Modeling and Analysis

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A mixed complementarity model for the US biofuel market with federal policy interventions

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Abstract: Policymakers in the USA have provided various mechanisms to grow the domestic biofuel industry. One of the most significant policies in the USA is the volume mandate specified within the Renewable Fuel Standard (RFS). There are a number of other overlapping factors that impact the use of biofuels, namely the so-called blend wall, or the 10% blend limit of ethanol in gasoline, along with a complex system of tax credits. All of these policies directly affect the value of a Renewable Identification Number (RIN), the tradable compliance certificate created as part of the RFS. Regulators track RIN prices carefully because they are a measure of the cost of compliance. In this work a mixed complementarity problem (MCP) is presented to combine these market dynamics into one model. This tool was specifically designed for policymakers to compare scenarios and study the effects on key market variables including RIN, gasoline, and diesel prices, along with production quantities for a number of different finished blended fuels. Our results suggest that RIN prices will increase with an increase in the volume of biofuel mandated by the Environmental Protection Agency (EPA); however the behavior of the different RIN prices depends on how the biofuel volumes are assigned among all the subcategories. Under scenarios investigated in this study, it is likely that a primary compliance strategy is to blend more biodiesel into diesel fuel. This behavior would increase the price of the D4 RIN but the premium could be mitigated by reinstating the biodiesel production tax credit. © 2015 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: market model; mixed complementarity problem; policy; renewable fuel standard; tax credits; renewable identification number

Introduction

Understanding how the biofuels market operates is challenging. Even though the USA is the one of the largest producers and consumers of biofuel in the world, its simultaneous reliance on petroleum fuels directly impacts how biofuel markets operate. Additionally, consumer application can vary widely depending on the type of biofuel being consumed. Further complicating the biofuel market is the fact that there are a number of different federal policies that directly and indirectly encourage the consumption of biofuel. Perhaps the most significant policy

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support is referred to as the Renewable Fuel Standard (RFS). The RFS requires certain volumes of renewable fuel to be blended with gasoline and diesel from 2010 to 2022.[1] The RFS is unique because the consumption mandates for different types of biofuel are nested, regardless of the end-use application. As a result of this interwoven network of markets, it can be difficult for policymakers and obligated parties to untangle a least-cost compliance strategy.

Obligated parties under the 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 renewable identification numbers (RINs), and retiring them to the Environmental Protection Agency (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. RINs function much in the same way as renewable energy credits or carbon credits that might be part of a cap-and-trade policy. In the absence of other policy distortions, a simple pricing RIN model might look like an arbitrage condition between the biofuel product price and the price of an equivalent petroleum-based product.[2] However, reality must include a number of other policy distortions and effects, such as tax credits and supply/demand effects from the *blend wall*, a shorthand name for the fact that ethanol/gasoline blends in the US are effectively capped at 10% by volume.[3]

All of these overlapping market forces have the potential to disrupt the least cost compliance strategy for an obligated party, thereby affecting RIN prices. As an example, an obligated party may shift to purchasing RINs from other obligated parties that may have an excess supply, which could drive up RIN prices. However, due to the nested structure of the RFS, there may be options under which RINs could be generated from other fuels and used for compliance. Since RIN prices directly affect the total compliance cost for an obligated party, there is political risk in allowing these prices to go too high, as evidenced by a number of hearings held in the House of Representatives Committee on Energy and Commerce in June/July of 2013.

Biofuel market models (or agricultural models that also include biofuels) present in the literature include: *Biofuel and Environmental Policy Analysis Model (BEPAM); Forest and Agriculture Sector Optimization Model (FASOM),* a model developed by the Food and Policy Research Institute (FAPRI)*; National Energy Modeling System (NEMS); Biofuel Breakeven Model (BIOBREAK); Biomass Scenario Model (BSM);* and *Global Trade Analysis Project (GTAP).*[4–11] Many of these models were recently reviewed by Zhang *et al*. and have been classified as top-down models.[12] A top-down model evaluates the system from aggregate economic variables. In contrast, bottom-up models incorporate more detail about technological options or consider specific supply chain or other market elements.[13]

This model was developed with the goal of evaluating volume proposals that must be performed by EPA on an annual basis. As such, the effort that was undertaken in this work was specifically designed to capture the interaction of economically significant market participants in the RFS (producers, importers, refiners, blenders, consumers, and government). The novelty of this paper is that the authors focus on a bottom-up modeling approach in order to simulate the interaction between D4, D5, and D6 RIN markets, including critical policy elements of RIN banking and applicable tax policies. Recently, Zhang *et al.* focused exclusively on D3 RIN markets and only applied their problem to a case study in Iowa. FAPRI studies have included other important RIN markets and have calculated RIN prices from complementary slackness equations that balance supply and demand of a particular biofuel.[14] These complementary slackness conditions are included in a larger framework that does not explicitly maximize profits for all of the various market participants, as the model here does. Moreover, none of these models includes aspects of banking biofuels, which can have an impact on short-term prices.

There are many technical details included in the RFS, and a full description of the program is beyond the scope of this paper. Instead the interested reader is directed to additional references for policy context and other information.[15–18] For a comprehensive discussion of the tax credit system and how it differs from the RFS, see recent work by Christensen and Lausten.[19] Beyond tax policies and the RFS, biofuels receive additional support from agencies like United States Department of Agriculture (USDA) and the Department of Energy (DoE). Additional support from these agencies is not modeled due to data limitations, however, further discussion has been detailed by Koplow.[20,21]

This model will address the aforementioned issues within an equilibrium (complementarity) framework. Such a framework has been extensively used in other energy markets.[22–27] Note that there has been several efforts to model fuel markets.[28–31] None of these efforts have focused on developing a national biofuel market model that (i) could be useable as a tool to investigate least cost compliance strategies on an annual basis, (ii) investigate details of how RIN prices are established, and (iii) includes details of tax policy that could enable a detailed study of tax credit incidence. Although this last point is left as future research, our model is set up in a way to easily do this.

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This paper is organized into five main parts. The next section details the reasoning for how the market model is structured. We then include all the notational details as well as each market participant's optimization problem and the constraints imposed by various policies/market dynamics. We move on to detail the results of the model runs and begin by explaining how the scenarios are developed. Finally we summarize our findings and draw some general conclusions for future work in this area.

Model formulation

Market structure

The five different types of RINs that can be generated under the RFS are referred to by their *D-code* and enumerated as D3–D7. However, there are only three types of RINs being modeled in this work based on the type of fuel that is being produced: D4 (biodiesel RINs), D5 (advanced RINs), and D6 (renewable fuel RINs). The EPA publishes public RIN data on a monthly basis.[32] Using this data, only strongly relevant market players can be identified. To date less than 1% of all generated RINs are cellulosic RINs (D3 and D7), therefore their influence in the operating RIN market is ignored. These assumptions simplify the biofuel production market down to essentially three participants: ethanol producers, biodiesel producers, and sugarcane ethanol importers.

General considerations

This model will focus on representing the biofuel market from producer/importer to ultimate end-user. The three identified biofuel market participants are each represented as an aggregate industry. Aggregation is appropriate because each of these markets is competitive as measured by the Herfindahl-Hirschman Index (HHI). The HHI is calculated by summing all the squares of the market shares of each competing firm. An HHI of 10 000 indicates a perfect monopoly while an HHI of zero indicates a

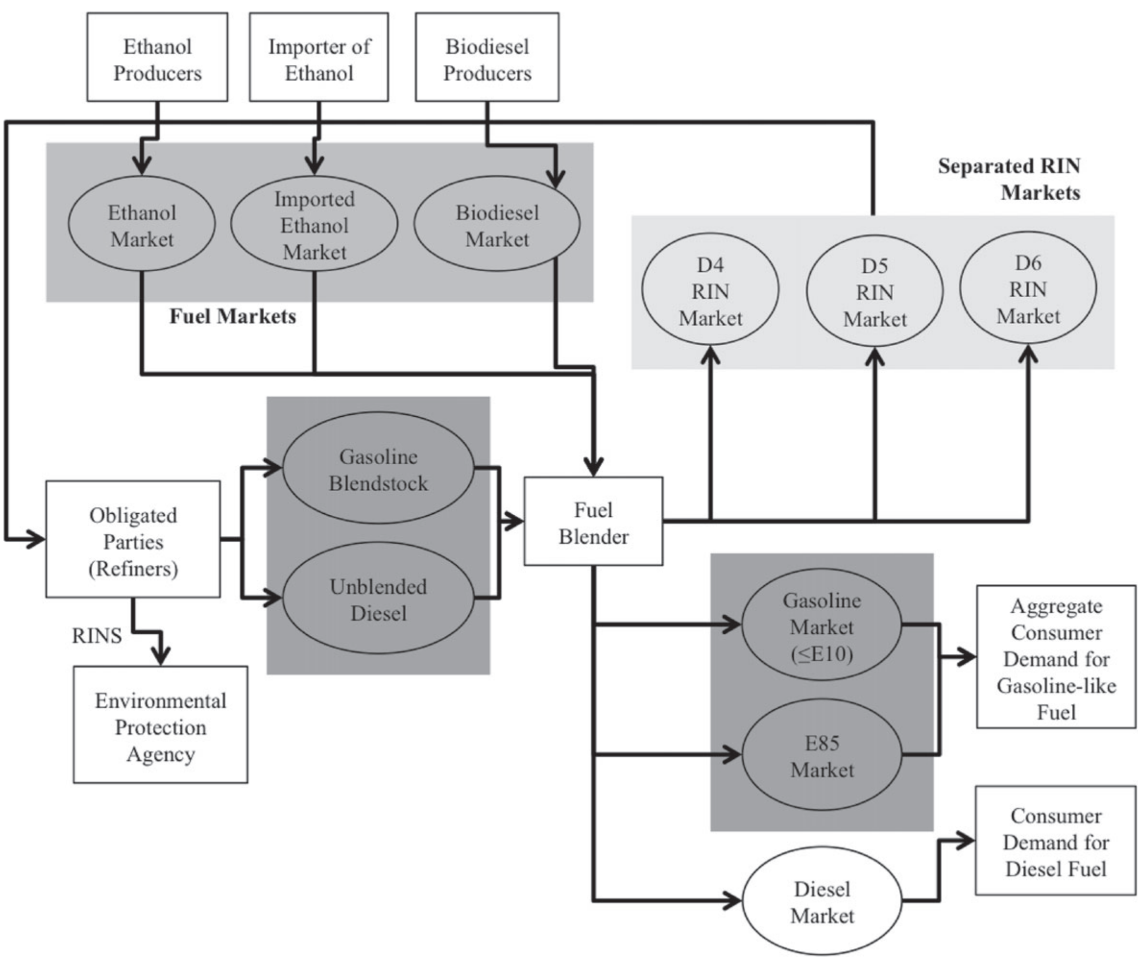

Figure 1. Graphical representation of the biofuels market model.

market that is perfectly competitive. Using biofuel production capacity as a proxy measure for market share one can calculate the HHIs of approximately 400 and 720 for the ethanol and biodiesel industries, respectively. Data for these calculations were taken from the Renewable Fuels Association and the National Biodiesel Board.[33,34]

This model currently does not contain any spatial aspects and adding in spatial information is part of ongoing research. Spatial information is important for a more detailed study of supply-chain operation, but this study focuses only on national level RIN market performance since RIN market prices are only available at a national-level index price.

The model assumes perfect foresight and contains time periods defined on a calendar year basis. This model is run until 2020, a timeline short enough that perfect foresight is a reasonable assumption.

Following the structure of the RFS, each of the three major biofuel market participants sells their products to a blender. The refiner purchases crude oil, refines it, and then sells gasoline and diesel blendstocks to the blender. From this point it is the blender's responsibility to produce finished (blended) fuel for consumer markets. Using the language found in the RFS, when a biofuel producer sells fuel to a blender, that fuel also has an *attached* RIN associated with it. Once the blender mixes the biofuel with a petroleum blendstock, the attached RIN is then considered a *separated* RIN; the blender then sells separated RINs to the refiner so they can maintain compliance with the RFS. While there may be an implicit attached RIN price, this is not stated explicitly anywhere; pricing data is only available for separated RINs.

In this formulation, the blender has the option to produce three-finished fuel products in order to meet consumer demand, which is assumed to be perfectly inelastic. The blender can sell: finished gasoline containing 10% ethanol, commonly referred to as E10; finished gasoline containing 85% ethanol, commonly referred to as E85; and diesel/biodiesel blends at any blend levels. The entire market model is shown in Fig. 1 for clarity.

Notation/optimization problems

Model variable

$q^{P,corn}_{eth,t}$	quantity of domestic corn ethanol produced (gal)
$q^{P,oils}_{bbd,t}$	quantity of biodiesel produced (gal)
$q^{P,sugar}_{eth,t}$	quantity of sugar ethanol imported (gal)
$q^{B}_{BOB,t}$	quantity of blendstock for oxygenate blending (BOB) purchased (gal)
$q^{B}_{desb,t}$	quantity of unblended diesel purchased (gal)
$q^{B,corn}_{eth,t}$	quantity of corn ethanol purchased (gal)
$q^{B}_{D6,t}$	quantity of D6 RINs separated (RINs)
$q^{B,oils}_{bbd,t}$	quantity of biodiesel purchased (gal)
$q^{B}_{D4,t}$	quantity of D4 RINs separated (RINs)
$q^{B,sugar}_{eth,t}$	quantity of sugar ethanol purchased (gal)
$q^{B}_{D5,t}$	quantity of D5 RINs separated (RINs)
$q^{B\rightarrow E85}_{BOB,t}$	quantity of BOB purchased for use in E85 (gal)
$q^{B,corn\rightarrow E85}_{eth,t}$	quantity of corn-ethanol purchased for use in E85 (gal)
$q^{B,sugar\rightarrow E85}_{eth,t}$	quantity of imported ethanol purchased for use in E85 (gal)
$q^{B\rightarrow E10}_{BOB,t}$	quantity of BOB purchased for use in E10 (gal)
$q^{B,corn\rightarrow E10}_{eth,t}$	quantity of corn-ethanol purchased for use in E10 (gal)
$q^{B,sugar\rightarrow E10}_{eth,t}$	quantity of imported ethanol purchased for use in E10 (gal)
$q^{R}_{BOB,t}$	quantity of blendstock for oxygenate blending (BOB) produced (gal)
$q^{R}_{desb,t}$	quantity of unblended diesel produced (gal)
$B^{R}_{D4,t}$	quantity of D4 RINs banked in time period t (RINs)
$B^{R}_{D5,t}$	quantity of D5 RINs banked in time period t (RINs)
$B^{R}_{D6,t}$	quantity of D4 RINs banked in time period t (RINs)
$\pi^{corn}_{eth,t}$	price for corn ethanol ($/gal)
$\pi^{sugar}_{eth,t}$	price for imported sugarcane ethanol from Brazil ($/gal)
$\pi^{oils}_{bbd,t}$	price for biodiesel fuel ($/gal)
$\pi_{BOB,t}$	price for gasoline blendstock for oxygenate blending (BOB) ($/gal)
$\pi_{desb,t}$	price for unblended diesel ($/gal)
$\pi_{D4,t}$	price for D4 RINs ($/RIN)
$\pi_{D5,t}$	price for D5 RINs ($/RIN)
$\pi_{D6,t}$	price for D6 RINs ($/RIN)
$\pi_{gas,t}$	price for finished gasoline-like fuels (E10 and E85) ($/gal)
$\pi_{des,t}$	price for finished diesel fuel ($/gal)
$\mu_{bbd,t}$	marginal cost for complying with the biomass-based diesel sub-mandate
$\mu_{adv,t}$	marginal cost for complying with the advanced fuel sub-mandate
$\mu_{rf,t}$	marginal cost for complying with the overall renewable fuel mandate
$\mu^{cap,oils}_{bbd,t}$	dual variable for biomass-based diesel capacity constraint
$\mu^{cap,corn}_{eth,t}$	dual variable for domestic corn ethanol capacity constraint
$\mu^{cap,sugar}_{eth,t}$	dual variable for imported sugarcane ethanol capacity constraint
$\mu^{cap}_{corn,t}$	dual variable for limit on corn ethanol that can qualify under the RFS

$\mu^{bank}_{bbd,t}$	dual variable for constraint on the number of banked RINs that qualify for the biomass-based diesel sub-mandate
$\mu^{bank}_{adv,t}$	dual variable for constraint on the number of banked RINs that qualify for the advanced fuel sub-mandate
$\mu^{bank}_{rf,t}$	dual variable for constraint on the number of banked RINs that qualify for the overall renewable fuel mandate
$\lambda_{D4,t}$	dual variable for equality constraint for D4 RIN separation
$\lambda_{D5,t}$	dual variable for equality constraint for D5 RIN separation
$\lambda_{D6,t}$	dual variable for equality constraint for D6 RIN separation
$\lambda_{E10,t}$	dual variable for the E10 blend wall constraint
$\lambda_{E85,t}$	dual variable for the E85 blending limit
$\lambda^{bal,sugar}_{eth,t}$	dual variable for the imported ethanol volume balance constraint
$\lambda^{bal,corn}_{eth,t}$	dual variable for the corn ethanol volume balance constraint
$\lambda^{bal}_{BOB,t}$	dual variable for the BOB volume balance constraint
EV_{eth}	equivalence value for ethanol (unitless)
EV_{bbd}	equivalence value for biodiesel (unitless)
$P^{P}_{bbd,t}$	net policy intervention for the biodiesel producer ($/gal)
$P^{P}_{eth,t}$	net policy intervention for the corn ethanol producer ($/gal)
$P^{P,sugar}_{eth,t}$	net policy intervention for the importer sugarcane ethanol ($/gal)
$P^{B}_{bbd,t}$	net policy intervention for the blender to blend biodiesel ($/gal)
$P^{B}_{eth,t}$	net policy intervention for the blender to blend ethanol ($/gal)
$\bar{q}_{des,t}$	perfectly inelastic consumer demand for diesel fuel (gal)
$\bar{q}_{gas,t}$	perfectly inelastic consumer demand for motor gasoline fuel; E10 & E85 (gal)
$\bar{q}^{P,corn}_{eth,t}$	total production capacity for corn-ethanol in the United States (gal)
$\bar{q}^{P,sugar}_{eth,t}$	total import capacity for sugarcane ethanol from Brazil (gal)
$\bar{q}^{P,oils}_{bbd,t}$	total production capacity for biodiesel in the United States (gal)

Corn ethanol producer's profit maximization problem

The corn ethanol producer is represented as an aggregate industry with the profit maximization problem shown below and is subject to a capacity constraint. The dual variables are represented in parentheses next to each capacity constraint.

$$\max_{q^{P,corn}_{eth,t}} \sum_t \left(q^{P,corn}_{eth,t}\pi^{corn}_{eth,t} - \int MC^{corn}_{eth,t}\,\mathrm{d}q^{P,corn}_{eth,t} + P^{P}_{eth,t}q^{P,corn}_{eth,t}\right)$$

s.t.

$$q^{P,corn}_{eth,t} \le \bar{q}^{P,corn}_{eth,t} \quad \left(\mu^{cap,corn}_{eth,t}\right) \tag{1}$$

Endogenous capacity investments are not considered in this modeling framework, and thus exogenous data for the capacity constraint must be used. Industry-wide production capacity is publically available through the Renewable Fuels Association on an annual basis. The marginal cost of production (*MC*) is a function of the quantity of produced biofuel. This marginal cost curve is represented as a Golombek function.[35]

$$MC^{corn}_{eth,t}\left(q^{P,corn}_{eth,t}\right) = \alpha_t + \beta_t q^{P,corn}_{eth,t} + \gamma_t \ln\left(1 - \frac{q^{P,corn}_{eth,t}}{\bar{q}^{P,corn}_{eth,t}}\right) \tag{2}$$

The Golombek function has been widely used in energy market models to represent marginal cost of production. The function mimics increasing marginal costs, which increase at a faster rate as production reaches capacity.

Brazilian sugarcane ethanol importer's profit maximization problem

All ethanol imports into the USA are assumed to be from Brazil through a single aggregate importer. In 2011, Brazilian exports accounted for approximately 60% of all ethanol imports; in 2012 it climbed to over 80%.[36] The importer is represented by the profit maximization problem shown in Eqn (3) and is subject to a capacity constraint. The capacity constraint here should be viewed as an approximation for shipping capacity between the USA and Brazil.

$$\max_{q^{P,sugar}_{eth,t}} \sum_t \left(q^{P,sugar}_{eth,t}\pi^{sugar}_{eth,t} - \int MC^{sugar}_{eth,t}\,\mathrm{d}q^{P,sugar}_{eth,t} + P^{P,sugar}_{eth,t}\, q^{P,sugar}_{eth,t}\right)$$

s.t.

$$q^{P,sugar}_{eth,t} \le \bar{q}^{P,sugar}_{eth,t} \quad \left(\mu^{cap,sugar}_{eth,t}\right) \tag{3}$$

An attempt to model the supply and demand dynamics within Brazil is not made at this stage. This marginal cost is, again, represented as a Golombek function.

Biodiesel producer's profit maximization problem

The biodiesel producer is also represented as an aggregate industry. Aggregating the entire biodiesel industry implicitly assumes that all producers are perfect substitutes for each other. The aggregate biodiesel player is represented by the profit maximization problem shown below and is also subject to a capacity constraint.

$$\max_{q^{P,oils}_{bbd,t}} \sum_t \left(q^{P,oils}_{bbd,t} \pi^{oils}_{bbd,t} - \int MC^{oils}_{bbd,t} \mathrm{d}q^{P,oils}_{bbd,t} + P^{P}_{bbd,t} q^{P,oils}_{bbd,t} \right)$$

s.t.

$$q^{P,olis}_{bbd,t} \le \bar{q}^{P,oils}_{bbd,t} \quad \left(\mu^{cap,oils}_{bbd,t} \right) \tag{4}$$

Industry-wide production capacity is publically available through the National Biodiesel Board and through the Energy Information Administration (EIA).[37,34] The marginal cost of production takes the same form as Eqn (2).

Fuel blender player's profit maximization problem

The blender purchases unfinished fuel, typically referred to as a blendstock, from the refiner and then mixes in various chemicals in order to produce a finished fuel. A finished fuel must then meet a certain ASTM (American Society for Testing and Materials) standard and can be burned in an engine. For purposes of our modeling, the fuel blender is assumed to only blend biofuels to meet the complicated fuel standard requirements.

$$\begin{aligned}\max_x \sum_t \Big[& \left(q^{B}_{BOB,t} + q^{B,corn}_{eth,t} + q^{B,corn}_{eth,t} \right) \pi_{gas,t} + \left(q^{B}_{desb,t} + q^{B}_{bbd,t} \right) \pi_{des,t} \\ & + q^{B}_{D4,t}\pi_{D4,t} + q^{B}_{D5,t}\pi_{D5,t} + q^{B}_{D6,t}\pi_{D6,t} - q^{B,sugar}_{eth,t}\pi^{sugar}_{eth,t} \\ & + q^{B,sugar}_{eth,t} P^{B}_{eth,t} - q^{B,corn}_{eth,t}\pi^{corn}_{eth,t} + q^{B,corn}_{eth,t} P^{B}_{eth,t} - q^{B,oils}_{bbd,t}\pi^{oils}_{bbd,t} \\ & + q^{B,oils}_{bbd,t} P^{B}_{bbd,t} - q_{BOB,t}\pi_{BOB,t} - q_{desb,t}\pi_{desb,t} \Big]\end{aligned}$$

where

$$\begin{aligned} x \in \Big(& q^{B}_{BOB,t}, q^{B}_{desb,t}, q^{B,corn}_{eth,t}, q^{B,sugar}_{eth,t}, q^{B,sugar\to E85}_{eth,t}, q^{B,corn\to E85}_{eth,t}, q^{B\to E85}_{BOB,t}, \\ & q^{B,sugar\to E10}_{eth,t}, q^{B,corn\to E10}_{eth,t}, q^{B\to E10}_{BOB,t}, q^{B}_{D4,t}, q^{B}_{D5,t}, q^{B}_{D6,t} \Big) \end{aligned} \tag{5}$$

The blending limits for both E10 and E85 are shown:

$$\frac{\left(q^{B,corn\to E10}_{eth,t} + q^{B,sugar\to E10}_{eth,t} \right)}{\left(q^{B\to E10}_{BOB,t} + q^{B,corn\to E10}_{eth,t} + q^{B,sugar\to E10}_{eth,t} \right)} = 0.10 \left(\lambda_{E10,t} \right) \tag{6}$$

$$\frac{\left(q^{B,corn\to E85}_{eth,t} + q^{B,sugar\to E85}_{eth,t} \right)}{\left(q^{B\to E85}_{BOB,t} + q^{B,corn\to E85}_{eth,t} + q^{B,sugar\to E85}_{eth,t} \right)} = 0.74 \left(\lambda_{E85,t} \right) \tag{7}$$

Equations (6) and (7) are formulated as equality constraints to aid in solving the model, as it is a reasonable assumption that the blending limits are binding given the number of gasoline stations that sell blends other than E10 and E85.[38] These constraints also mean that we assume that there are no other mid-level fuel blends available, E15 for example.[39] The E85 blending condition is set to reflect the average ethanol content in E85 over the course of a calendar year of 74%.[40] In order to track the volume of ethanol from each feedstock used to produce E10 and E85, explicit variables were included in the model formulation. These relationships are shown in Eqns (8)–(10).

$$q^{B,corn\to E10}_{eth,t} + q^{B,corn\to E85}_{eth,t} = q^{B,corn}_{eth,t} \left(\lambda^{bal,corn}_{eth,t} \right) \tag{8}$$

$$q^{B,sugar\to E10}_{eth,t} + q^{B,sugar\to E85}_{eth,t} = q^{B,sugar}_{eth,t} \left(\lambda^{bal,sugar}_{eth,t} \right) \tag{9}$$

$$q^{B\to E10}_{BOB,t} + q^{B\to E85}_{BOB,t} = q^{B}_{BOB,t} \left(\lambda^{bal}_{BOB,t} \right) \tag{10}$$

Equations (11)–(13) represent constraints on the blender for generating RINs that can later be sold to the refiner. These constraints represent an ethanol-equivalent energy conversion between the number of gallons of biofuel used and the number of RINs generated; in this way, biodiesel, which is approximately 1.5 times more energy dense than ethanol generated 1.5 times more RINs per gallon used.

$$q^{B}_{D4,t} - EV_{bbd} q^{B,oils}_{bbd,t} = 0 \left(\lambda^{B}_{D4,t} \right) \tag{11}$$

$$q^{B}_{D5,t} - EV_{eth} q^{B,sugar}_{eth,t} = 0 \left(\lambda^{B}_{D5,t} \right) \tag{12}$$

$$q^{B}_{D6,t} - EV_{eth} q^{B,corn}_{eth,t} = 0 \left(\lambda^{B}_{D6,t} \right) \tag{13}$$

There is an upper limit on the amount of corn ethanol that can be used to comply with the RFS, that policy decision is represented as the following constraint on the fuel blender.

$$q^{B,corn}_{eth,t} - corncap_t \le 0 \left(\mu^{cap}_{corn,t} \right) \tag{14}$$

Obligated party (refiner) player's profit maximization problem

As described earlier, obligated parties under the RFS are approximated as oil refiners. The refiner's profit maximization function is shown in Eqn (15).

$$\begin{aligned}\max_x \sum_t \; & q^{R}_{BOB,t}\pi_{BOB,t} + q^{R}_{desb,t}\pi_{desb,t} - q^{R}_{D4,t}\pi_{D4,t} - q^{R}_{D5,t}\pi_{D5,t} \\ & - q^{R}_{D6,t}\pi_{D6,t} - \int MC_{BOB,t} \mathrm{d}q_{BOB,t} - \int MC_{desb,t} \mathrm{d}q_{desb,t} \Big]\end{aligned}$$

where

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$$x \in \left(q^R_{BOB,t}, q^R_{desb,t}, q^R_{D4,t}, q^R_{D5,t}, q^R_{D6,t}, B^R_{D4,t}, B^R_{D5,t}, B^R_{D6,t}\right) \tag{15}$$

In Eqn (15), the marginal costs for production of both BOB and diesel fuel are approximated by a function with the following general form:

$$MC_t = \alpha_t + \beta_t q \tag{16}$$

This model does not contain any details of the refinery operation. Therefore, the marginal costs (crude oil costs + refining costs) are estimated from the wholesale price of gasoline and diesel fuel in the US minus all taxes, distribution and marketing costs. The marginal cost for producing gasoline is then approximately 77% of the final wholesale cost, while for diesel fuel is it slightly less at 73%.[41] It is assumed that US gasoline and diesel markets are considered competitive, and therefore refiners set their prices equal to their marginal costs. There is evidence that this assumption is not perfect as measured by the HHI, but only the refining market in the East Coast region increased from a moderately concentrated level of 1136 in 1990 to a highly concentrated level of 1819 in 2000; other regions were considered to be unconcentrated or only moderately concentrated.[42]

The following constraints are used to model the RFS (renewable fuel, advanced fuel and biomass-based diesel mandates respectively), including the banking constraints as well as the limit on the amount of corn ethanol that can be used to demonstrate compliance.

$$q^R_{D4,t} - B^R_{D4,t} + B^R_{D4,t-1} + q^R_{D5,t} \cdots$$
$$-B^R_{D5,t} + B^R_{D5,t-1} + q^R_{D6,t} - B^R_{D6,t} + B^R_{D6,t-1} - RFS_{rf,t} \geq 0\left(\mu_{rf,t}\right) \tag{17}$$

$$q^R_{D4,t} - B^R_{D4,t} + B^R_{D4,t-1} + q^R_{D5,t} - B^R_{D5,t} + B^R_{D5,t-1} - RFS_{adv,t} \geq 0\left(\mu_{adv,t}\right) \tag{18}$$

$$q^R_{D4,t} - B^R_{D4,t} + B^R_{D4,t-1} - RFS_{bbd,t} \geq 0\left(\mu_{bbd,t}\right) \tag{19}$$

The 20% RIN banking limits are expressed as:

$$B^R_{D4,t} + B^R_{D5,t} - 0.2RFS_{adv,t+1} \geq 0\left(\mu^{bank}_{adv,t}\right) \tag{20}$$

$$B^R_{D4,t} + B^R_{D5,t} + B^R_{D6,t} - 0.2RFS_{rf,t+1} \geq 0\left(\mu^{bank}_{rf,t}\right) \tag{21}$$

$$B^R_{D4,t} - 0.2RFS_{bbd,t+1} \geq 0\left(\mu^{bank}_{bbd,t}\right) \tag{22}$$

Market clearing conditions

The following market clearing conditions are for the RINs as well as the physical biofuel being sold to the refiner. The corresponding dual variables are shown in parentheses.

$$\begin{aligned}
q^R_{D4,t} &= q^B_{D4,t} & &\left(\pi_{D4,t}\right)\\
q^R_{D5,t} &= q^B_{D5,t} & &\left(\pi_{D5,t}\right)\\
q^R_{D6,t} &= q^B_{D6,t} & &\left(\pi_{D6,t}\right)\\
q^{B,corn}_{eth,t} &= q^{P,corn}_{eth,t} & &\left(\pi^{corn}_{eth,t}\right)\\
q^{B,sugar}_{eth,t} &= q^{P,sugar}_{eth,t} & &\left(\pi^{sugar}_{eth,t}\right)\\
q^{B,oils}_{bbd,t} &= q^{P,oils}_{bbd,t} & &\left(\pi_{bbd,t}\right)\\
q^B_{BOB,t} &= q^R_{BOB,t} & &\left(\pi_{BOB,t}\right)\\
q^B_{desb,t} &= q^R_{desb,t} & &\left(\pi_{desb,t}\right)
\end{aligned} \tag{23}$$

The consumer demand for diesel fuels is relatively straightforward. For purposes of this model the projected demand from Table 11 from the 2013 Annual Energy Outlook (AEO2013) is used as a perfectly inelastic demand.[40] The demand for diesel fuels can be met by supplying petroleum based diesel but also the blended biodiesel. It is therefore assumed that diesel and biodiesel are perfect substitutes for each other. The market clearing condition for the finished diesel fuel market is:

$$q^B_{desb,t} + q^{B,oils}_{bbd,t} - \overline{q}_{des,t} = 0\left(\pi_{des,t}\right) \tag{24}$$

The consumer demand for finished gasoline is more complex, and a number of necessary simplifications were made for this study. First the market clearing condition is presented:

$$\left(q^{B\to E10}_{BOB,t} + q^{B,sugar\to E10}_{eth,t} + q^{B,corn\to E10}_{eth,t}\right)\cdots$$
$$+\rho\left(q^{B\to E85}_{BOB,t} + q^{B,corn\to E85}_{eth,t} + q^{B,sugar\to E85}_{eth,t}\right) - \overline{q}_{gas,t} = 0\left(\pi_{gas,t}\right) \tag{25}$$

In Eqn (25), the first term in parentheses represents the volume of fuel used to blend E10; the second term is the volume of fuel used to blend E85. The ρ is a discount factor and for this study is set to 0.782 to reflect the difference in energy densities between E85 and E10; remembering that the average annual ethanol content in E85 is actually 74%. As with the exogenous consumer demand for diesel fuel, Table 11 from the AEO2013 was used to project demand for gasoline fuels. Including the discount factor implicitly values the consumer's ability to drive a specified distance rather than obtaining a specified volume of fuel from a retail location. There is some initial evidence in Brazil that consumers will arbitrage their fuel preferences based on the energy content of the fuel.[43] Other details of using E85 in the transportation system are not explicitly included in the model at this time. There are a number of studies that focus on the intersection of consumer behavior, E85 adoption, infrastructure challenges, and pricing.[44–50]

Results

Intuition from the Karush-Kuhn-Tucker (KKT) conditions

The full set of KKT conditions is provided in the Appendix, but some brief conclusions are pointed out regarding the individual RIN values (D4, D5, and D6). As described in the *RIN market operation* section of this paper, the value of a RIN is nested among all the other RINs as a consequence of the nested mandate structure of the RFS.[51] This intuitive explanation is confirmed when the KKT conditions are derived. The value of the D6 RIN is equal the marginal cost of compliance with the renewable fuel mandate ($\mu_{rf,t}$), the D5 RIN is equal to the marginal cost of compliance with both the renewable fuel mandate and the advanced fuel mandate ($\mu_{adv,t} + \mu_{rf,t}$), and the D4 RIN price is equal to the marginal cost of compliance with all three sub-mandates ($\mu_{bbd,t} + \mu_{adv,t} + \mu_{rf,t}$). This structure ensures that D6 RINs act as a price floor for all the other RINs. The D5 RIN is a price floor for the D4 RIN; in mathematical terms, D4 ≥ D5 ≥ D6. Historical RIN values are presented in Fig. 2.

Policy scenarios

The model that has been described in the preceding sections was expressed as a mixed complementarity problem, written into GAMS, and solved with several scenarios using the PATH algorithm.[52,53] There were three different volume scenarios that were considered for this analysis; additionally, each of these volume scenarios was run with and without a $1/gal biodiesel tax credit for 2014. One volume scenario was proposed by Irwin.[54] The other scenarios correspond to the recent proposal released by the EPA.[55] Since the EPA requested comment on a range of biofuel volumes, this scenario includes two separate sub-scenarios that reflect the upper and lower bounds on how many gallons of biofuel must be consumed per annum for each biofuel category.

The model was run for years 2011–2022 (with the last two years ignored in the results to mitigate end of horizon effects). The EPA has the authority to revise and set the volume standards on an annual basis, and there is significant uncertainty around these values. Therefore, for purposes of modeling, the required volumes from 2015 to 2022 are held constant. To include all of this uncertainty, it is likely that this model would need to be recast as a stochastic program. As formulated here, it is expected that simulation results would need to be reanalyzed annually if used in a regulatory setting. Table 1 details the three different scenarios that were modeled for this study alongside

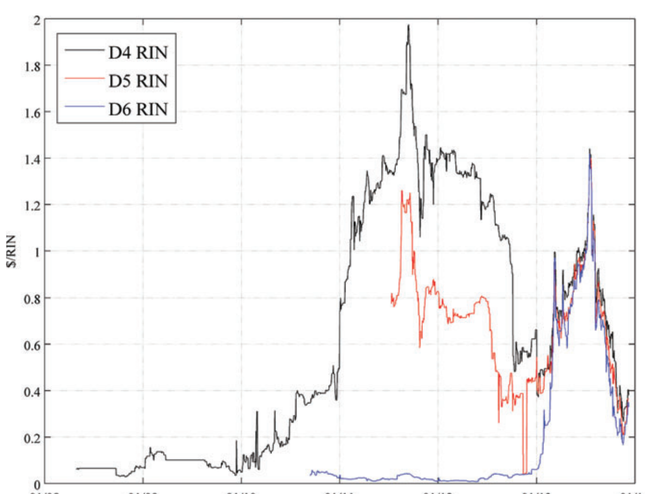

Figure 2. Historical RIN prices. Prices presented here are simple averages of the different vintages of RINs that might be available at any given date. While there is a small spread between RIN vintages, the spread is small; the RIN vintage is not currently captured within this modeling framework.

Table 1. Modeled volume scenarios for this study in Billions of Gallons. Revised years are a result of EPA action and are part of the normal regulatory calendar for implementing the Renewable Fuel Standard.

	EPA low (Base Case)	EPA high	Irwin	Statute
Biomass- Based Diesel				
2011	0.8	0.8	0.8	0.8
2012	1	1	1	1
2013	1.28	1.28	1.28	1 (revised to 1.28)
2014	1.28	1.28	1.28	1 (proposed 1.28)
2015	1.28	1.28	1.28	1 (proposed 1.28)
Advanced Fuel				
2011	1.35	1.35	1.35	1.35
2012	2	2	2	2
2013	2.75	2.75	2.75	2.75
2014	2	2.51	2.75	3.75
2015	2	2.51	2.75	5.5
Renewable Fuel				
2011	13.95	13.95	13.95	13.95
2012	15.2	15.2	15.2	15.2
2013	16.55	16.55	16.55	16.55
2014	15	15.52	16.55	18.15
2015	15	15.52	16.55	20.5

 | *Biofuels, Bioprod. Bioref.* (2015); DOI: 10.1002/bbb

Table 2. RIN prices used to calibrate the model, units are $/RIN.

RIN Type	2011	2012	2013
D4	1.30	1.09	0.73
D5	0.90	0.58	0.67
D6	0.02	0.02	0.59

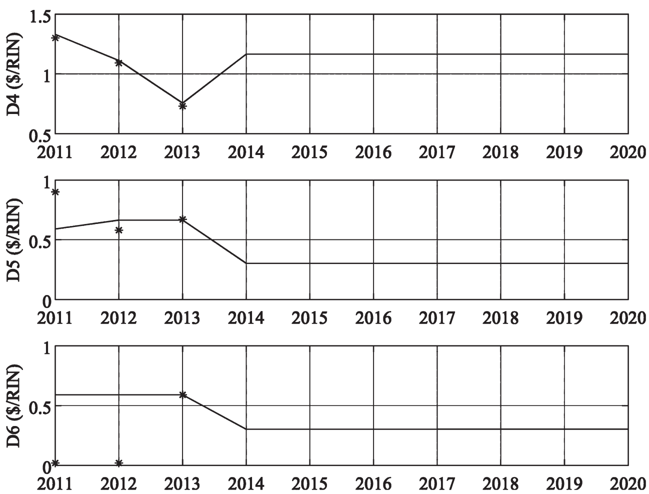

Figure 3. Calibration results for RIN price for the base case (*EPA Low*) volume recommendations.

the actual statute. Mandated volumes in the statue are included for completeness only and were not used to generate output.

Model calibration

Reasonable attempts were made to calibrate the model to a historical simple-average RIN price for 2011–2013; the base case that is calibrated was specified as the *EPA Low* scenario. The EPA Low scenario case was chosen as the base case because it represented the most conservative volume mandate scenario that EPA was considering. The prices that were used to calibrate the model are shown in Table 2.

The authors used the coefficients of the marginal cost functions as well as the production capacity as points of calibration. Production capacities for each of the biofuels modeled in the work are largely known quantities, but knowing the exact time evolution for operating capacity can be difficult.[33,37,56] Therefore, each of these parameters can also be treated as a point of calibration, albeit they are less flexible than other parameters. General agreement was found with model results and historical patterns, although some trends were not reproducible, as seen in Fig. 3. Specifically, it is hypothesized that a combination of the perfect foresight assumption and other inefficiencies in the D6 RIN market led to an overvaluing in 2011 and 2012. It is important for the reader to remember that these markets are still very new and the RIN prices that exist may not necessarily reflect the underlying fundamentals.

The final parameters used for calibration of the model are documented in Table 3.

Once the model was calibrated, all of the exogenous parameters used to define the marginal cost functions

Table 3. Model input parameters for calibration of the base case (EPA Low).

Fuel	Parameter	2011	2012	2103	2014…2022
Corn Ethanol	α_t	2.00	2.02	2.04	+1% each year
Corn Ethanol	β_t	0.05	0.034	0.034	0.034
Corn Ethanol	γ_t	–0.49	–0.49	–0.49	–0.49
Corn Ethanol Capacity (billion gal)	$\bar{q}^{P,corn}_{eth,t}$	14.90	14.90	14.90	14.90
Sugar Ethanol	α_t	2.25	2.27	2.30	+1% each year
Sugar Ethanol	β_t	0.04	0.04	0.04	0.04
Sugar Ethanol	γ_t	–1.0	–1.81	–1.81	–1.81
Sugar Ethanol Capacity (billion gal)	$\bar{q}^{P,sugar}_{eth,t}$	1.0	0.85	0.85	0.85
Biodiesel	α_t	3.50	3.54	3.57	+1% each year
Biodiesel	β_t	0.15	0.1	0.1	0.1
Biodiesel	γ_t	–1.3	–1.1	0.8	–0.8
Biodiesel Capacity (billion gal)	$\bar{q}^{P,oils}_{bbd,t}$	1.0	2.0	2.0	2.0
Gasoline Blendstock	α_t	2.55	2.58	2.60	+1% each year
Gasoline Blendstock	β_t	0.002	0.002	0.002	0.002
Unblended Diesel	α_t	2.50	2.53	2.55	+1% each year
Unblended Diesel	β_t	0.002	0.002	0.002	0.002

were sampled from distributions in a Monte Carlo style analysis; other exogenous parameters such as consumer demand and production capacity are assumed to not have any associated uncertainty. It is assumed that each of sampled parameters can be described by a normal distribution. The standard deviation for the α parameters was calculated from historical market data. Historical market data was used to calculate the standard deviation for the α parameters, the median value for α was considered to be a point of model calibration. The standard deviations for all parameters are summarized in Table 4.

The α parameters in each of the marginal cost functions (for biofuels and petroleum blendstocks) represent the cost of the first gallon of production. The standard deviation associated with each α parameter was not considered to be a point of calibration; instead historical market data (Chicago Board of Trade, NYMEX, NY Harbor Spot Price, São Paulo Ethanol landed in USA) was used to define these values. The consumer demand for gasoline and diesel fuels is not subject to any assumptions regarding uncertainty and is merely held as a constant.

Table 4. Standard deviations that were assumed to define the shape of the normal distribution used in the Monte Carlo analysis.

Fuel	Parameter	2011	2012	2103	2014…2022
Corn Ethanol	α_t	0.2014	0.166	0.3018	0.3018
Corn Ethanol	β_t	0.01	0.01	0.01	0.01
Corn Ethanol	γ_t	0.1	0.1	0.1	0.1
Sugar Ethanol	α_t	0.1686	0.1885	0.1821	0.1821
Sugar Ethanol	β_t	0.01	0.01	0.01	0.01
Sugar Ethanol	γ_t	0.1	0.1	0.1	0.1
Biodiesel	α_t	0.2472	0.1571	0.1256	0.1256
Biodiesel	β_t	0.01	0.01	0.01	0.01
Biodiesel	γ_t	0.1	0.1	0.1	0.1
Gasoline Blendstock	α_t	0.2643	0.2267	0.1675	0.1675
Gasoline Blendstock	β_t	0.0001	0.0001	0.0001	0.0001
Unblended Diesel	α_t	0.1754	0.1760	0.1138	0.1138
Unblended Diesel	β_t	0.0001	0.0001	0.0001	0.0001

Results

The results presented here are the result of 5000 individual Monte Carlo runs. To present the resulting distributions compactly the following graphs show the median value in bold and the interquartile range as the bounding non-bold lines.

The first three figures (Figs 4, 5, and 6) show the projected RIN prices under the three different volume scenarios outlined in Table 1. The median RIN price is very sensitive to the volume mandated by EPA. Beginning with the base case (*EPA low*), the 2014 RIN prices were estimated to be \$1.12/RIN (D4), \$0.00/RIN (D5), and \$0.00/RIN (D6). In particular, the D5/D6 RINs experienced a significant price decrease from 2013 to 2014 as a result

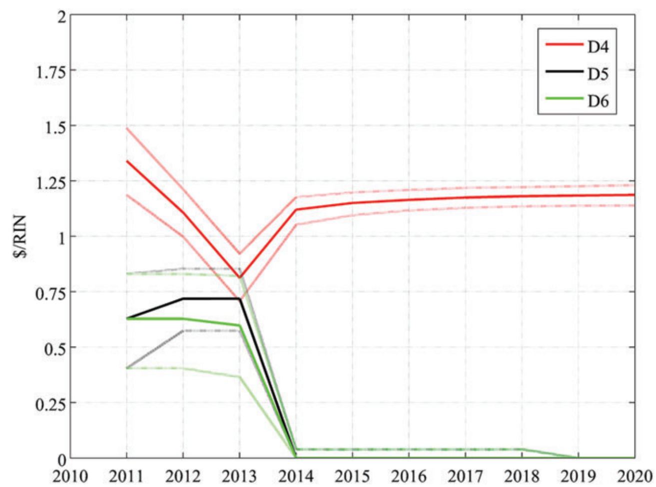

Figure 4. RIN price projection under the *EPA low* scenario, no biodiesel tax credit after 2013.

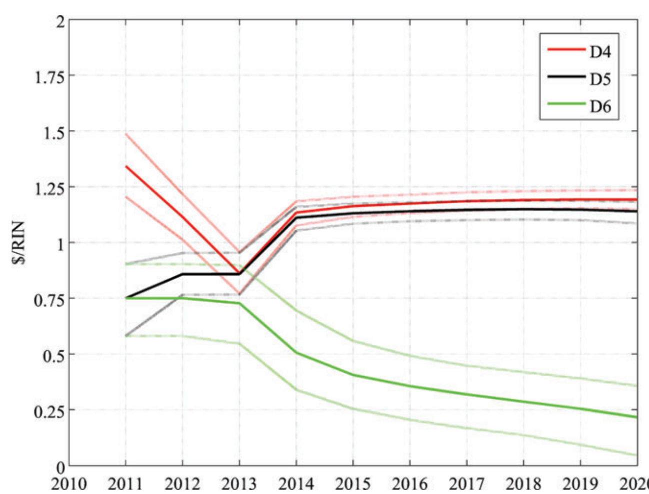

Figure 5. RIN price projection under the *EPA high* scenario, no biodiesel tax credit after 2013.

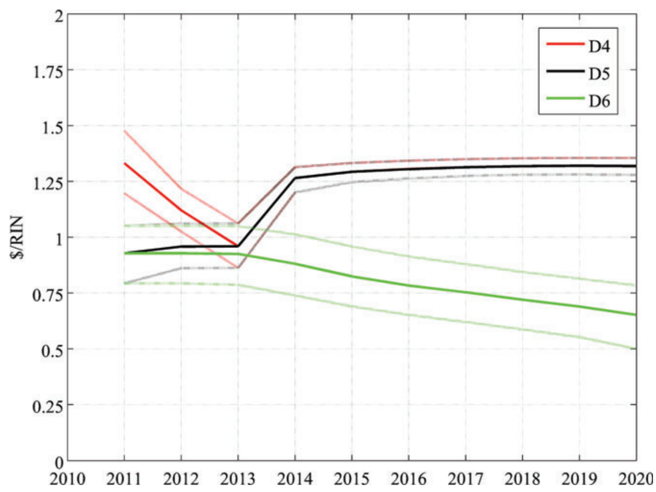

Figure 6. RIN price projection under the *Irwin* scenario, no biodiesel tax credit after 2013.

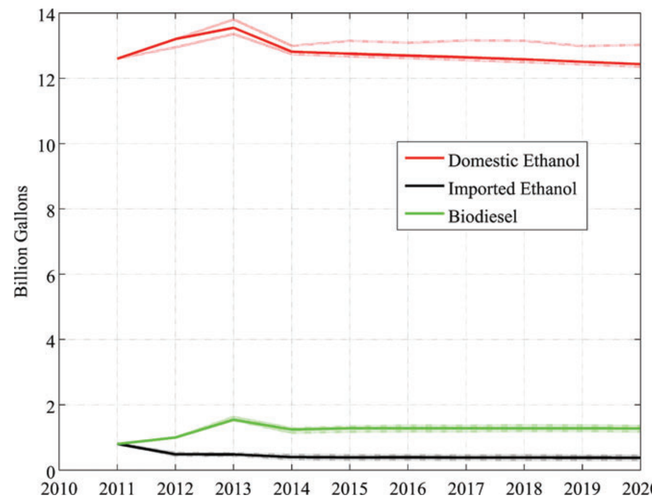

Figure 7. Quantities of biofuel used for compliance with the *EPA low* scenario, no biodiesel tax credit after 2013.

of the decrease in the overall renewable fuel mandate, and subsequent decrease in the advanced fuel mandate mapped out in this scenario. In the *EPA High* scenario, the median 2014 D5/D6 RIN prices were $1.11 and $0.51, respectively. The *Irwin* scenario results in RIN prices that are even higher. This sensitivity is not unexpected as the RIN price is the shadow price for the RFS compliance constraints. Intuitively if regulators were to require more biofuel to be consumed, the RIN price should also increase as long as there increasing marginal costs when approaching full production capacity. The EPA is currently considering setting the 2014 volume standards at some point between *EPA low* and *EPA high*, but even within this range the D6 RIN price can vary widely. This sensitivity illustrates the difficult role that EPA plays in establishing appropriate volume standards balancing the legal requirements in the RFS with the burden of compliance. From Figs 5 and 6 it is also possible to see exactly how the D4 RIN price behaves as a ceiling for the D5 RIN price, meaning that at some point it is more advantageous to use biodiesel to comply with both the biomass-based diesel and the advanced fuel requirements in the RFS (rather than importing sugarcane ethanol to fill the advanced fuel requirement).

The volumes required for compliance under the *EPA low* scenario are shown in Fig. 7. Graphs for the other volume scenarios are not included for brevity, but for the *Irwin* scenario the amount of biodiesel used for compliance increased by approximately 14% over *EPA low* (~1.24 billion gal) for 2014; the *EPA high* scenario required biodiesel volumes to increase by approximately 1% over *EPA low*.

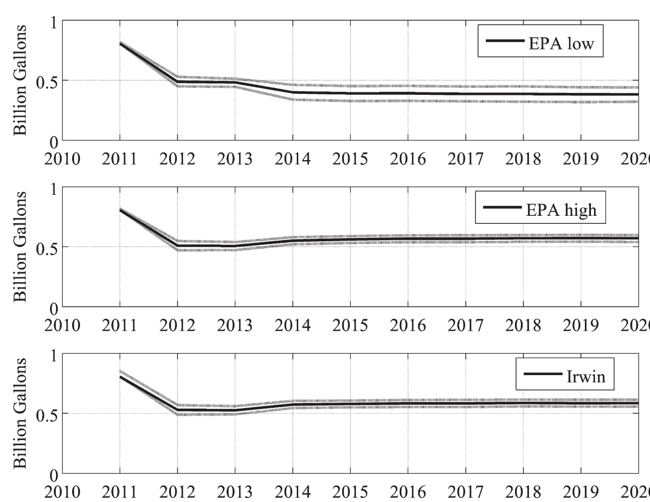

Figure 8. Quantity imported sugar ethanol from Brazil used for compliance under the three volume scenarios.

In Fig. 8 the consumption of sugar ethanol has been plotted for each of the three scenarios. Most recognizable is the trend with the *EPA low* scenario; the use of imported ethanol decreases significantly over time. This is driven by the fact that the volumes specified in the *EPA low* scenario are set just slightly below the 10% ethanol blend wall. By doing this, it effectively eliminates the need for additional imported ethanol when a slight uptick in biodiesel consumption would help satisfy both the biomass-based diesel mandate as well as the advanced mandate.

Other interesting effects of the blend wall show up when the quantity of consumed E85 is compared across scenarios. As can be seen in Fig. 9, there is a greater need to produce E85 in the more aggressive volume scenario (*Irwin*)

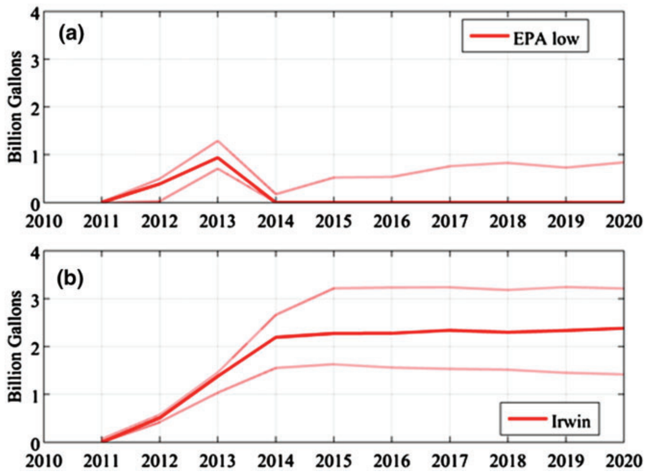

Figure 9. Quantities of E85 that are consumed for compliance under the *EPA low* (a) and *Irwin* (b) scenarios.

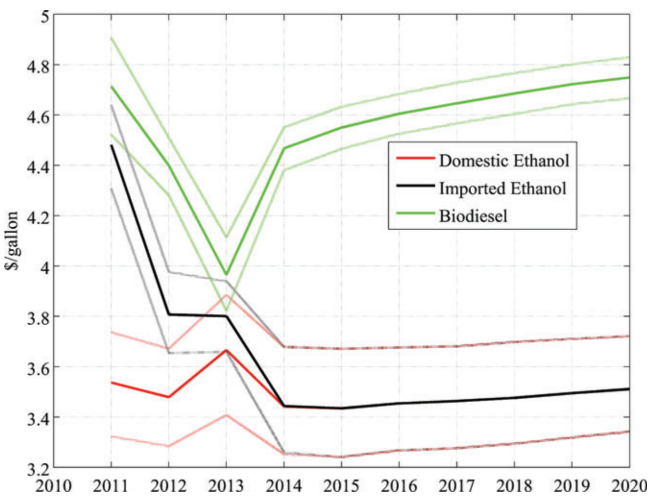

Figure 10. Biofuel prices under the *EPA low* scenario, no biodiesel tax credit after 2013.

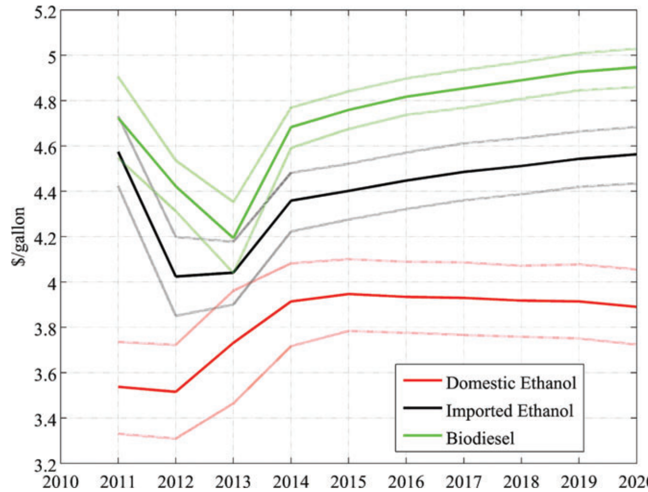

Figure 11. Biofuel prices under the *Irwin* scenario, no biodiesel tax credit after 2013.

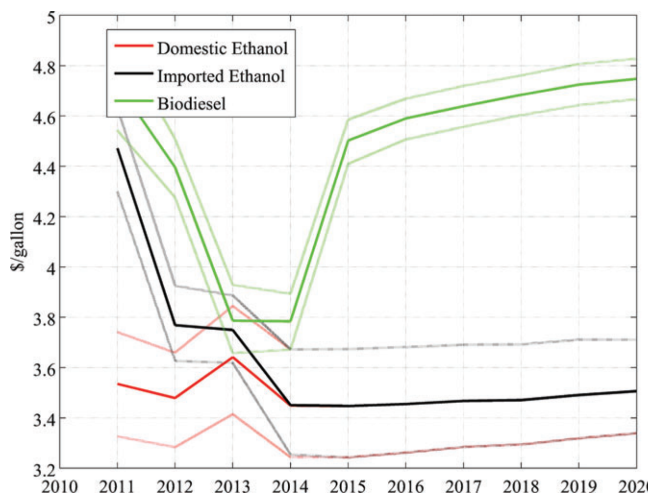

Figure 12. Biofuel prices under the *EPA low* scenario, with a $1/gal biodiesel tax credit for 2014.

whereas there is very little incentive to produce E85 if the volumes set in *EPA low* are set just below the E10 blend wall; this is captured as a near-zeroing out of required E85 volumes after 2013.

The volume mandated in each of the scenarios also affects the price of the physical biofuel being purchased by the blender from the biofuel producer/importer. Figures 10 and 11 show the price trends for the three main biofuels being modeled. For all these simulations, it is assumed that there are no capacity expansions that take place. This assumption may exaggerate the price impact, but absent a clear long-term vision of increasing biofuel consumption, it is questionable whether the market would respond by raising the huge amount of capital to finance capacity expansions for of first-generation biofuels.[57,58]

In analyzing the *EPA low* scenario results, it is possible to see that post-2013 the price of imported ethanol begins to track that of domestically produced corn ethanol. This is because a gallon of sugarcane ethanol contains no additional value above domestically produced corn ethanol, primarily due to the low advanced biofuel use requirements that are specified in this scenario. This case is reversed in the *Irwin* scenario, as there is a need to consume ethanol beyond the blend wall. There is also additional value for consuming sugarcane ethanol as an obligated party can satisfy both the renewable and advanced fuel mandates by collecting the corresponding D5 RIN.

In Fig. 12 the biofuel prices resulting from the EPA low scenario are presented, although this time a $1/gal biodiesel tax credit is added for one year, 2014. This tax credit represents a hypothetical situation in which Congress would extend the recently expired tax credit. This tax credit is given directly to the producer of the biofuel (not the fuel blender), and should impact the ultimate price of biodiesel. The model developed here suggests that the credit incidence is approximately 48% for the biodiesel producer, meaning that the producer is able to keep roughly $0.48 of every dollar of tax credit as profit, the other $0.52 is passed on to the fuel blender in the form of lower purchase prices. It should be noted that this model ignores the complicated history of the biodiesel tax credit, where Congress, more than once, has extended the credit retroactively. A retroactive extension allowed the biodiesel industry to claim a tax benefit for a previous year where there was no available credit. A full history of the biodiesel tax credit can be found in a review by Christensen and Lausten.[19]

Summary and conclusions

This model was developed with the goal to evaluate volume proposals that must be performed by EPA on an annual basis. There are several overlapping policies that affect the biofuel market, and understanding the interaction between all these policy levers is important to setting more effective policy. The main conclusions from this analysis can be summed up as:

- If the 2014 RFS volumes are set at the *EPA low* scenario levels, it is likely the median 2014 D5 and D6 RIN price will *decrease* to $0.00/RIN as a result of a non-binding RFS mandate.
- Under any scenario, the tax credit for biodiesel *decreases* the ultimate contract price for biodiesel. However the decrease is less than the full value of the tax credit.
- If the 2014 RFS volumes were set at a more aggressive volume standard (*Irwin scenario*), it is likely that the D6 RIN price will increase to approximately $1/RIN and will remain at that level until there are more substantial market changes.
- If the 2014 RFS volumes were set at the lowest volume proposal (*scenario EPA Low*), it would nearly eliminate the need to blend E85 alternative fuels. In the *Irwin* scenario, blenders will have an incentive to blend E85 fuels at increasing volumes in order to meet the additional requirement to consume ethanol.

The model developed here allows policymakers to probe *least-cost compliance strategies* that obligated parties might use to comply with the RFS. This model is the first to capture all of the economically significant market participants on a national scale, and also includes strategic options associated with banking of RINs.

Appendix A

Biodiesel Producer KKT Conditions

$$0 \le q_{bbd,t}^{P,oils} \perp -\pi_{bbd,t} + MC_{bbd,t}\left(q_{bbd,t}^{P,oils}\right) - P_{bbd,t}^{P} + \mu_{bbd,t}^{cap,oils} \ge 0$$

Domestic Ethanol Producer KKT Conditions

$$0 \le q_{eth,t}^{P,corn} \perp -\pi_{eth,t}^{corn} + MC_{eth,t}^{corn}\left(q_{eth,t}^{P,corn}\right) - P_{eth,t}^{P} + \mu_{eth,t}^{cap,corn} \ge 0$$

Ethanol Importer KKT Conditions

$$0 \le q_{eth,t}^{P,sugar} \perp -\pi_{eth,t}^{sugar} + MC_{eth,t}^{sugar}\left(q_{eth,t}^{P,sugar}\right) - P_{eth,t}^{P,sugar} + \mu_{eth,t}^{cap,sugar} \ge 0$$

Refiner KKT Conditions

$$0 \le q_{BOB,t}^{R} \perp MC_{BOB,t}\left(q_{BOB,t}^{R}\right) - \pi_{BOB,t} \ge 0$$

$$0 \le q_{desb,t}^{R} \perp MC_{desb,t}\left(q_{desb,t}^{R}\right) - \pi_{desb,t} \ge 0$$

$$0 \le q_{D4,t}^{R} \perp \pi_{D4,t} - \mu_{bbd,t} - \mu_{adv,t} - \mu_{rf,t} \ge 0$$

$$0 \le q_{D5,t}^{R} \perp \pi_{D5,t} - \mu_{adv,t} - \mu_{rf,t} \ge 0$$

$$0 \le q_{D6,t}^{R} \perp \pi_{D6,t} - \mu_{rf,t} \ge 0$$

$$0 \le B_{D4,t}^{R} \perp \mu_{bbd,t}^{bank} + \mu_{adv,t}^{bank} + \mu_{rf,t}^{bank} + \mu_{bbd,t} - \mu_{bbd,t+1} + \mu_{adv,t} - \mu_{adv,t+1} + \mu_{rf,t} - \mu_{rf,t+1} \ge 0$$

$$0 \le B_{D5,t}^{R} \perp \mu_{adv,t}^{bank} + \mu_{rf,t}^{bank} + \mu_{adv,t} - \mu_{adv,t+1} + \mu_{rf,t} - \mu_{rf,t+1} \ge 0$$

$$0 \le B_{D6,t}^{R} \perp \mu_{rf,t}^{bank} + \mu_{rf,t} - \mu_{rf,t+1} \ge 0$$

Blender KKT Conditions

$$0 \le q_{D4,t}^{B} \perp \lambda_{D4,t} - \pi_{D4,t} \ge 0$$

$$0 \le q_{D5,t}^{B} \perp \lambda_{D5,t} - \pi_{D5,t} \ge 0$$

$$0 \le q_{D6,t}^{B} \perp \lambda_{D6,t} - \pi_{D6,t} \ge 0$$

$$0 \le q_{BOB,t}^{B} \perp \pi_{BOB,t} - \lambda_{BOB,t}^{bal} - \pi_{gas,t} \ge 0$$

$$0 \le q_{BOB,t}^{B\to E10} \perp -0.10\lambda_{E10,t} + \lambda_{BOB,t}^{bal} \ge 0$$

$$0 \le q_{BOB,t}^{B\to E85} \perp -0.74\lambda_{E85,t} + \lambda_{BOB,t}^{bal} \ge 0$$

$$0 \le q_{eth,t}^{B,corn} \perp \mu_{corn,t}^{cap} - \lambda_{eth,t}^{bal,corn} - P_{eth,t}^{B} - \pi_{gas,t} + \pi_{eth,t}^{corn} - EV_{eth}\lambda_{D6,t} \ge 0$$

$$0 \le q_{eth,t}^{B\to E10,corn} \perp \lambda_{eth,t}^{bal,corn} - \lambda_{E10,t}(0.10-1) \ge 0$$

$$0 \le q_{eth,t}^{B\to E85,corn} \perp \lambda_{eth,t}^{bal,corn} - \lambda_{E85,t}(0.74-1) \ge 0$$

$$0 \le q_{eth,t}^{B,sugar} \perp \pi_{eth,t}^{sugar} - \lambda_{eth,t}^{bal,sugar} - \pi_{gas,t} - P_{eth,t}^{B} - EV_{eth}\lambda_{D5,t} \ge 0$$

$$0 \le q_{eth,t}^{B\to E10,sugar} \perp \lambda_{eth,t}^{bal,sugar} - \lambda_{E10,t}(0.10-1) \ge 0$$

$$0 \le q_{eth,t}^{B\to E85,sugar} \perp \lambda_{eth,t}^{bal,sugar} - \lambda_{E85,t}(0.74-1) \ge 0$$

$$0 \le q_{desb,t}^{B} \perp \pi_{desb,t} - \pi_{des,t} \ge 0$$

$$0 \le q_{bbd,t}^{B,oils} \perp \pi_{bbd,t} - P_{bbd,t}^{B,oils} - \pi_{des,t} - EV_{bbd}\lambda_{D4,t} \ge 0$$

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