,s,y-1}^k + bnkrin_o^k &\geq RVO_{s,y}^{bbd,std} \\ \forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4\} \end{aligned} \quad (7)$$

$$\begin{aligned} \sum_k (rin_{p,s,y}^k - bnkrin_{p,s,y}^k + bnkrin_{p,s,y-1}^k + bnkrin_o^k) &\geq RVO_{s,y}^{adv,std} \\ \forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4, D5\} \end{aligned} \quad (8)$$

$$\begin{aligned} \sum_k (rin_{p,s,y}^k - bnkrin_{p,s,y}^k + bnkrin_{p,s,y-1}^k + bnkrin_o^k) &\geq RVO_{s,y}^{rf,std} \\ \forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4, D5, D6\} \end{aligned} \quad (9)$$

Here, the $bnkrin_o^k$ terms represent the initial carryover RINs from the original RFS 1 program [25]. The renewable volume obligation (RVO) is specific to each obligated party based on the projected production of petroleum fuels for that year. In this way the RFS is a policy that is established *ex ante*. This need to use projected fuels volumes complicates the solution procedure since the biofuel volumes consumed in year y are unknown, which impact the total volume of petroleum fuels produced through the blending constraints (Equations 5-7). Consequently, the solution procedure requires an initial guess to the amount of biofuel consumed, and then this guess is adjusted iteratively in order to reach convergence. It is our experience that convergence, defined by the difference in projected biofuel volume and actual consumed biofuel volume, can be achieved in <10 iterations (fixed point iteration method).

The RFS banking constraints are given below:

$$B_{p,s,y}^k \leq 0.20RVO_{bdd,s,y+1}^{std}$$

$$\forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4\} \quad (10)$$

$$\sum_k B_{p,s,y}^k \leq 0.20RVO_{adv,s,y+1}^{std}$$

$$\forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4, D5\} \quad (11)$$

$$\sum_k B_{p,s,y}^k \leq 0.20RVO_{rf,s,y+1}^{std}$$

$$\forall y, s(p) \subset S, p \in \{Refiner\}, k \in \{D4, D5, D6\} \quad (12)$$

The following equations, when taken together, represent the California-CLFS program balancing constraints that the refiner faces. In words, credits can be acquired by purchase or withdrawal of previously banked credits, and inventory constraints ensure that the number of credits in the bank is never negative.

Primary compliance equation (retired credits + withdrawals = deficits generated from the use of petroleum fuels):

$$r_{p,y} + w_{p,y} = \sum_{bl} d_{p,bl,y}$$

$$\forall bl, y, p \in \{Refiner, Transporter\} \quad (13)$$

LCFS credit banking relationship:

$$a_{p,y} - r_{p,y} = bnk_{p,y}$$

$$\forall y, p \in \{Refiner, Transporter\} \quad (14)$$

Total number of banked LCFS credits (total = banked in current year – withdrawn in current year + carryover from previous year):

$$bnktot_{p,y} = bnk_{p,y} - w_{p,y} + bnktot_{p,y-1}$$

$$\forall y, p \in \{Refiner, Transporter\} \quad (15)$$

Total number of LCFS credits withdrawn from the bank cannot exceed the amount in the bank from the previous year (i.e., cannot bank and then withdraw the same LCFS credit in year y)

$$w_{p,y} \leq bnktot_{p,y-1}$$

$$\forall y, p \in \{Refiner, Transporter\} \quad (16)$$

Other state-level tax policies including minimum blend mandates were identified through the Department of Energy's Alternative Fuel Data Center policy database [56]. In addition to the network of tax incentives and blend mandates, most states tax gasoline and diesel at different rates. Fuel tax rates are available from the American Petroleum Institute's series of State Motor Fuel Tax reports [21].

2.2.7 Fuel Transporter

Fuel transporters move fuels across origin-destination arcs in a network. In this model, there are two networks (LCFS and non-LCFS), and thus the transporter arbitrages these two fuel types (non-LCFS fuels and LCFS fuels). At each node the transporter is subject to typical conservation of volume constraints. The only fuel that is not transported is renewable diesel, as most of the volumes are imported into CA and are then consumed in CA. Transportation costs are not based on distance shipped but rather a simple markup following the methodology outlined by EIA in the LFMM module documentation [54]. Transporters of petroleum products are also subject to LCFS constraints, similar to those developed in Section 2.2.6 for a CA-based refiner.

2.2.8 Market Clearing Conditions

Most market clearing conditions follow a standard form and represent a balance of product produced/refined, transported in/out, and ultimately purchased by a blender. These market clearing conditions are for all y, s, c, l . This relationship is:

$$\sum_{p \in \{producer\}} q_{p,c,s,y}^l + \sum_{p \in \{transporter\}} (purch_{p,c,s,y}^l - sales_{p,c,s,y}^l) - \sum_{p \in \{blender\}} q_{p,c,s,y}^l = 0 \quad (17)$$

However, there are several details for the LCFS credit market, finished gasoline markets, and finished diesel markets that require further documentation. The finished gasoline market clearing condition is given as:

$$\sum_{\substack{p \in \{blender\} \\ c \in \{ethanol, \\ sugarethanol\}}} q_{p,c,s,y}^{E10} + e \sum_{\substack{p \in \{blender\} \\ c \in \{ethanol, \\ sugarethanol, \\ BOB\}}} q_{p,c,s,y}^{E85} = gasdemand_{s,y} \quad (18)$$

Here, e is the energy content ratio of E85/E10, which is set to a constant value of 0.782. This discount factor implicitly assumes that consumers value how many miles they can drive per gallon of fuel, rather than just the volume of the fuel.

The finished diesel market clearing condition is as follows:

$$\sum_{\substack{l, p \in \{blender\} \\ c \in \{biodiesel, \\ renewablediesel, \\ petroldiesel\}}} q_{p,c,s,y}^l = dieseldemand_{s,y} \quad (19)$$

Below is the LCFS credit market clearing condition:

$$\begin{aligned}
& \sum_{\substack{s,b \\ p \in \{\text{producer} \\ \text{importer}\}}} cr_{p,b,s,y} + ZEVcredits_y + CNGcredits_y + RefineryCredits_y \\
& + RenewableGasCredits_y + CellulosicCredits_y + S_y \\
& = \sum_{p \in \{\text{refiner} \\ \text{transporter}\}} a_{p,y}
\end{aligned} \tag{20}$$

In plain language, the left-hand side of Equation (20) is the sum of all LCFS credits generated by biofuel producers, zero emission vehicles (ZEVs), and vehicles fueled by compressed natural gas (CNG), including biogas. Credits generated from ZEVs, CNG, renewable gasoline, cellulosic ethanol and refinery credits are all exogenous parameters. $ZEVCredits_y$, $CNGcredits_y$, $RefineryCredits_y$, $RenewableGasCredits_y$, and $CellulosicCredits_y$ are derived from a California Air Resources Board (CARB) generated illustrative scenario [57]. Producer players or refiners for these credits are not specifically modeled as it is assumed that their credits will never be the marginal credit generated; additionally, there is very little data available on the costs associated with these fuel choices. This assumption can be relaxed in future research should this data become available.

Meanwhile, the term S_y represents the LCFS credit shortage for year y and is included in the model as a decision variable. This variable is used to relax the LCFS constraint, as it quantifies how many additional credits the LCFS program needs to generate in order to reach feasibility over the simulation period. The total cost function includes a large penalty for generating a credit shortage; in this way, when minimizing the total cost, the credit shortage term will only be non-zero if the capacity from other low carbon sources is insufficient to satisfy the policy. The right hand side of the equation represents the demand for all deficits generated by refiners in California and transporters of petroleum blendstocks into that state.

2.2.9 Carbon Intensity Data

Even though both the RFS and the LCFS require thorough carbon accounting of all participating fuels, the policies differ in significant ways when it comes to utilizing those carbon intensities. Under the RFS, carbon accounting is set as a threshold, meaning that a fuel simply has to meet a certain carbon reduction target compared to its petroleum equivalent. This structure does not provide a reward for fuels that provide additional carbon savings.

Carbon intensities (CIs) for all approved fuel production pathways are publicly available from CARB (2015b). Specific plant locations are given in this database as well as feedstock and energy input information, but production capacity is not. Therefore, for a state aggregate model, a representative CI metric must be estimated. To calculate a state's average CI for a particular fuel, a simple average of all plants was calculated from data publically available from the CARB [58]. The resulting estimates are shown in Table 8 in the appendix.

The CI metrics will periodically go through review as the state of knowledge evolves regarding lifecycle analysis. As part of a lifecycle assessment, California includes emissions from indirect land use change (iLUC); this parameter is subject to considerable uncertainty [59]. At the time of writing, many of these CI values were being revisited, and in many cases, lowered [60].

2.3 Summary

In summary, the model that we use to investigate scenarios in Section 3 is the combination of the primary objective function, Equation 1, and all of the technical and policy constraints written out in Equations (2)-(20).

3. Definition of Policy Scenarios

At the highest levels, this model was developed to be a single tool that policymakers at CARB or other regulatory agencies could use to model scenarios and design improved policy compliance strategy. If data allowed, this framework could be expanded further and this model could also be used to price LCFS credits. In addition, this model also allows for other studies on the interactions of biofuels markets and state/federal policies. In this work, we focus in on two policy stories: 1) we examine the feasibility of the LCFS assuming that there is the existence of a biodiesel “blend wall” (i.e., a restriction on the percentage of biodiesel that can be mixed into diesel fuel) and 2) we also look at how RIN prices and LCFS credit prices might influence each other.

We first tackle these two questions by generating a baseline scenario that closely represents historical market conditions. As Table 7 summarizes, the baseline scenario includes all previously mentioned capacity constraints on fuel production, while also including a B5 biodiesel blending constraint shown in Equation (7). For this particular scenario, banked LCFS credits for 2011-2014 were constrained to equal real market data published by CARB on banked credits. The credit shortage term, S_y , is not included as a decision variable in this scenario. In essence, if this model has a feasible solution, then the CARB credit generation assumptions will help to carry the policy through 2022 without a need for large changes in the CA fuel market or regulations. An infeasible solution in the baseline scenario could also signal that obligated parties did not bank enough credits in the first few years of the program to bring them into compliance in the later years of the program. As will be discussed in the next section, the baseline scenario was found to be infeasible, even when CARB’s credit generation outlook is explicitly included. Therefore, in Scenario #1, we look at what it would take to achieve a feasible solution by introducing the credit shortage term, S_y , as a decision variable into the model.

Scenario #2 was developed to address the second policy story of interest here – how the RFS/LCFS credit markets interact. In this scenario it is possible to look at a world with/without the RFS and with/without the LCFS.

Table 1: Policy scenarios

Number	Scenario	Constraints
0	Baseline	<ul style="list-style-type: none"> All previously mentioned capacity constraints

		<ul style="list-style-type: none"> • No LCFS credit shortage term • 5% biodiesel blending constraint • Historical levels of LCFS credit banking (2011-2014)
1	Modified Baseline	<ul style="list-style-type: none"> • All previously mentioned capacity constraints • Included LCFS credit shortage term • 5% biodiesel blending constraint • Historical levels of LCFS credit banking (2011-2014)
2	RFS/LCFS Interactions	<ul style="list-style-type: none"> • All previously mentioned capacity constraints • No LCFS credit shortage term • No constraint on biodiesel blending • Historical levels of LCFS credit banking (2011-2014)

4. Results

4.1 Baseline (Scenario #0) and Modified Baseline (Scenario #1)

The CA-LCFS carbon intensity standard was designed so that compliance in later years would be likely only if obligated parties banked a significant number of credits in the first few years. This is because the standard was relatively easy to meet in the beginning few years but then increased, non-linearly, in stringency. As alluded to in Section 3, we are concerned about the feasibility of the LCFS program with a biodiesel “blend wall” of 5% (B5). It is true that many manufacturers warranty their engines up to levels that are greater than biodiesel blends >5%; however, according to CARB data, biodiesel blending reached 5% only for a short period of time (fourth quarter of 2013) [61]. It is difficult to envision a situation in the near future where biodiesel blending could reach >>5% for a sustained period of time.

Indeed, it turns out that a baseline scenario that included a 5% cap on the blending of biodiesel is infeasible. If the model is relaxed by removing the 5% blending constraint (Equation 7), then it was possible to find an optimal solution. The dynamics of LCFS credit acquisition, retirement, and banking are mapped out in Figure 3. As can be seen, it is crucial that enough credits be banked early in the program because compliance relies on sufficient banked credits to draw from in later years. As a consequence of removing the biodiesel blending constraint, this model wants to blend at levels that may be technically infeasible; by 2016, 21% of diesel in CA would need to be biodiesel.

Figure 3: Optimal LCFS operation for the baseline scenario with the biodiesel blend cap removed completely. All quantities are annual quantities. Positive *net banking* numbers represent annual deposits into the bank, while negative *net banking* values represent annual withdrawals.

In addition to ambitious levels of biodiesel blending, the model also wanted to blend approximately 380 million gallons of E85 by 2020 increasing up to ~1 billion gallons in 2022. Projections for E85 consumption are highly uncertain; however, other models produce nationwide estimates of E85 consumption of ~300 million gallons in 2020 [62]. This model does not attempt to include issues of consumer choice or other fueling infrastructure compatibility issues, but even without these model considerations, it is quite apparent that there will need to be a dramatic shift away from petroleum fuels if compliance with the LCFS is to be maintained. This dramatic shift needs to occur in a short period of time, which casts some doubt on whether it can be accomplished. A critical assumption in this model run was that biodiesel blending could occur at any level given that the LCFS credit bank was constrained to actual banked credit amounts for 2011-2014.

Of course it is also possible that obligated parties simply did not bank enough LCFS credits in the beginning part of this program to temper the necessary biodiesel blends. To test this, another model run was formulated in which the biodiesel blend constraint is reinstated in the model, but the LCFS credit banking constraint is removed. This solution of this problem reveals that obligated parties should have banked approximately 9 times more credits in by the end of 2014 than they actually did. To even achieve this level of credit banking, it would have been necessary to blend large volumes of lower CI ethanol, mostly from Kansas, into an unrealistic volume of E85 (i.e., >1 billion gallons in 2012). Even though obligated parties might not have banked an optimal number of credits during 2011-2014, it was impossible to expect that the fuels market could move so quickly to bank sufficient credits to achieve long-term compliance.

Therefore, with the aid of scenario #0, we have established that compliance with the LCFS will be difficult in later years unless rapid changes in the adoption of low CI fuels takes place, particularly with regard to the adoption of low CI biodiesel. However

scenario #0 also relied on some generous assumptions with regard to biodiesel blending and credit banking. Therefore the question remains: if we impose more realistic conditions, what would need to change in the market for compliance to be achieved? Scenario #1 is then formulated with the B5 blend constraint as well as a constraint that caps banked credits in 2011-2014 to actual market data. It has been established that this particular model will yield an infeasible solution, so we also include the credit shortage variable, S_y , to relax the requirements of the LCFS program. The credit banking dynamics that result from this model is presented in Figure 4. As a reminder, credits that are purchased as “shortage” represents the number of credits that would need to be purchased in order to achieve compliance with the LCFS; no assumptions are made regarding the actual physical availability of these credits.

Figure 4: LCFS operation for scenario #1. All quantities are annual quantities. Positive *net banking* numbers represent annual deposits into the bank, while negative *net banking* values represent withdrawals.

As can be seen from Figure 4, almost 34 million LCFS credits would need to be made available in order to ensure long-term compliance. This amount of credits is, of course, not available as the market is currently structured. Additionally, we emphasize that the model decides to purchase shortage credits in the most economically efficient manner, meaning that a huge amount of credits are purchased relatively early in the simulation. Including CARB projections from other advanced fuels such as cellulosic ethanol, renewable diesel, and other biogases is not enough to bring the LCFS into compliance in later years. This shortage of credits could cause an unpredictable rise in the LCFS credit price if it were not contained through the recently implemented cost containment provisions mentioned briefly in Section 1.1. Despite the difficulties that the LCFS faces in later years, regulators still hope that compliance will be achieved, although compliance scenarios presented by CARB also require significant drawdowns of banked credits beginning in 2019 [57].

There are two primary differences between our model and the CARB analyses: 1) our model is more pessimistic with regard to the amount of low CI sugarcane ethanol that is

imported in to CA, and 2) our model does not include assumptions with regard to the time evolution of the CI for each fuel. CARB makes the assumption that the average CI will decrease throughout the lifetime of the LCFS program. This trend is shown in Figure 5 along with the LCFS credits assumed to be generated from four of the main fuels. We make mention of the CI trends because it will be important for stakeholders to carefully study how these values are chosen, although the details of these analyses are beyond the scope of this paper. Even still, it is important to recognize that overly generous carbon accounting could ease the apparent burden of achieving programmatic goals, a strategy that might become attractive for regulators, at least in the short term, if low CI advanced fuels are not available in expected quantities.

Figure 5: *Upper* – CI assumptions mapped out by CARB in their compliance scenario. Credits generated from the four primary fuels. *Lower* – LCFS credits generated from these same fuels.

4.2 Scenario #2 – RFS/LCFS Price Interactions

In this scenario, we focus on interactions between RIN prices and LCFS credit price. It is commonly mentioned that these two programs are “independent”, meaning that a biofuel produced outside of CA would generate a RIN, but if that same fuel were then transported into CA and consumed, that same gallon of biofuel could also produce an LCFS credit. Both RINs and LCFS credits can be an extra source of revenue for a biofuel producer. As an example, a rough estimate of the credit value for (\$/gal) for renewable diesel in CA based on the value of carbon reductions would be approximately \$0.28/gal ($((\$24/\text{MT CO}_2\text{e reduction})(134.47 \text{ MJ/gal})(102.3 \text{ gCO}_2\text{e/MJ} - 16.21 \text{ gCO}_2\text{e/MJ})(10^{-6} \text{ MT/g}))$). This would be an optimistic value because it assumes a used cooking oil pathway, which has a very low CI. RINs could be valued as much as ~\$1.36/gal for renewable diesel if they produce a D4 RIN ($80¢ \times 1.7$, where 1.7 represents an energy content adjustment factor). The total support from a fuel that could participate in both of these programs could therefore be on the order of \$1.50/gal. However, these programs are linked, indirectly, through the larger biofuels market operation. These indirect effects have not been investigated before; this model formulation provides a tool for studying this effect.

We begin this analysis by removing the constraint on biodiesel blending, and also adding in the constraint on banked LCFS credits from 2011-2014. This model proved to be feasible, and even though there is a certain level of doubt about the feasibility of the required biodiesel blending, for our analysis these concerns are secondary. They are secondary because we are looking at the magnitude of differences, rather than absolute prices. With this base scenario, we then alternate removing the LCFS and RFS program constraints and record the resulting prices, presented in Table 8.

Table 2: Changes in credit prices with/without specific policy constraints.

Scenario	Credit Type	2015	2016	2017
RFS/no LCFS	D4	+23%	+26%	+23%
RFS/no LCFS	D5	-0.5%	-0.5%	-0.4%
RFS/no LCFS	D6	0%	0%	0%
no RFS/LCFS	LCFS Credit	+52%	+52%	+52%

Table 8 can be read as saying that the LCFS credit price could be expected to increase by approximately 52% if the constraints of the RFS program were eliminated. The D4 RIN price could be expected to increase if the LCFS program were eliminated. However, the LCFS program has very little impact on the D5/D6 RIN price.

These results are interesting for two major reasons. First, it shows that programmatic influence is directional, which meshes with intuition; the larger federal RFS has a strong impact on the smaller state level LCFS credit price. However, it is somewhat surprising that the LCFS program could also impact the D4 RIN price in significant ways, albeit less so than the RFS impact upon the LCFS credit price. This point highlights the second interesting result; it is clear that compliance with both programs hinges on biodiesel/renewable diesel being available for consumption. The LCFS program attracts imports of biodiesel/renewable diesel into CA, where those gallons benefit from the support of an LCFS credit and a RIN. The burden of supplying a more expensive fuel into the transportation infrastructure can be borne by two market mechanisms. In effect, the RFS and LCFS work to reduce each other's individual program costs.

5. Conclusions and Policy Implications

Recent rulemaking activities held at the California Air Resources Board suggest that there may be underlying concerns regarding the long-term feasibility and cost of compliance with the LCFS. The fear is of a large spike in the LCFS credit price, something that could dramatically increase the burden of compliance for obligated parties (i.e., oil refiners in CA). Regulatory actions are currently being designed around the idea of a price cap on the price of an LCFS credit [63]–[65].

The model and analyses of this paper are developed with these regulatory concerns in mind and were undertaken in order to provide a framework to investigate whether or not the LCFS is feasible, under certain assumptions. If the LCFS program is found to be infeasible, our model can be used to investigate ways in which compliance can be achieved. Additionally, we have used this model to estimate the magnitude of the indirect

price impacts between the RFS and the LCFS. In the following paragraphs we highlight some of the major findings and discuss some policy implications.

With regard to the first primary research question on LCFS feasibility, the model shows that efficient long-term compliance with the LCFS relies on three key elements. First, obligated parties should have banked more credits in the beginning years of the program than they did in reality. Second, biodiesel blending will need to increase dramatically within a short period of time (i.e., by 2016 all diesel fuel would need to be B20). This rate of change casts doubt on whether these targets are achievable. Third, the carbon intensity (CI) of biofuels entering into CA will need to decrease, in some cases, by ~25% or more. This may be possible, but CARB would need to hasten the biofuel pathway approval process so that more low CI fuels can participate in the LCFS [66]. There are number of pathways that are currently waiting approval that could allow more biodiesel (from waste sources) and sugarcane derived ethanol into CA. Additional new low carbon fuels will likely need to be biodiesel or renewable diesel rather than gasoline replacements such as cellulosic ethanol. Renewable diesel has an advantage over biodiesel in that there are no blending restrictions, whereas biodiesel may suffer from lower blend limits (due to infrastructure compatibility issues). The ethanol blend wall is still working to prevent the incorporation of more ethanol into the transportation system. In addition to these technical issues, it will be necessary to swap more corn ethanol in CA for sugarcane ethanol from Brazil. Imported sugarcane ethanol already serves a key niche in providing CA with relatively inexpensive low carbon ethanol. CARB predicts that sugar ethanol has less than half of the associated emissions compared to petroleum gasoline.

The second primary research question was concerned with the indirect impacts of LCFS credits markets and RIN markets. To test this effect, two variants of scenario #2 were developed: 1) a world where only the RFS existed, and 2) a world with only the LCFS. The results show that the LCFS credit, if it exists, works to reduce the D4 RIN price by approximately 20% over a scenario where the LCFS credit market was not available. Recollect that D4 RINs are generated by biodiesel/renewable diesel fuels; thus, these two fuels are critical for future compliance of the LCFS. Following this, it makes sense that the model indicates that the LCFS credit market does not impact the D5/D6 RIN markets in a significant way. In essence, fuel blenders are only willing to pay a certain price for these diesel replacements, knowing that there is significant value in generating RINs and LCFS credits. If one of these revenue streams were to vanish, the other credit market would adjust accordingly. This effect is particularly evident in the scenario where only the LCFS existed; credit prices increased by more than 50% for 2015-17.

Both the EPA and CARB have continually been developing new implementation rules and it is likely that future rules will necessitate additional scenario development. The framework and model presented here is general enough to accommodate many different program modifications, and to analyze their impacts.

6. Acknowledgments

This work was performed under NSF Award SEES #12-15839.

7. Appendix – Challenges Faced by Regulators

With the passage of the Energy Independence and Security Act in 2007, Congress created a mandate for the number of gallons of biofuel to be consumed in the US. The Act also established a number of different categories of biofuel that corresponded to different reductions from baseline lifecycle GHG emissions. Those categories include cellulosic, advanced, biomass-based diesel, and renewable fuel [67]. The volume requirements that Congress wrote might have been viewed as achievable at the time, but they have since proven overly ambitious for the cellulosic fuel category: for instance, the law required 1 billion gallons of cellulosic fuel to be consumed in 2013, when in reality only 281,000 gallons were produced [25]. Congress did give some flexibility to EPA to adjust the volume standard if actual production of fuel fell short, but Congress still required EPA to determine the volume obligations every year, even if there were revisions to the standard (42 USC 7545(o)(3)). This annual process of setting the volume standard has become EPA's de facto policy lever for controlling the biofuel market as well as the response of the RIN market, which we describe in more detail in Section 1.3. At the time of this writing, EPA had decided to pull back the proposed rule that established volume obligations in 2014; this rule will now be implemented more than one year late [68]. When this rule was originally released it was met with significant political opposition, which has influenced its ultimate release date [69]–[71].

The California LCFS has also encountered its share of legal challenges from oil refiners, which have played out in Courts; ultimately, the state was allowed to move forward with implementation of the program [72]. Unlike the RFS, the LCFS mandates an average carbon intensity of fuel produced/imported in California. The specified carbon intensities correspond to a 10% decrease in carbon equivalent emissions by 2020 [73]. As such, many other compliance pathways are possible under the LCFS regulations (e.g., electric vehicles and oil refining efficiency upgrades). Due to the structure of the program, it was important for regulated parties to over-comply in the early years of the program in order to bank enough credits for future compliance use. Even with the ability to bank credits indefinitely, concerns over potentially high prices of LCFS credits led to the California Air Resources Board (CARB) to design mechanisms to cap credit prices [63]. Concerns over the cost of compliance credits indicates that market parties believe that there might be a shortage of credits in the later years of the program; CARB might be trying to prevent an unbounded credit price spike, or they might also be looking to avoid political pushback should a spike occur.

8. Appendix – The US Renewable Fuel Standard (RFS): National Level Policy

Obligated parties under the national RFS are considered to be any supplier of petroleum-based transportation fuel, and generally consist of all refiners of fuel. Obligated parties demonstrate compliance with the RFS by collecting a certain number of certificates, referred to as RINs, and retiring them to the EPA at the end of a year. RINs are generated by biofuel producers, can be banked for the next year's compliance, and can also be traded among obligated parties. In fact, RINs function in much the same way as the renewable energy credits or emissions credits that are traded under cap-and-trade

policies, and consequently provide an additional revenue stream for new renewable fuel producers. RIN markets are more complex, however, because different types of biofuels generate different categories of RINs; these categories are enumerated as D4, D5 and D6 RINs. For purposes of this paper, biodiesel and renewable diesel fuels only generate D4 RINs, ethanol produced from sugarcane generates a D5 RIN, and corn ethanol generated a D6 RIN.

Absent other policy distortions, a simple RIN pricing model might look like an arbitrage condition between the biofuel product price and the equivalent petroleum based product [74]. However, reality must include a number of other policy features and possible distorting effects, including multiple obligated parties (i.e., refiner players), tax credits, and supply/demand effects from the “blend wall”, which is a shorthand name for the fact that ethanol/gasoline blends in the US are effectively capped at ~10% as a result of engine compatibility issues with higher blends [75]. Additional information regarding the operation of the RFS is available elsewhere [55], [67], [76], [77].

The model formulation provide here could be extended to include more international policies, but additional datasets would be necessary to that would describe the demand dynamics in those countries. International biofuel policies are outlined more extensively in the following references [78]–[80].

9. Appendix – Model Notation

Table 3: Set definitions

Set Definition	Description	Elements
$y \in Y$	Years	{2011-2022}
$s \in S$	States	{All states in the RFS}
$c \in C$	Component Fuels	{ethanol, biodiesel, sugar ethanol, BOB, unblended diesel, renewable diesel}
$b \subset C$	Biofuels	{ethanol, biodiesel, sugar ethanol, renewable diesel}
$bl \subset C$	Petroleum Blendstocks	{BOB, unblended diesel}
$l \in L$	Registered in LCFS or not	{LCFS, NLCFS}
$k \in K$	RIN types	{D4, D5, D6}
$p \in P$	Market Participants	{Producer, Importer, Refiner, Blender, Transporter}
$f \in F$	Finished (blended) transportation fuels	{Gasoline, Diesel}
$i \in I$	Biofuel process inputs	Biodiesel: {electricity, methanol, nat gas, oil feedstock} Corn Ethanol: {electricity, nat gas, corn} Renewable Diesel: {electricity, hydrogen, oil feedstock} Sugar Ethanol: {none}
$j \in J$	Biofuel process co-products	Corn Ethanol: {distillers grains} Renewable Diesel: {LNG, jet fuel, naphtha, propane} Biodiesel: {none} Sugar Ethanol: {none}
$arc(s, s')$	Transportation Arcs, no self-shipsments	{All states, All states}
$arcpetrol(bl, s, s', y)$	Petroleum Fuel Transportation Arcs, no self-shipsments	{Blendstocks, All states, All states, years}
$arcpetrol^{LCFS}(bl, s, s', y)$	Petroleum Fuel Transportation Arcs for fuels in LCFS, no self-shipsments	{Blendstocks, All states with refining capacity, 'California', years}
$arcbiofuel^{LCFS}(b, s, s', y)$	Biofuel Transportation Arcs for fuels in LCFS, no self-shipsments	{Biofuels, All states with production capacity, 'California', years}

Table 4: Decision variable definitions

Decision Variable	Description
$a_{p,y}$	LCFS credits acquired for compliance by <i>market players p</i> , in <i>year y</i> . Units: reduced metric tons of CO ₂ e
$bnk_{p,y}$	LCFS credits added to a <i>market player's p</i> bank, in <i>year y</i> . Units: reduced metric tons of CO ₂ e
$bnkrin_{p,s,y}^k$	D4, D5, or D6 RINs banked by a refiner for use later in the RFS. Units: # of RINs
$bnktot_{p,y}$	Total number of banked LCFS credit available for withdraw from <i>market player's p</i> bank in <i>year y</i> . Units: reduced metric tons of CO ₂ e
$cr_{p,b,s,y}$	LCFS credits produced or purchased by a <i>market player p</i> , by a <i>biofuel b</i> , in <i>state s</i> , in <i>year y</i> . Units: reduced metric tons of CO ₂ e
$d_{p,bl,y}$	Deficits generated by <i>market players p</i> of <i>petroleum blendstocks bl</i> in <i>year y</i>

$flow_{p,c,s,s',y}^l$	Volume flow of <i>component fuels c</i> between <i>two states s and s'</i> by <i>market player p</i> . Units: gallons
$r_{p,y}$	LCFS credits retired for compliance by <i>market players p</i> , in <i>year y</i> . Units: reduced metric tons of CO2e
$rin_{p,s,y}^k$	Quantity of <i>RINs k</i> produced or purchased by a <i>market player p</i> , in <i>state s</i> , in <i>year y</i> . Units: # of RINs
$rinflow_{p,s,s',y}^k$	Volume flow of <i>RINs k</i> between <i>two states s and s'</i> by <i>market player p</i> . Units: # of RINs
$rinpurch_{p,s,y}^k$	Volume of <i>RINs k</i> purchased from <i>market player p</i> in <i>state s</i> . Units: gallons
$rin sales_{p,s,y}^k$	Volume of <i>RINs k</i> sold to <i>market player p</i> in <i>state s</i> . Units: gallons
$purch_{p,c,s,y}^l$	Volume of <i>component fuels c</i> purchased from <i>market player p</i> in <i>state s</i> . Units: gallons
$q_{p,c,s,y}^l$	Fuels (biofuels or petrol fuels) that are produced or purchased by a <i>market player p</i> , in <i>state s</i> , in <i>year y</i> . Set <i>l</i> controls if the fuel is sent to CA under the LCFS or not. Units: gallons
$q_{p,c,s,y}^{E10}$	Volume of <i>component fuels c</i> blended into E10 by a <i>market player p</i> in <i>state s</i> . Units: gallons
$q_{p,c,s,y}^{E85}$	Volume of <i>component fuels c</i> blended into E85 by a <i>market player p</i> in <i>state s</i> . Units: gallons
$sales_{p,c,s,y}^l$	Volume of <i>component fuels c</i> sold to <i>market player p</i> in <i>state s</i> . Units: gallons
$w_{p,y}$	LCFS credits withdrawn from a <i>market player's p</i> bank in <i>year y</i> . Units: reduced metric tons of CO2e

10. Appendix – Data Tables and Model Parameters

Table 5: Exogenous data parameters for a modeled renewable diesel producer.

Product	Symbol	Input/Co-product	Value	Data Source
Electricity	$\alpha_{\text{electricity}}$	Input	0.358 kWh/ renewable diesel gallon	US Average for Industrial Customers [81]
Hydrogen	α_{hydrogen}	Input	0.258 lbs/ renewable diesel gallon	\$0.66/lb [42]
Bio-Oils	$\alpha_{\text{bio-oils}}$	Input	9.61 lbs/ renewable diesel gallon	US average soybean oil price [82]
Natural Gas	α_{natgas}	Input	8.97 ft ³ / renewable diesel gallon	
LNG	β_{LNG}	Co-product	0.034 gal/ renewable diesel gallon	LNG export price [83]
Propane	β_{propane}	Co-product	0.088 gal/ renewable diesel gallon	Spot price from Mont Belvieu, TX [84]
Naphtha	β_{naphtha}	Co-product	0.029 gal/ renewable diesel gallon	New York Harbor conventional gasoline spot prices [85]
Jet Fuel	β_{jet}	Co-product	0.14 gal/renewable diesel gallon	US Gulf spot prices [86]

Table 6: Data input sources for production cost modeling of biodiesel.

Product	Symbol	Input/Co-product	Value	Data Source
Electricity	$\alpha_{\text{electricity}}$	Input	0.19 kWh/biodiesel gallon	Price for Industrial Customers by state [81]
Methanol	α_{methanol}	Input	0.7208 lbs/biodiesel gallon	Methanol price [87]
Bio-Oils	$\alpha_{\text{bio-oils}}$	Input	7.78 lb/biodiesel gallon	US soybean oil price, state data available for IA, IL, and MN only [82]
Natural Gas	α_{natgas}	Input	3.45 standard ft ³ /biodiesel gallon	Industrial natural gas price by state [88]

Table 7: Data input sources for production cost modeling of corn ethanol.

Product	Symbol	Input/Co-product	Value	Data Source
Electricity	$\alpha_{\text{electricity}}$	Input	0.7 kWh/ethanol gallon	Price for Industrial Customers by state [81]
Corn	α_{corn}	Input	2.81 bushels/ethanol gallon	Corn prices, state data available for CA, IA, IL, KS, KY, MI, MN, MO, NC, ND, NE, OH, OR, PA, SD, TN, TX, WI only [89]
Natural Gas	$\alpha_{\text{electricity}}$	Input	27589 BTU/ethanol gallon	Industrial natural gas price by state [88]
Distillers Grains	β_{ddgs}	Co-product	5.9 lbs/ethanol gallon	DDG prices, state data available for CA, IA, IL, KS, MN, MO, NE, OR, SD, WI only [82]

Table 8: Carbon intensities used in scenario modeling (all units are in gCO₂e/MJ)

	Ethanol	Sugar Ethanol	Biodiesel	Renewable Diesel
CA	78.84	66.83	29.4	31.01
CO	90.1	--	--	--
IA	90.11	--	46.02	--
ID	90.1	--	--	--
IN	--	--	50.99	--
IL	--	--	20.97	--
KS	79.11	--	--	--

KY	93.19	--	--	--
MI	--	--	41.83	--
MN	--	--	45.88	--
MO	94.25	--	35.32	--
ND	98.4	--	--	--
NE	88.34	--	--	--
NM	85.81	--	--	--
NV	--	--	16.28	--
OK	--	--	40.85	--
OR	--	--	18.72	--
SD	91.15	--	--	--
TX	89.23	--	--	--
UT	--	--	37.98	--
WA	--	--	50.08	--
WI	--	--	4	--

References

- [1] Energy Information Administration, "Annual Energy Outlook 2013 - Table 58 Light-Duty Vehicle Stock by Technology Type," 2013. [Online]. Available: http://www.eia.gov/forecasts/aeo/supplement/suptab_58.xlsx.
- [2] National Biodiesel Board, "OEM Information," 2015. [Online]. Available: <http://biodiesel.org/using-biodiesel/oem-information>. [Accessed: 07-Apr-2015].
- [3] Environmental Protection Agency, *Control of air pollution from motor vehicles: Tier 3 motor vehicle emission and fuel standards*. 2014.
- [4] A. Christensen and C. Lausten, "Fundamental inconsistencies between federal biofuels policy and their implications," *Environmental Law Review*, vol. 44, pp. 10395–10412, 2014.
- [5] California Air Resources Board, "Low Carbon Fuel Standard Program," 2009. [Online]. Available: <http://www.arb.ca.gov/fuels/lcfs/lcfs.htm>. [Accessed: 07-Apr-2015].
- [6] Governor Schwarzenegger, "Executive Order S-01-07," 2007. [Online]. Available: <http://www.arb.ca.gov/fuels/lcfs/eos0107.pdf>. [Accessed: 07-Apr-2015].
- [7] Environmental Protection Agency, *EPA Finalized Regulations for a Renewable Fuel Standard (RFS) Program for 2007 and Beyond*. 2007.
- [8] Oregon Department of Environmental Quality, "Oregon Clean Fuels Program," 2015. [Online]. Available: <http://www.deq.state.or.us/aq/cleanFuel/regulations.htm>. [Accessed: 07-Apr-2015].
- [9] Washington Office of Financial Management, "Washington Clean Fuel Standards," 2015. [Online]. Available: <http://ofm.wa.gov/initiatives/cleanfuelstandards/>. [Accessed: 07-Apr-2015].
- [10] J. Bushnell and E. Mansur, "Vertical targeting and leakage in carbon policy," *The American Economic Review*, vol. 101, no. 3, pp. 263–267, May 2011.

- [11] E. T. Mansur, "Upstream versus Downstream Implementation of Climate Policy," *National Bureau of Economic Research Working Paper Series*, vol. No. 16116, no. published as Erin T. Mansur. "Upstream versus Downstream Implementation of Climate Policy," in Don Fullerton and Catherine Wolfram, editors, "The Design and Implementation of U.S. Climate Policy" University of Chicago Press (2012), 2010.
- [12] S. Meyer and W. Thompson, "FAPRI-MU US Biofuels, Corn Processing, Distillers Grains, Fats, Switchgrass, and Corn Stover Model Documentation," University of Missouri-Columbia, FAPRI-MU Report #09-10, 2010.
- [13] W. Thompson, J. Whistance, and S. Meyer, "Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions," *Energy Policy*, vol. 39, no. 9, pp. 5509–5518, Sep. 2011.
- [14] W. Thompson, S. Meyer, and P. Westhoff, "The New Markets for Renewable Identification Numbers," *Applied Economic Perspectives and Policy*, vol. 32, no. 4, pp. 588–603, Dec. 2010.
- [15] J. Whistance and W. Thompson, "The role of CAFE standards and alternative-fuel vehicle production credits in U.S. biofuels markets," *Energy Policy*, vol. 74, no. 0, pp. 147–157, Nov. 2014.
- [16] California Air Resources Board, "California Cap and Trade System," 2011. [Online]. Available: <http://arb.ca.gov/cc/capandtrade/capandtrade.htm>.
- [17] L. Zhang, G. Hu, L. Wang, and Y. Chen, "A bottom-up biofuel market equilibrium model for policy analysis," *Annals of Operations Research*, Nov. 2013.
- [18] P. Tittmann, N. Parker, Q. Hart, and B. Jenkins, "A spatially explicit techno-economic model of bioenergy and biofuels production in California," *Journal of Transport Geography*, vol. 18, no. 6, pp. 715–728, 2010.
- [19] N. Parker, P. W. Tittmann, Q. Hart, R. Nelson, K. Skog, A. Schmidt, E. Gray, and B. Jenkins, "Development of a biorefinery optimized biofuel supply curve for the Western United States," *Biomass and Bioenergy*, vol. 34, no. 11, pp. 1597–1607, 2010.
- [20] Federation of Tax Administrators, "State Motor Fuel Tax Rates," 2014.
- [21] American Petroleum Institute, "State Motor Fuel Taxes," 2014.
- [22] A. Christensen and S. Siddiqui, "A Mixed Complementarity Model for the US Biofuel Market with Federal Policy Interventions," *Biofuels, Bioproducts and Biorefining*, vol. 9, no. 4, p. 397, 2015.
- [23] S. Gabriel, A. Conejo, J. D. Fuller, B. Hobbs, and C. Ruiz, *Complementarity modeling in energy markets*. Springer, 2012.
- [24] S. Siddiqui and S. Gabriel, "An SOS1-based approach for solving MPECs with a natural gas market application," *Networks and Spatial Economics*, vol. 13, no. 2, pp. 205–227, 2013.
- [25] Environmental Protection Agency, "RFS EMTS Information Data," 2014. [Online]. Available: <http://www.epa.gov/otaq/fuels/rfsdata/index.htm>.
- [26] Energy Information Administration, "Annual Energy Outlook 2013," 2013. [Online]. Available: <http://www.eia.gov/forecasts/aeo/er/index.cfm>. [Accessed: 12-Apr-2014].
- [27] W. W. Hogan, "Energy policy models for project independence," *Computers & Operations Research*, vol. 2, no. 3, pp. 251–271, 1975.

- [28] F. H. Murphy and M. V. Mudrageda, "A decomposition approach for a class of economic equilibrium models," *Operations Research*, vol. 46, no. 3, pp. 368–377, 1998.
- [29] Government Accountability Office, "Energy Markets - Effects of mergers and market concentration in the US petroleum industry," 04-96, 2004.
- [30] S. Pouliot, "Arbitrage between ethanol and gasoline: evidence from motor fuel consumption in Brazil," presented at the Agricultural & Applied Economics Association Annual Meeting, Washington, DC, 2013.
- [31] B. Babcock and S. Pouliot, "Feasibility and cost of increasing US ethanol consumption beyond E10," Center for Agricultural and Rural Development, Iowa State University, 14-PB 17, 2014.
- [32] B. Babcock and S. Pouliot, "RFS Compliance: Death spiral or investment in E85?," Center for Agricultural and Rural Development, Iowa State University, 13-PB 16, 2013.
- [33] B. Babcock and S. Pouliot, "How much E85 can be consumed in the United States?," Center for Agricultural and Rural Development, Iowa State University, 13-PB 15, 2013.
- [34] B. Babcock and S. Pouliot, "Impact of sales constraints and entry on E85 demand," Center for Agricultural and Rural Development, Iowa State University, 13-PB 12, 2013.
- [35] B. Babcock and S. Pouliot, "Price it and they will buy: How E85 can break the blend wall," Center for Agricultural and Rural Development, Iowa State University, 13-PB 11, 2013.
- [36] D. Greene, "Vehicles and E85 stations needed to achieve ethanol goals," National Academies, Transportation Research Board, 2008.
- [37] C. Liu and D. Greene, "Modeling the demand for E85 in the United States," Oak Ridge National Laboratory, ORNL/TM-2013/369, Sep. 2013.
- [38] UCD and UCB, "California Renewable Diesel Multimedia Evaluation," 2010.
- [39] Energy Information Administration, "Company Level Imports," 2014. [Online]. Available: <http://www.eia.gov/petroleum/imports/companylevel/>. [Accessed: 20-Mar-2015].
- [40] R. Kotrba, "The renewable diesel invasion," *Biodiesel Magazine*, 12-Jun-2013.
- [41] M. Pearlson, C. Wollersheim, and J. Hileman, "A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production," *Biofuels, Bioproducts and Biorefining*, vol. 7, no. 1, pp. 89–96, 2013.
- [42] M. N. Pearlson, "A techno-economic and environmental assessment of hydroprocessed renewable distillate fuels," Massachusetts Institute of Technology, 2011.
- [43] California Air Resources Board, "Neste NExBTL Renewable Diesel Singapore Plant - Tallow Pathway Description," 2013. [Online]. Available: <http://www.arb.ca.gov/fuels/lcfs/2a2b/apps/neste-aus-rpt-031513.pdf>. [Accessed: 31-Mar-2015].
- [44] Energy Information Administration, "Petroleum and Other Liquids - Stocks by Type," 2014. [Online]. Available: http://www.eia.gov/dnav/pet/pet_stoc_typ_c_nus_epoord_mbb1_m.htm. [Accessed: 02-Apr-2015].

- [45] Energy Information Administration, "Biofuels issues and trends," 2012. [Online]. Available: <http://www.eia.gov/biofuels/issuestrends/>.
- [46] National Biodiesel Board, "Comprehensive survey on energy use for biodiesel production," 2008. [Online]. Available: <http://www.biodiesel.org/docs/ffs-production/comprehensive-survey-on-energy-use-for-biodiesel-production.pdf?sfvrsn=4>.
- [47] Energy Information Administration, "Monthly Biodiesel Production Report," 2014. [Online]. Available: <http://www.eia.gov/biofuels/biodiesel/production/>.
- [48] Energy Information Administration, "US Imports by Country of Origin, Brazil," 2014. [Online]. Available: http://www.eia.gov/dnav/pet/pet_move_impcus_d_nus_NBR_mbbbl_m.htm.
- [49] Environmental Protection Agency, "Fuels Reporting Registration," 2015. [Online]. Available: <https://cdxnodengn.epa.gov/cdx-otaq-reg-II/action/reportExternal/Part80FuelsProgramslist>. [Accessed: 08-Apr-2015].
- [50] UNICA - Brazilian Sugarcane Industry Association, "UNICA Data," 2015. [Online]. Available: <http://www.unicadata.com.br/index.php?idioma=2>. [Accessed: 15-Apr-2015].
- [51] B. Strogen, A. Horvath, and T. E. McKone, "Fuel miles and the blend wall: Costs and emissions from ethanol distribution in the United States," *Environmental science & technology*, vol. 46, no. 10, pp. 5285–5293, 2012.
- [52] Nebraska Energy Office, "Ethanol Production by State," 2015. [Online]. Available: http://www.neo.ne.gov/statshtml/121_archive.htm. [Accessed: 16-Apr-2015].
- [53] Energy Information Administration, "Refiner Petroleum Product Prices by Sales Type," 2015. [Online]. Available: http://www.eia.gov/dnav/pet/pet_pri_refoth_dcu_nus_m.htm. [Accessed: 16-Apr-2015].
- [54] Energy Information Administration, "Liquid Fuels Market Module," 2013. [Online]. Available: <http://www.eia.gov/forecasts/aeo/assumptions/pdf/liquidfuels.pdf>.
- [55] A. Christensen, S. Searle, and C. Malins, "A conversational guide to Renewable Identification Numbers (RINs) in the US Renewable Fuel Standard," International Council on Clean Transportation, May 2014.
- [56] Department of Energy - EERE, "Alternative Fuels Data Center - Federal and State Laws and Incentives," 2015. [Online]. Available: <http://www.afdc.energy.gov/laws>. [Accessed: 07-Apr-2015].
- [57] California Air Resources Board, "Illustrative Scenario," 2015. [Online]. Available: http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040115_LCFS_Update_to_Illustrative_Compliance_Scenario.xlsx. [Accessed: 27-Jul-2015].
- [58] California Air Resources Board, "Carbon Intensities (CIs) and Other Information from Registered Biofuel Facilities," 2015. [Online]. Available: <http://www.arb.ca.gov/fuels/lcfs/reportingtool/registeredfacilityinfo.htm>. [Accessed: 03-Apr-2015].
- [59] R. J. Plevin, A. D. Jones, M. S. Torn, and H. K. Gibbs, "Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated," *Environmental science & technology*, vol. 44, no. 21, pp. 8015–8021, 2010.

- [60] California Air Resources Board, "Pathway CI Comparison Table," 2015. [Online]. Available:
http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040115_pathway_ci_comparison.pdf. [Accessed: 28-Jul-2015].
- [61] California Air Resources Board, "Low Carbon Fuel Standard Reporting Tool Quarterly Summaries," 2015. [Online]. Available:
<http://www.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm>. [Accessed: 20-Apr-2015].
- [62] Energy Information Administration, "Annual Energy Outlook 2015," 2015. [Online]. Available: <http://www.eia.gov/forecasts/aeo/>. [Accessed: 27-Apr-2015].
- [63] California Air Resources Board, "Proposed Compliance Curves and Cost Containment Provision," 2014. [Online]. Available:
http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/lcfs_compliance_curves_and_cost_containment_10232014_pres.pdf. [Accessed: 07-Apr-2015].
- [64] G. E. Lade and C.-Y. C. Lin, "The Design and Economics of Low Carbon Fuel Standards," *Research in Transportation Economics*, vol. 52, pp. 91–99, 2015.
- [65] G. Lade and C. Lin, "A Report on the Economics of California's Low Carbon Fuel Standard and Cost Containment Mechanisms. Prepared for the California Air Resources Board. Institute of Transportation Studies, University of California, University of California - Davis, Research Report UCD-ITS-RR-13-23, 2013.
- [66] California Air Resources Board, "Facilities with Physical Pathways Pending," 2015. [Online]. Available:
http://www.arb.ca.gov/fuels/lcfs/reportingtool/pending_physical_pathways_051915.xlsx. [Accessed: 31-Jul-2015].
- [67] S. Searle and A. Christensen, "How the Renewable Fuel Standard Works," International Council on Clean Transportation, 2014.
- [68] Environmental Protection Agency, "Notice of delay in issuing 2014 standards for the Renewable Fuel Standard Program," 21-Nov-2014. [Online]. Available:
<http://www.epa.gov/otaq/fuels/renewablefuels/documents/fr-notice-2014-rf-standards.pdf>.
- [69] Environmental Protection Agency, *2014 Standards for the Renewable Fuel Standard Program*. 2013.
- [70] House of Representatives - Committee on Energy and Commerce, *Overview of the Renewable Fuel Standard: Government Perspectives*. Washington, DC, 2013.
- [71] House of Representatives - Committee on Energy and Commerce, *Overview of the Renewable Fuel Standard: Stakeholder Perspectives*. Washington, DC, 2013.
- [72] *Rocky Mountain Farmers Union v. Corey*. 2013.
- [73] A. Baral, "Summary report on low carbon fuel-related standards," International Council on Clean Transportation, 2009.
- [74] N. Miller, A. Christensen, J. E. Park, A. Baral, C. Malins, and S. Searle, "Measuring and addressing investment risk in the second-generation biofuels industry," International Council on Clean Transportation, Dec. 2013.
- [75] S. Searle, F. P. Sanchez, C. Malins, and J. German, "Technical barriers to the consumption of higher blends of ethanol," International Council on Clean Transportation, 2014.

- [76] J. Whistance and W. Thompson, "A Critical Assessment of RIN Price Behavior and the Implications for Corn, Ethanol, and Gasoline Price Relationships," *Applied Economic Perspectives and Policy*, vol. 36, no. 4, pp. 623–642, 2014.
- [77] J. Whistance and W. Thompson, "FAPRI-MU US Biofuels, Corn Processing, Biomass-based Diesel, and Cellulosic Biomass," University of Missouri-Columbia, FAPRI-MU Report #03-14, 2014.
- [78] M. Balat and H. Balat, "Recent trends in global production and utilization of bio-ethanol fuel," *Applied energy*, vol. 86, no. 11, pp. 2273–2282, 2009.
- [79] G. Sorda, M. Banse, and C. Kemfert, "An overview of biofuel policies across the world," *Energy policy*, vol. 38, no. 11, pp. 6977–6988, 2010.
- [80] International Council for Clean Transportation and DieselNet, "TransportPolicy.net," 2015. [Online]. Available: <http://www.transportpolicy.net>. [Accessed: 14-Apr-2015].
- [81] Energy Information Administration, "Electricity - Average Retail Price of Electricity By End-Use Sector," 2015. [Online]. Available: http://www.eia.gov/electricity/monthly/xls/table_5_03.xlsx. [Accessed: 02-Apr-2015].
- [82] United States Department of Agriculture, "USDA Agricultural Marketing Service - Feedstuff Report," 2015. [Online]. Available: <https://marketnews.usda.gov/mnp/ls-report-config?category=Feedstuff>. [Accessed: 14-Apr-2015].
- [83] Energy Information Administration, "Natural Gas Prices - Exports Price," 2015. [Online]. Available: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm. [Accessed: 02-Apr-2015].
- [84] Energy Information Administration, "Petroleum and Other Liquids - Mont Belvieu, TX Propane Spot Price," 2015. [Online]. Available: http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epllpa_pf4_y44mb_dp&f=d. [Accessed: 02-Apr-2015].
- [85] Energy Information Administration, "Weekly Retail Gasoline and Diesel Prices," 2014. [Online]. Available: http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_w.htm.
- [86] Energy Information Administration, "Petroleum and Other Liquids - US Gulf Coast Kerosene-Type Jet Fuel Spot Price," 2015. [Online]. Available: http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epjk_pf4_rgc_dp&f=d. [Accessed: 02-Apr-2015].
- [87] Methanex, "Methanex Methanol Price History," 2015. [Online]. Available: https://www.methanex.com/sites/default/files/methanol-price/MxAvgPrice_Mar%2027%202015.pdf. [Accessed: 14-Apr-2015].
- [88] Energy Information Administration, "Natural Gas Prices - Industrial Price," 2015. [Online]. Available: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm. [Accessed: 02-Apr-2015].
- [89] United States Department of Agriculture, "USDA National Agricultural Statistics Service - Agricultural Prices," 2015. [Online]. Available: http://www.nass.usda.gov/Statistics_by_Subject/Economics_and_Prices/index.asp. [Accessed: 14-Apr-2015].