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Fuel price impacts and compliance costs associated with the Renewable Fuel Standard (RFS)

Adam Christensen [a,*], Sauleh Siddiqui [b]

[a] Johns Hopkins University, Department of Geography and Environmental Engineering, 3400 N Charles St, Ames Hall 313, Baltimore, MD 21218, United States
[b] Johns Hopkins University, Department of Civil Engineering, 3400 N Charles St, Latrobe Hall 109, Baltimore, MD 21218, United States

HIGHLIGHTS

- The most recent EPA could cause the biodiesel RIN price to rise to >$1.00/RIN.
- D5/D6 RIN prices are most sensitive to the volume of E85 consumed.
- Retail prices for fuel do not change dramatically.
- 2017 compliance costs could fall by 50% if more E85 were consumed.

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ABSTRACT

US policy instruments concerning vehicle biofuels are currently being revisited. For example, as part of an on-going annual Renewable Fuel Standard (RFS) implementation, the Environmental Protection Agency (EPA) requests stakeholder feedback/analysis of programmatic effects, including impacts on gasoline/diesel prices and compliance costs. Motivated by the need for regulatory-specific feedback, a novel regional market model is developed that quantifies price impacts across different regional markets for a number of market variables, including several types of compliance certificates known as Renewable Identification Numbers (RINs). An analysis of the most recent EPA proposal suggests that the D4 (biodiesel) RIN price could rise to >$1.00/RIN. Sensitivity results show that the D4 RIN price is highly sensitive to soybean oil prices, while D5/D6 RIN prices are most sensitive to the volume of E85 consumed. It was found that the projected costs associated with the RFS in 2017 could be reduced by approximately 50% if an additional 600 million gallons of E85 were consumed. The analysis also suggests that the RFS does not dramatically affect the retail price of either gasoline and diesel fuels paid by consumers.

1. Introduction

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 (US) fleet that can burn pure, or high percentage blends of biofuel. For 2014 the Energy Information Administration (EIA) estimated that 6% of the light truck and car market *can* consume ethanol in blends up to 85% (E85), but only a small proportion of these vehicles actually burn E85 due to fuel availability issues (Energy Information Administration, 2013a). 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) (National Biodiesel Board, 2015).

As a consequence, the *second* challenge is that biofuel must compete on a cost basis with many other chemicals that are mixed together to create transportation fuel. Fuel blenders are those entities in the supply chain that mix final transportation fuel (i.e., *gasoline* and *diesel*); the final fuel product must meet relevant ASTM standards as well as fuel quality standards enforced by the Environmental Protection Agency (EPA) (Environmental Protection Agency, 2014a). 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 produce pure hydrocarbon fuel products (crude oil refiners,

* Corresponding author.
E-mail addresses: adam.christensen@jhu.edu (A. Christensen), siddiqui@jhu.edu (S. Siddiqui).

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natural gas liquid producers, other chemical manufacturers).

Third, there are many and varied policies at the state and federal levels that encourage the production/consumption of biofuel. However, the variability between policies creates a complex system of market distortions with certain, and likely unintended, consequences (Christensen and Lausten, 2014). Beyond the special tax treatment and minimum blending requirements that biofuels receive, policy makers are working to incentivize the consumption of biofuels with lower lifecycle greenhouse gas (GHG) emissions. These policies have taken the form of the national Renewable Fuel Standard (RFS) and the California Low Carbon Fuel Standard (CA-LCFS) (California Air Resources Board, 2009; Environmental Protection Agency, 2007; Governor Schwarzenegger, 2007). Regulating lifecycle GHG emissions poses some unique challenges and results in market distortions since the emissions are an extrinsic rather than intrinsic property of the biofuel product (Bushnell and Mansur, 2011; Mansur, 2010).

As a result of the interwoven network of policies and markets at various levels (federal, state and local), it can be difficult for policy makers to anticipate the impacts of potential policy changes; it can also be difficult for obligated parties (e.g., fuel suppliers) to discern a least-cost compliance strategy. The work presented here is an effort to model the biofuel market including all relevant state tax policies and mandates. This model also includes policy details of the RFS and the embedded Renewable Identification Number (RIN) compliance credit markets. Previous models that have focused on RIN markets have held various RIN categories as exogenous (i.e., select sub-mandates have been omitted) or have been developed within a framework that does not explicitly consider the behaviors of all the different liquid fuel market players (Meyer and Thompson, 2010; Thompson et al., 2010, 2011; Whistance and Thompson, 2014a, 2014b). Other more recent models are being developed that do include a wide variety of markets, but lack spatial details (Whistance and Thompson, 2014c). Our model includes all immediately relevant sub-mandates (biomass-based diesel, advanced, and renewable) as well as potentially strategic details of RIN banking disaggregated by state level regions. Further modeling assumptions and motivations are provided in Section 3.

In the below subsections, we provide background in the form of a review of the challenges faced by regulators charged with implementing the RFS program (Section 1). We briefly describe the programmatic requirements associated with the RFS, as well as a state level biofuel policy, in this section. Section 2 is devoted to outlining the model structure and solution methodology, as well as underlying assumptions. Section 2 also describes the policy scenarios modeled in this analysis. Section 3 presents the results of the model simulations for the policy scenarios developed in Section 2. A significant section of Section 3 is also devoted to model calibration results as baseline validation. Sections 4 and 5 provide a final discussion and a summary of the results and their policy implications.

1.1. *Policy relevance – challenges faced by regulators*

A contextual discussion of the RFS is necessary in order to motivate this research. Congress created the RFS in its current form with the passage of the Energy Independence and Security Act in 2007 (Energy Independence and Security Act of 2007, n.d.). In this law, Congress mandated the number of gallons of biofuel to be consumed in the US. Congress also created a number of categories of biofuel that corresponded to different reductions from a baseline lifecycle GHG emission. Those categories are referred to as cellulosic, advanced, biomass-based diesel, and renewable fuels (Searle and Christensen, 2014). The volume requirements that Congress wrote might have been realistic at the time, but have since proven aspirational for the cellulosic fuel category: in 2013, the law required 1 billion gallons of cellulosic fuel to be consumed, when in reality only 281,000 gal were produced (Environmental Protection Agency, 2014b). Congress did give some flexibility to EPA to adjust the volume requirements 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. At the time of this writing, EPA has just released a new multi-year volume proposal (2014–2016, and 2017 biomass-based diesel volumes) (Environmental Protection Agency, 2015). Previously, EPA had decided to pull back the proposed rule that established volume obligations in 2014, which is now being set more than one year late (Environmental Protection Agency, 2014c). When the 2014 rule was originally released it was met with significant political opposition and received over 300,000 public comments, all of which likely influenced its ultimate release date (Environmental Protection Agency, 2013; House of Representatives-Committee on Energy and Commerce, 2013a, 2013b).

The market model developed here is specifically designed to aid in this annual volume setting process. More specifically, this compact model can be used to calculate RIN prices but additional information on the flow of biofuel/RINs around the country is also available as output variables. The model is formulated as a linear program and is therefore general enough to allow for additional policy to be considered; for example, future work could include influences of the California cap and trade system (AB32) (California Air Resources Board, 2011). Beginning on January 1, 2015 the suppliers of gasoline blendstocks and diesel fuel oils in California have a compliance obligation for all GHG emissions that would result from combustion of all such fuels (17 California Code of Regulations §95852). This requirement should encourage the use of more renewable feedstocks and/or efficiency upgrades; however large emissions reductions may take many years to materialize as a certain number of free allowances are distributed to the refining sector (California Air Resources Board, 2015a).

1.2. *Brief overview of the Renewable Fuel Standard (RFS)*

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 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 carbon credits often integrated into a cap-and-trade policy, and consequently provide an additional revenue stream for new renewable fuel producers. 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 (McPhail et al., 2011; McPhail, 2012; Miller et al., 2013). However, reality must include a number of other policy distortions and effects, including multiple obligated parties (i.e., refiner players), 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% (Searle et al., 2014).

1.3. *State-level tax policy*

State-level fuel tax policies vary widely throughout the US. For example as of July 1, 2014 New York state taxes gasoline at a rate of 50.5 cents/gal while Alaska only taxes gasoline at 18.4 cents/gal

(American Petroleum Institute, 2014; Federation of Tax Administrators, 2014). With a few exceptions, most states simply leverage these excise taxes on fuel. If there are tax benefits for biofuels they typically surface as a lower excise tax rate. At the time of writing there were no state-level tax credits that were available (although should they become available, their effect would be easy to account for in the modeling framework presented here). Other state-level tax policies were researched through the Department of Energy's Alternative Fuel Data Center policy database (Department of Energy-EERE, 2015). Most states tax gasoline and diesel at different rates. The full time series of fuel tax rates were collected from the American Petroleum Institute's State Motor Fuel Tax reports (American Petroleum Institute, 2014).

In addition to different tax treatment several states have mandates for minimum blending requirements that must be considered. Five states (Montana, Minnesota, Hawai'i, Missouri, and Oregon) have minimum blending requirements for ethanol of 10% (Department of Energy, 2014a, 2014b, 2014c, 2014d, 2014e). Effectively, these mandates for blending ethanol are non-binding because most of the gasoline available in this country is E10 (Energy Information Administration, 2012). Several other states have binding blend mandates for biodiesel. Minnesota's mandate is the strictest and requires 10% (B10) biodiesel blends at present, and ramps up to B20 by 2018 (Department of Energy, 2014f). Oregon and New Mexico follow closely behind with B5 mandates, while Pennsylvania, Washington and Louisiana require B2 (Department of Energy, 2014b, 2014g, 2014h, 2014i, 2014j). It should be noted that Washington only requires B2 for government fleet vehicles, but in this analysis this requirement is approximated as a requirement for all vehicles in Washington.

2. Methods

The model is formulated as a linear program (LP) written in GAMS and solved using the CPLEX algorithm; default solver settings were found to be sufficient for reasonable solution times. The LP formulation was motivated by a related mixed complementarity problem (MCP) version of the liquid fuel market model presented elsewhere (Christensen and Siddiqui, 2015). Both models are initially constructed by formulating the appropriate profit maximization function and accompanying constraints for each market participant. For the LP version of this model, a social cost function is constructed and used as the primary objective function, shown in Eq. (1)

$$z = \sum_{s}\sum_{y}\gamma_y\left(\sum_{b} C^{P}_{b,s,y} + C^{R}_{s,y} + C^{B}_{s,y} + \sum_{c} C^{T}_{c,s,y}\right) \tag{1}$$

The index s represents all states that are covered under the RFS, y the simulation years (2011–2022), b is the set of all biofuel types and c is the superset of all fuels used to blend final transportation fuels. The superscripts on the cost variable C represent P (producer), R (refiner), B (blender), and T (transporter). In this framework importers of fuel are classified as *producers*, but have a different cost function. Due to the market assumptions inherent with the LP formulation, the profit maximization objectives are equivalent to a total cost minimization problem (i.e., prices that are taken by market participants are set by the marginal price). All functions used to describe the market are convex, thus, a local minimum is also guaranteed to be a global minimum.

2.1. Model formulation

2.1.1. Overall 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 currently being produced in the US: D4 (biodiesel RINs), D5 (advanced RINs), and D6 (renewable fuel RINs). EPA publishes public RIN data on a monthly basis (Environmental Protection Agency, 2014b). 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 negligible. While D3/D7 RINs are ignored in this work, it may be necessary that future work include these additional RIN categories. As of April 15, 2015 there were ~19 million D3 RINs generated and just 14 million D5 RINs generated. The vast majority of these D3 RINs were generated from biogas fuels. This shift in RIN generation could be the beginning of a longer-term compliance strategy by fuel producers/obligated parties. Renewable diesel producers/importers are included in this framework and generate D4 RINs.

These assumptions simplify the biofuel production market down to essentially four participants: ethanol producers, biodiesel producers, renewable diesel importers, and sugarcane ethanol importers. The other participants in this market model 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 (AEO) 2015 (Energy Information Administration, 2015a).

Each of these market players is located within a geographic region, assuming there is physical production capacity available. Geographic regions are defined here on the state level. Fuel traders and RIN traders operate between states and can profit from arbitraging these products. This means that each region has a local market for ethanol, sugarcane ethanol, biodiesel, renewable diesel, blendstock for oxygenate blending (BOB), unblended diesel, finished gasoline, finished diesel, and D4/D5/D6 RINs. Prices and quantities of each of these commodities are determined endogenously.

Distribution costs between all of these regions were considered by adding a markup to the product being shipped between regions. This markup is used in-lieu of a full transportation network model and is referenced from Table 11.4 of the Liquid Fuel Market Model (LFMM) assumptions document (Energy Information Administration, 2013b). Distribution markups for biodiesel and renewable diesel were assumed to be the same as those for distillate fuel oil (diesel). Traders of RINs are not subject to distribution costs as they are only trading credits electronically. A market diagram is shown in Fig. 1.

2.1.2. General considerations

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 the fuel production pathways for lifecycle GHG emissions. All fuels in this model have been approved for use in the RFS by the EPA and therefore, implicitly account for land use implications to 2022 (Environmental Protection Agency, 2010).

This model is focused on representing the biofuel market from producer/importer to ultimate end-user. All market players in the model are considered to be rational profit maximizers. Speculation is not considered in this analysis. Within each region the biofuel market participants are each represented as an aggregate industry player. Aggregation is appropriate because each of these markets is competitive as measured by the Herfindahl–Hirschman Index (HHI). The HHI is calculated by summing 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 market that is perfectly competitive. Using biofuel production capacity as a proxy

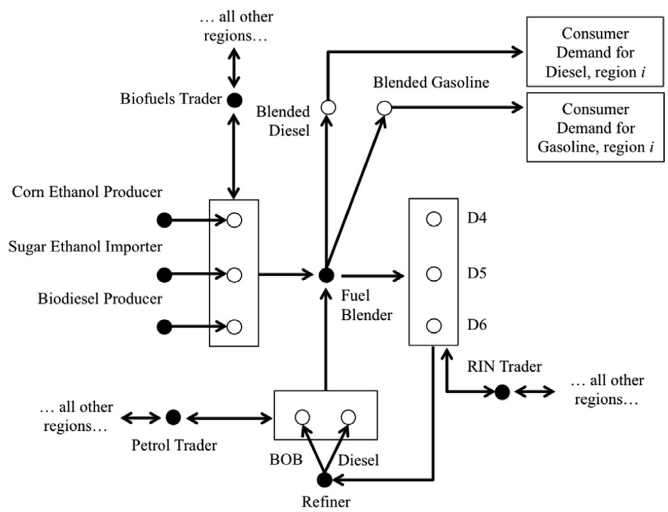

Fig. 1. Market diagram. All solid circles are market players, open circles indicate where an endogenous price can be calculated. This basic structure is repeated in all regions; regions trade only unblended fuel products. Finished fuels are supplied to the region by a fuel blender player within that region.

measure for market share one can calculate HHIs of approximately 400 and 720 for the ethanol and biodiesel industries, respectively (data from the Renewable Fuels Association and the National Biodiesel Board (National Biodiesel Board, 2014; Renewable Fuels Association, n.d.)).

Consequently, it is assumed that US gasoline and diesel markets are 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 not concentrated or only moderately concentrated (Government Accountability Office, 2004).

The model assumes perfect foresight and defines time periods on a calendar year basis. Results from this model are presented through 2017; however, the model is actually run for several years following in order to eliminate any end of horizon effects. As a result of the rulemaking cycle that EPA engages in, reliable policy inputs for the RFS are not available for a longer timeframe than 2017. It is expected that the model would need to be updated and re-run every year of EPA rulemaking activities.

2.1.3. Supply chain

Following the structure of the RFS, each of the four 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. Once the blender mixes the biofuel with a petroleum blendstock, the RIN that was associated with the biofuel can be sold to a refiner for their compliance obligation or to a RIN trader who will sell the RIN into another region (i.e., state).

In this formulation the blender has the option to produce any of three finished fuel products in order to meet consumer demand. The blender can sell: finished E10 gasoline, finished E85 fuel, and diesel/biodiesel blends at any blend levels. It is assumed that E85 would be valued on an energy content basis compared to standard finished gasoline (E10). There is some initial evidence from Brazil that consumers will arbitrage their fuel preferences based on the energy content of the fuel (Pouliot, 2013). Following this, it is assumed that consumers in the US would make similar decisions. There are a number of unique technical constraints to adopt E85 that US consumers face (i.e., number of flex fuel vehicles in the US fleet); while these constraints will affect the actual adoption of E85, they 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 (Babcock and Pouliot, 2013a, 2013b, 2013c, 2013d, 2014; Greene, 2008; Liu and Greene, 2013). In contrast, our model is expected to predict excess production of E85; assumptions of E85 consumption potential can be accounted by using a separate constraint on the total E85 consumption. Further discussion will be provided in Section 3.2.

2.2. Developing policy scenarios

The scenarios mapped out here are not meant to be exhaustive of all policy changes being proposed. The motivation behind the following policy scenarios is to study the impacts of policy changes that are forward looking, but not considered quantum changes to the currently existing policy. This was done for two reasons: 1) the policy landscape does not change rapidly and 2) regulators are legally bound to adjust only certain policy aspects and do not have the authority to consider other, potentially more economically direct, options (Hassett et al., 2007; Parry et al., 1999). As mentioned previously, EPA only has the authority to adjust the volumes of biofuel required for compliance with the RFS.

2.2.1. Baseline scenario and model calibration

The baseline scenario to which all other scenarios are compared was developed to most closely represent historical market operation as well as a future regulatory requirement that can be considered likely, but not certain. Since this model is primarily designed to investigate RIN market operation many parameters are taken as exogenous in order to limit the size and complexity of the model. These exogenous parameters were used in a Leontief-type production function (fixed proportion input–output model) specific for each type of biofuel produced. In general, all the fuel producers' cost minimization problems are of the form shown in Eq. (2)

$$C_b^P = \sum_y \sum_{s \subset S} \left(\sum_i \alpha_i E_i q_{b,s,y} - \sum_j \beta_j E_j q_{b,s,y} + E_{b,s,y}^{net} q_{b,s,y} \right) \tag{2}$$

In this representation, the producer of a biofuel, b, is physically located in a subset of S (i.e., in a particular state). The first term then represents the total cost of all feedstock/energy inputs needed to make a biofuel, is a yield parameter and is an exogenous price of the input. For the case of biodiesel, i would be all elements of a set {electricity, natural gas, methanol, oils}. The second term would represent all valuable co-products produced and sold at an exogenous price E_j; for biodiesel, it is assumed that there are no co-products. The final term is the net tax policy impact from both state and federal levels of intervention, and is equal to all applicable tax rates minus all available tax credits. Table 1 details all the data inputs and yield parameters for all biofuel producers.

BOB and unblended diesel production capacity were estimated from the ultimate demand for these fuels from Table 11 of the AEO 2015 divided by the refiner utilization; historically the refiner utilization has hovered around 89% as an annual average (Energy Information Administration, 2014a, 2015a). The volume of finished motor gasoline that is reported by EIA includes the volume of ethanol in gasoline; this volume was removed to estimate the refinery capacity for producing BOB. This methodology assumes that there is no importing of finished gasoline or finished diesel into the US. This assumption is justified because the US imports less than 1% of its finished gasoline and a similar amount of finished diesel (ultra-low sulfur diesel; renewable diesel is

Table 1
Data used as model input and sources.

Biofuel producer	Parameter	Value	Reference	Exogenous price (*E*)
Renewable diesel	$\alpha_{electricity}$	0.358 kW h/gal	(Pearlson, 2011)	US Average for Industrial Customers (Energy Information Administration, 2015b)
	$\alpha_{hydrogen}$	0.258 lbs/gal	(Pearlson, 2011)	$0.66/lb (Pearlson, 2011)
	$\alpha_{bio\text{-}oils}$	9.61 lbs/gal	(Pearlson, 2011)	US average soybean oil price (United States Department of Agriculture, 2015)
	α_{natgas}	8.97 ft^3/gal	(Pearlson, 2011)	Industrial natural gas price by state (Energy Information Administration, 2015c)
	$\beta_{propane}$	0.088 gal/gal renewable diesel	(Pearlson, 2011)	Spot price from Mont Belvieu, TX (Energy Information Administration, 2015d)
	β_{LNG}	0.034 gal/gal renewable diesel	(Pearlson, 2011)	LNG export price (Energy Information Administration, 2015e)
	$\beta_{naphtha}$	0.029 gal/gal of renewable diesel	(Pearlson, 2011)	New York Harbor conventional gasoline spot prices (Energy Information Administration, 2015f)
	β_{jet}	0.14 gal/gal renewable diesel	(Pearlson, 2011)	US Gulf spot prices (Energy Information Administration, 2015g)
Biodiesel	$\alpha_{bio\text{-}oils}$	7.7834 lbs/gal	(National Biodiesel Board, 2008)	US soybean oil price, state data available for IA, IL, and MN only, other states with production use US average prices (United States Department of Agriculture, 2015)
	$\alpha_{methanol}$	0.7208 lbs/gal	(National Biodiesel Board, 2008)	Methanol price (Methanex, 2015)
	$\alpha_{electricity}$	0.19 kW h/gal	(National Biodiesel Board, 2008)	Price for Industrial Customers by state (Energy Information Administration, 2015b)
	α_{natgas}	8.97 ft^3/gal	(National Biodiesel Board, 2008)	Industrial natural gas price by state (Energy Information Administration, 2015c)
Sugarcane ethanol	–	–		Prices in USD are available through UNICA at Sao Paulo. Transportation costs are assumed to be $0.22/gal (Strogen et al., 2012; UNICA-Brazilian Sugarcane Industry Association, 2015)
Corn ethanol	α_{corn}	2.81 bu/gal	(Wu, 2008)	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, other states with production use US average prices (United States Department of Agriculture, 2015)
	$\alpha_{electricity}$	0.7 kW h/gal	(Wu, 2008)	Price for Industrial Customers by state (Energy Information Administration, 2015b)
	α_{natgas}	27,589 BTU/gal	(Wu, 2008)	Industrial natural gas price by state (Energy Information Administration, 2015c)
	β_{ddgs}	5.9 dry lbs/gal	(Wu, 2008)	DDG prices, state data available for CA, IA, IL, KS, MN, MO, NE, OR, SD, WI only, other states with production use US average prices (United States Department of Agriculture, 2015)

considered an unfinished diesel product) (Energy Information Administration, 2014b, 2014c).

For the baseline analysis and model calibration all other policy influences at the federal and state level were assumed to be those currently written into law. For years 2011–2014 the policy inputs were held constant to those incentives that were actually available during that year. This time period saw several significant changes in biofuels policies with the expiration of the ethanol import tariff, the ethanol blenders tax incentive, and the on–off cycle of the biodiesel production tax credit. While model results are only presented out to 2017, the model is run out several more years in order to eliminate end-of-horizon effects with regard to banking of RINs. All policy variables were simply held constant after 2016 for advanced and renewable fuels and 2017 for biomass-based diesel.

2.2.2. Scenarios for sensitivity analysis

There are a number of exogenous assumptions embedded in this model, but the sensitivity analysis focuses on three key areas: E85 consumption, consumer demand for transportation fuels, and biofuel feedstock prices. While EPA may not be able to influence these factors directly, or at all, it is important for regulators to understand the range of policy options and resulting impacts on the biofuels market. policy design space. Many sub-scenarios were run to test model sensitivity to each of these factors; for brevity these tests are classified into the 3 categories enumerated in Table 2. Results are presented in Section 3.

3. Results

3.1. Baseline scenario

The main output of interest in this model is RIN price, but the structure of the model allows for many other endogenous parameters, such as product flows, to be investigated in order to help reveal RFS compliance strategies. While these parameters cannot be calibrated due to data limitations, they may still be of interest to regulators/policy makers. Results presented here focus on parameters that can be compared to historical data. Fig. 2 shows the resulting RIN prices for the baseline scenario along with historical market data for the three RINs considered in this analysis. As can be seen, if EPA were to finalize the current proposal, which increases in stringency over 2014–16, it is likely that there would be an increase in D4 RIN prices. These results must be interpreted

Table 2
Policy scenarios that were investigated in this study and the effects of interest in formulating these scenarios.

Sensitivity scenario	Number	Primary objective of analysis
All policy held constant as written in law. RFS required volumes from recent rulemaking.	Baseline	Model calibration
All policy held constant as in baseline scenario, introduced E85 consumption constraint	1	Assess sensitivity of RIN prices, prices for finished motor gasoline and blended diesel, and compliance costs from changes in E85 consumption
All policy held constant as in baseline scenario, introduced demand changes in future years	2	Assess sensitivity of RIN prices, prices for finished motor gasoline and blended diesel, and compliance costs from changes in fuel demand
All policy held constant as in baseline scenario, introduced feedstock (corn/soy oil) price changes in future years	3	Assess sensitivity of RIN prices, prices for finished motor gasoline and blended diesel, and compliance costs from changes in biofuel feedstock changes

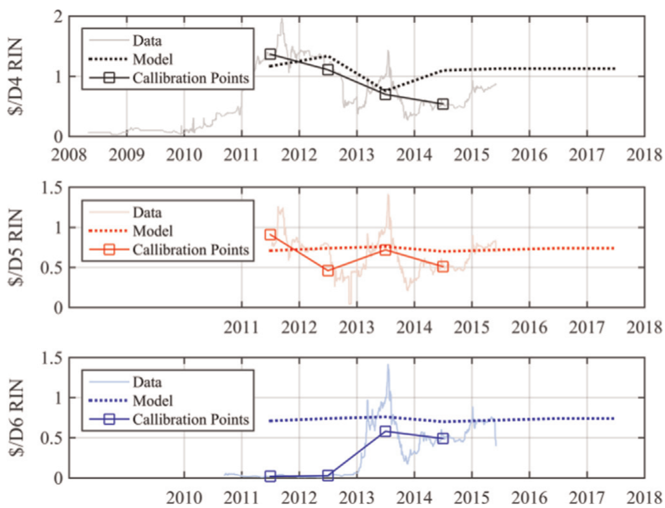

Fig. 2. RIN price results for the baseline scenario presented alongside market data. Data points represent annual average prices.

Table 3
RFS volume mandates specified in the model and are being proposed by EPA in the most recent rulemaking.

Year	Biomass-based diesel	Advanced fuel	Renewable fuel
2011	0.8	1.35	13.95
2012	1	2	15.2
2013	1.28	2.75	16.55
2014	1.63	2.68	15.93
2015	1.70	2.9	16.3
2016	1.80	3.4	17.40
2017	1.90	3.4[a]	17.40[a]

[a] These volumes are not specified by EPA, but are included in our modeling by assumption. Units for advanced/renewable fuel are in number of RIN credits; the biomass-based diesel category is in billion gallons.

carefully alongside the perfect foresight assumption. This assumption will result in high RIN prices in years where there are no binding mandates simply because that behavior helps minimize total costs. As an example, the blend wall was not binding in 2011–12, hence there were relatively low market prices for D6 RINs in those years; however, the model predicts high prices over all simulation years. Similarly, the current EPA proposal for 2014 and 2015 has fewer gallons of renewable fuel than did 2013 so it is reasonable to expect these years to also have higher RIN prices. The volume mandates investigated in this analysis are summarized in Table 3.

To work around this perfect foresight assumption two other sub-baseline models were solved which: 1) carried the volume for the 2014 standard forward and 2) carried the 2015 volume standard forward. Both of these sub-models showed that D6 RIN prices in years 2014 and beyond fell when compared to the baseline results; the first sub-model showed a D6 RIN price of ~$0.22 (−$0.59 from baseline) and the second sub-model showed a D6 RIN price of ~$0.68 (−$0.13 from baseline). Recently, D6 RIN prices have been shown to drop away from the D5 RIN, hinting that actual RIN prices may not be particularly sensitive to future policy, even if EPA is proposing exact volumes for future years.

While the main outputs of this model are RIN prices, the final retail gasoline and diesel prices should also be in general agreement since market data is available for these products. As part of the calibration procedure, the blender player's assumed fuel markup was adjusted such that the model reproduced the national average retail price of gasoline and diesel fuel for years 2011–2014. The petroleum blendstock price set by the refiner player was

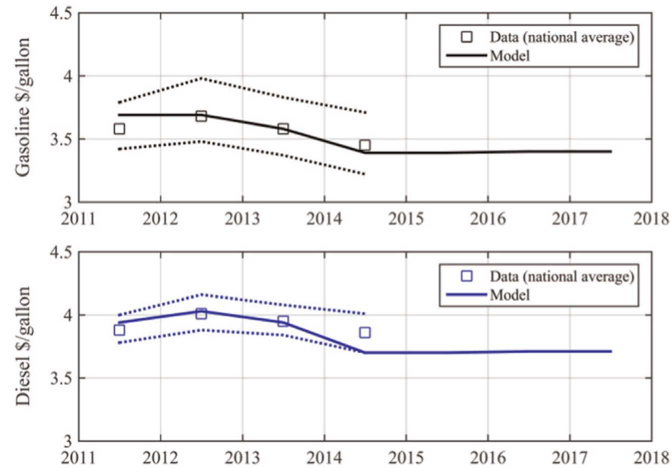

Fig. 3. National annual average fuel prices alongside model result. Dashed lines indicate the maximum/minimum prices.

assumed exogenous, and was defined using EIA data (Energy Information Administration, 2015h). National average fuel prices are shown alongside historical data in Fig. 3. The maximum difference between these model results and EIA reported data was less than 4% (Energy Information Administration, 2014d).

The quantities of biofuel consumed by the model are shown in Fig. 4. These quantities are included alongside historical data collected by EPA as part of RFS implementation (Environmental Protection Agency, 2014b). While the model ultimately chooses the quantity of fuel to produce, each of these biofuels is also subject to capacity constraints. For sugar ethanol the capacity to import was limited to just under 1 billion gallons, about 50% higher than the maximum volume imported within a single year; this capacity constraint was used for all simulation years. Biodiesel and corn ethanol were subject to full nameplate capacity constraints reported by EIA and the Renewable Fuels Association. There were no adjustments made to account for a plant capacity factor. Renewable diesel is a much newer fuel product, with the first domestic plant initially operated by Dynamic Fuels, in October 2010. It is assumed that in 2011 the plant is still ramping up to its full capacity of 75 millions gallons, so a capacity factor of 50% was included. It is assumed that in 2013 a 150 million gallon plant originally operated by Diamond Green Fuels (now owned by REG, Inc.) began production at full nameplate capacity (Milbrandt et al., 2013). Data on imports of renewable diesel are available from EIA

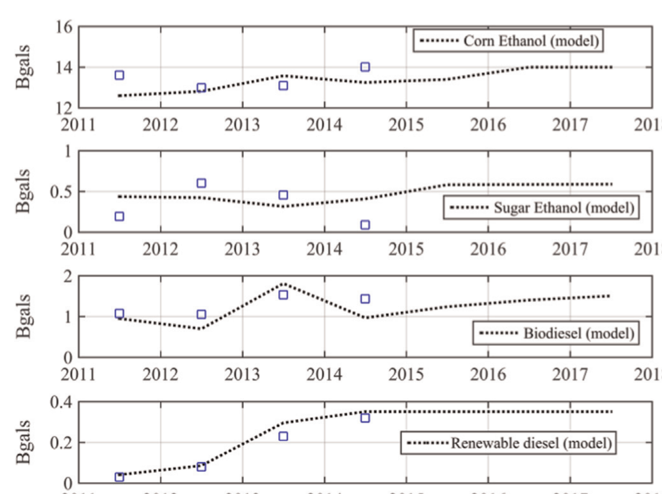

Fig. 4. Biofuel volumes from model results alongside historical volumes registered under the RFS program.

and were added in as additional production capacity (Energy Information Administration, 2014e). Results show that the maximum differences between modeled and observed volumes are 7%, 33%, 36% and 350% for corn ethanol, biodiesel, renewable diesel and sugarcane ethanol, respectively. The larger discrepancy in sugarcane ethanol volume could stem from a number of sources; the authors speculate that poor data availability on the true shipment costs to different ports may be partially to blame. Brazilian demand for ethanol has also not been considered in this framework and may also contribute to this discrepancy. Model refinements to the sugar ethanol supply chain are left for future research. The other volume discrepancies are considered acceptable given the data limitations and modeling goals, noting that this framework could be easily updated should more detailed data be made available.

In the baseline model the average biodiesel blend has been assumed 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). State level blending data is scarce or unavailable, the only publicly available data the authors are aware of is associated with California's Low Carbon Fuel Standard (California Air Resources Board, 2015b). The CA data suggests that average blends as high as 5% (B5) have been achieved for a three-month period of time. Due to uncertainty around these constraints a sensitivity analysis was performed and found that the B5 constraint does not dramatically impact the RIN price until very high average blends (> 50%) were allowed. At the time of writing very high average blends are considered to be infeasible. The biodiesel blend constraint was formulated as in Eq. (3). It is assumed the renewable diesel is a perfect substitute for petroleum diesel and therefore does not carry any blending restrictions

$$\frac{q_{s,y}^{biodiesel}}{q_{s,y}^{biodiesel} + q_{s,y}^{unblended\ diesel} + q_{s,y}^{renewable\ diesel}} \leq 0.05 \tag{3}$$

Another key constraint that does impact RIN prices significantly is the upper bound on the ultimate amount of E85 that is consumed. This constraint is formulated as in Eq. (4)

$$\sum_{s} q_{s,y}^{E85} \leq 300$$
$$y \in \{2011 \ldots 2014\} \tag{4}$$

As before, s is a sum over all states and y are years in the simulation model. In the recent proposed rule, EPA estimated that E85 consumption was approximately 130 million gallons in 2013 and somewhere in the range of 100–200 million gallons in 2014 (Environmental Protection Agency, 2015). EPA had previously estimated that 100–300 million gallons of E85 would be consumed in 2014 (Environmental Protection Agency, 2015). In the baseline scenario it was assumed that the market could consume 300 million gallons of E85 for 2011–14. The authors used this value as a point of RIN price calibration, but also attempted to incorporate real constraints in the market. Other simulation years were left unconstrained. Leaving these later years unconstrained may result in an over production of E85 by the model. The baseline case suggests that an optimal strategy would be to produce zero gallons of E85 in 2014 and 2015 but ramp up to 1.2 billion gallons by 2016. This overproduction could artificially lower the projected RIN price. Even if the market did not, ultimately, allow that much E85 to be consumed the D5/D6 RIN price would still be capped by the D4 price. The spread between the D4 and D6 RIN price may be an indication of whether or not E85 is entering the market. If the spread is zero, then E85 may be an economical way to produce RINs for compliance. If the spread is not zero, it may be a market indicator that additional E10 blending may be possible. At the time

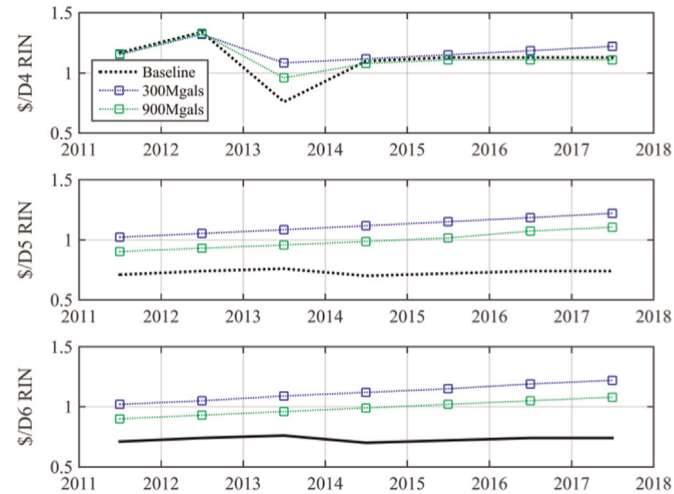

Fig. 5. RIN price response to changes in E85 consumption in years 2015+. Data points represent annual average prices.

of writing the spread between the D4/D6 RIN prices was approximately 50 cents. This spread appeared with the announcement of the most recent proposed rule on May 29, 2015, in which EPA acknowledged higher than expected demand for transportation fuel, in turn opening the market for further E10 blending.

3.2. Scenario #1 – sensitivity to E85 consumption

This analysis was formulated to investigate the impact that E85 consumption has on RIN prices, total volume of E85 produced/consumed, and whether there would be any impact at the pump for blended gasoline or diesel. As noted earlier, these variables are of primary interest because the results could trigger strong political opposition that might jeopardize the entire RFS program. The sensitivity study looked at upper bounds of E85 consumption of 300 and 900 million gallons, while the baseline case provides a lower bound on the RIN price. Fig. 5 shows the resulting impacts on RIN prices through 2017.

If years 2015+ are also limited to 300 million gallons of E85, D5/D6 RIN prices can be expected to increase by approximately 65% from baseline levels. In contrast, if the market changes to allow more E85 to be consumed, the RIN price response could be dampened significantly. D4 RIN prices were largely insensitive to the overall consumption of E85. Compliance cost impacts followed a similar trend with total compliance costs increasing by ~45% if E85 is constrained to 300 million gallons in years 2015+; Fig. 6 details these trends. The compliance cost of a regulation is typically the dual variable (i.e., the shadow price) associated with a particular policy constraint (Anderson and Sallee, 2011). In this case the RFS is composed of several nested constraints, which complicates estimates of the compliance cost. Compliance costs are defined here as the quantity of each type of RIN purchased by a refiner, multiplied by the corresponding RIN price as in Eq. (5)

$$\text{Compliance cost}_{s,y} = q_{s,y}^{D4}\pi_{D4} + q_{s,y}^{D5}\pi_{D5} + q_{s,y}^{D6}\pi_{D6} \tag{5}$$

RIN prices are uniform around the country since they are traded electronically, but the cost of compliance has a strong regional component as seen in Fig. 7. Obligated parties, those responsible for paying these compliance costs, are concentrated in certain areas of the country – primarily along the Gulf Coast where the vast majority of refiners are located. Fig. 7 shows the distribution of costs by state in 2015 as well as the percent difference if E85 consumption were limited to 300 million gallons. The results

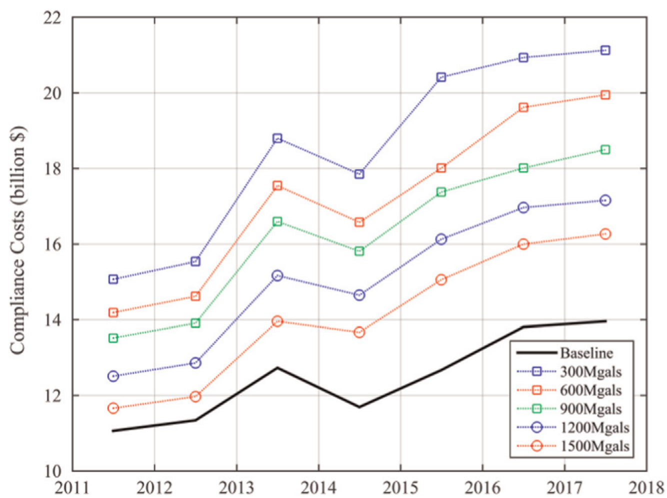

Fig. 6. Total compliance costs response to changes in E85 consumption in years 2015+. Data points represent annual average prices.

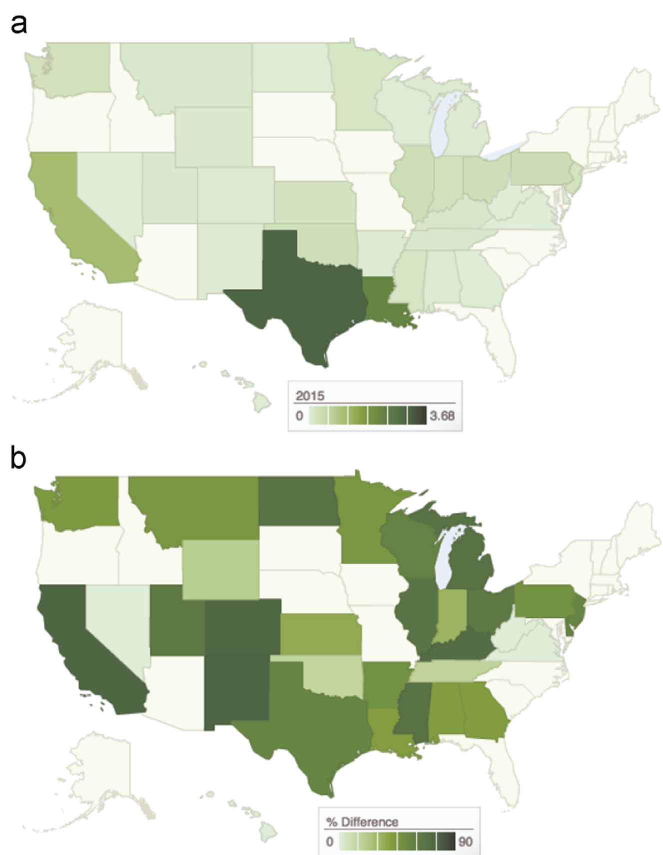

Fig. 7. Regional compliance costs (a) in B$ and the percent difference in compliance cost (b) if E85 consumption were limited to 300 million gallons in years 2015 and beyond. Both maps are for 2015 only.

suggest that New Mexico, California, Colorado Kentucky, Mississippi, Michigan and North Dakota could see compliance costs increases >80% for 2015 if the blending and consumption of E85 does not increase beyond 300 million gallons/year. In 2015, Texas would see the largest magnitude change in compliance costs (~$2.5 billion or approximately 65%).

In addition to the compliance costs, the impact on ultimate fuel costs for consumers is of interest to regulators. In 2016, when the baseline scenario suggests E85 blending should total 1.2 billion gallons, the average retail price for gasoline was $3.40/gal. If E85 consumption were tightly constrained to 300 million gallons the average gas price was $3.33/gal. This drop in gasoline price is offset by an increase in average diesel price from $3.71/gal to $3.75/gal. The increase in diesel price indicates a reliance on biodiesel/renewable diesel blending for compliance.

3.3. *Scenario #2 – sensitivity to demand changes*

In this exercise demand perturbations were limited to between −5% and +5% and were applied to both diesel and gasoline fuels independently. These demand changes were only applied to years 2015 and beyond. For perspective, EIA projections two years into the future varied by a maximum of 4% and 7.5% for motor gasoline and diesel fuels, respectively; it typically takes 2 years after an Annual Energy Outlook (AEO) is released to obtain a value for confirmed fuel consumption. The authors recognize that the AEO guides many energy market behaviors, and thus felt that demand sensitivity in the ±5% range was reasonable to study impacts on the RIN market.

When the diesel demand was varied in this range, there was only a negligible impact on the price for all RIN types, as well as on the total compliance cost and total finished fuel costs. The diesel demand sensitivity is largely dampened due to the fact that the biodiesel industry is largely overbuilt, and therefore is not bound by production limitations. Additionally, lower cost petroleum diesel can be added to the system to make up for extra demand. This is easily achieved since the biodiesel blend is more flexible than that of ethanol/gasoline fuels. The diesel demand sensitivity may be dampened since there were no data available on the quantities/prices available for different oil feedstocks to make biodiesel. It is assumed that all biodiesel is made from feedstocks that are sold for the same price as virgin soy oils. If more expensive oils have to be used to meet larger demand, the D4 RIN price would be expected to increase accordingly.

When gasoline demand was varied, there were slight changes in D5/D6 RIN prices. With a 5% decrease in gasoline demand the D5/D6 prices increased by a modest $0.01/RIN (+1.4%). This inverse relationship makes sense since it gets more difficult to force the same number of gallons of biofuel into a shrinking demand pool. As gasoline demand increased there was a negligible impact on RIN prices. If demand increased by 5% the model was infeasible, signaling that there is not enough capacity to supply E10 and E85 fuels to the market. It is the authors' assumption that additional ethanol production capacity could not be built in time to satisfy demand. Under these circumstances, a real world market response might be to blend slightly less ethanol into gasoline.

3.4. *Scenario #3 – sensitivity to biofuel feedstock prices*

In this scenario the authors look at the impact that corn and soybean oil prices have on RIN prices, retail fuel prices and compliance costs associated with the RFS. Corn prices represent approximately 90% of the price of ethanol price, and soybean oil prices represent approximately 80% of the final biodiesel price. It is expected that if these feedstock markets moved significantly, those changes would also manifest themselves in RIN markets. To explore these impacts the exogenous prices of corn and soybean oil were varied independently between −50% and +50% from the baseline model.

It was found that increased corn prices did not dramatically impact the RIN market until they reached 50% or greater, an increase that is large, but not unprecedented. When 2015+ corn prices were increased by 50%, D5/D6 prices increased by approximately 15%. Total compliance costs also showed a corresponding increase, but there was a negligible impact on retail fuel prices, as gasoline prices were shown to increase by only $0.01/gal.

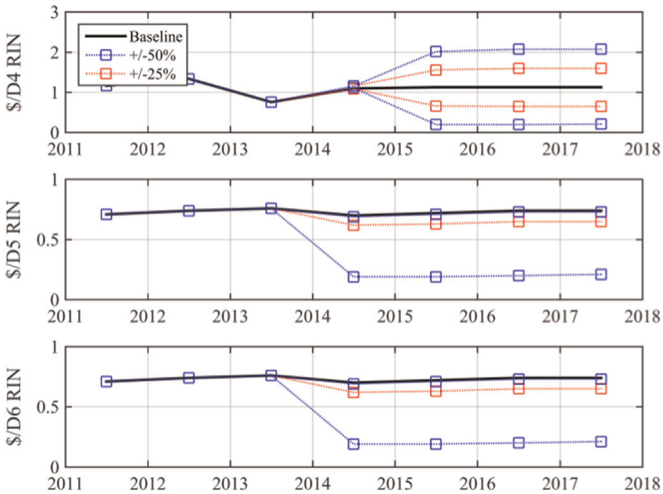

Fig. 8. RIN price impacts from changes in soybean oil prices for 2015 and beyond. Data points represent annual average prices.

Unlike corn prices, soybean oil prices can have dramatic impacts on the RIN market, primarily because biodiesel blending constraints are more flexible but also because of the nested structure of the RFS. The price of the D4 RIN behaves as a ceiling for the D5 and D6 RINs, and correspondingly, the D5 RIN serves as a ceiling price for the D6 RIN. If the price of soybean oil falls it is possible that a corresponding D4 price drop would depress the price for other RIN categories. This impact is shown in Fig. 8. If soybean oil prices increased D4 prices would also show a corresponding increase; results from these simulations suggest that a 25% increase in soybean oil prices results in a 40% increase in the D4 RIN price.

The impact of soybean oil prices on the retail price for diesel was small when compared to the impact on RIN prices. The results suggest that fuel prices could increase/decrease by 1.5% (∼$0.03) for a ∓50% change in soybean oil prices. These impacts are indirectly communicated to the consumer through higher/lower biodiesel prices.

4. Discussion

In this work a model of the RFS was developed that included several fuel categories that have been used to obtain compliance with the RFS. The optimal solution to this mathematical program represents a least-cost compliance strategy for the market, although due to geographical variations it is clear that not everyone can be a winner (i.e., achieve least-cost compliance). Through successive solutions to this model the authors were able to perform a sensitivity analysis and show which exogenous parameter changes could result in significant price impacts.

The development of this model was originally motivated by concern expressed by the White House Office of Management and Budget (OMB) about the sensitivity of RIN prices to the RFS volume standard (Peterka, 2014). At that time the White House's primary concern was that the rule did not include estimates of how E85 and RIN prices are coupled, an effect that is included here in a simplified form. Other concerns voiced by the White House OMB are related to the amount of policy flexibility and slack built into the proposal to ensure that RIN prices do not spike as they did in January 2013. Questions posed by stakeholders can be difficult to assess quickly without the aid of a compact form model such as the one discussed here. From this analysis there is evidence that EPA is proposing a volume mandate that attempts to balance compliance costs while mandating the consumption of a maximum volume of biofuel. This scenario may alleviate concerns voiced by OMB, but may also be seen as a political concession to the refining industry. The upper range may result in RIN price increases over the baseline scenario, but in all cases the RIN prices are significantly lower than observed in 2013. While this model can calculate RIN prices, EPA regulators still have the difficult task of evaluating exactly what their *ideal* RIN price might be.

There is very little impact on retail gasoline and diesel prices as a result of changing the proposed volume standard. Even still, pump prices have historically been an important political issue in certain regions of the US, particularly during presidential elections (Decker and Wohar, 2007). The authors hope that the political debate regarding the impacts of the RFS on retail fuel prices is deemphasized and instead focus is placed on a performance-based assessment of the RFS. As an example, these assessments could quantify carbon emissions savings using RIN data.

5. Conclusions and policy implications

To date, the fuel categories that are important for compliance with the U.S. Renewable Fuel Standard have all been first generation fuels. The blending requirements of the RFS as written into law continue to increase over the coming years, a fact that will draw increasing political attention to the basic structure of the policy. Proponents of the RFS will argue that the law was designed to force market changes that will allow for increasing consumption of biofuels, particularly cellulosic fuels. The hope is that additional revenue can be directed to these low carbon fuels through generation of a valuable D3 RIN (Carriquiry et al., 2011). Opponents of the RFS will argue that they cannot be responsible for blending next-generation cellulosic fuels if they are not available commercially, an argument that has been successful in the recent past in motivating removal of the cellulosic fuel blend requirement (Environmental Protection Agency, 2014d, 2014e). EPA has been given broad authority by Congress to adjust the mandated volumes on an annual basis to respond to actual market conditions such as the availability of certain renewable fuels. However, the decision to reduce the volume of required biofuel has far reaching implications throughout several markets. The market model structure that was developed here is capable of investigating a number of policy scenarios in order to help regulators thread the needle and advance the cause of biofuel proponents while balancing potentially burdensome regulatory impacts.

In addition to presenting the biofuel market model, this paper makes four main conclusions as follows. Specific policy implications are also highlighted.

- *Greater RIN market transparency could aid in more efficient RIN price discovery*. While the modeling effort has had the goal of reproducing RIN market dynamics, there is a fundamental lack of data that hinders additional analysis. From a research perspective, understanding market behavior hinges on having accurate price data linked with the quantities of RINs traded at those prices. EPA publishes lagged RIN volume data on a monthly basis, but does not publish prices. Instead RIN price data must come from third party market analysts, all of which have their own methodologies for calculating a RIN Index. Additional market transparency could help aid market efficiency and reduce compliance costs. As shown in this work, compliance costs can be significant and these costs are not uniformly distributed throughout the US. An efficient RIN trading market must maintained in order to achieve the primary policy objectives of the RFS.
- *The volume scenario proposed by EPA will not dramatically affect the retail price of fuel paid by consumers*. Even if the consumption

of E85 is severely constrained in future years, it is unlikely that retail fuel prices will change dramatically. This is important from a political risk perspective, as high pump prices have been a point of contention in past elections. It is the authors' assumption that EPA may be motivated to maximize carbon savings potential (subject to a number of market constraints). If this is true, EPA may be more willing to mandate a higher volume of biofuel if it anticipates that there would be little impact on retail fuel prices.

- *The D4 (biodiesel) RIN price is highly sensitive to the price of soybean oil*. Biodiesel can be blended with diesel fuel with more flexibility when compared to ethanol/gasoline. This flexibility allows for the price of the D4 RIN to be set based on production costs associated with biodiesel. In some scenarios D6 (ethanol) RIN prices were found to be insensitive to corn prices because their prices were set based on the ability to provide a specific blend % to market.
- *The ability to consume E85 in future years can dramatically impact the price of D5/D6 RINs, and subsequently will impact the overall cost of compliance associated with the RFS*. The projected total cost of compliance can be reduced by approximately 50% in 2017 if an additional 600 million gallons of E85 were consumed as a transportation fuel (assuming 300 million gallons are currently consumed). New initiatives under the Biofuel Infrastructure Partnership from the US Department of Agriculture to install blender pumps may be able to help deploy these fuels more widely.

While the results presented here have been cast as a short-term model, models that include investment decisions should be developed to understand the longer-term impacts of the RFS and cost implications of different volume targets. Capacity expansion models are not without serious challenges since RFS implementation has proven more challenging than originally anticipated. Under this additional uncertainty it is difficult to envision large investments in production capacity for new fuels. Beginning in 2016, EPA will be faced with another difficult challenge of reviewing the entire RFS program and all the volume targets originally required by Congress. The criteria that trigger this program-wide review can be found at the following reference (42 USC 7545(o)(7)(F)). It is a near certainty that this review will prove to be very contentious, and analytical tools such as the model presented in this paper, which can shed light on market impacts will help provide a timely and objective source of information for policy makers and regulators.

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References

American Petroleum Institute, 2014. State Motor Fuel Taxes.
Anderson, S., Sallee, J., 2011. Using loopholes to reveal the marginal cost of regulation: the case of fuel-economy standards. Am. Econ. Rev. 101, 1375–1409.
Babcock B., Pouliot S., 2014. Feasibility and Cost of Increasing US Ethanol Consumption Beyond E10 (No. 14-PB 17). Center for Agricultural and Rural Development, Iowa State University.
Babcock B., Pouliot S., 2013a. RFS Compliance: Death Spiral or Investment in E85? (No. 13-PB 16). Center for Agricultural and Rural Development, Iowa State University.
Babcock B., Pouliot S., 2013b. How Much E85 Can be Consumed in the United States? (No. 13-PB 15). Center for Agricultural and Rural Development, Iowa State University.
Babcock B., Pouliot S., 2013c. Impact of Sales Constraints and Entry on E85 Demand (No. 13-PB 12). Center for Agricultural and Rural Development, Iowa State University.
Babcock B., Pouliot S., 2013d. Price it and They Will Buy: How E85 Can Break the Blend Wall (No. 13-PB 11). Center for Agricultural and Rural Development, Iowa State University.
Bushnell, J., Mansur, E., 2011. Vertical targeting and leakage in carbon policy. Am. Econ. Rev. 101, 263–267.
California Air Resources Board, 2015a. Allocation to Refineries [WWW Document]. URL ⟨http://www.arb.ca.gov/cc/capandtrade/allowanceallocation/refineryallocation.htm⟩ (accessed 05.05.15.).
California Air Resources Board, 2015b. Low Carbon Fuel Standard Reporting Tool Quarterly Summaries [WWW Document]. URL ⟨http://www.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm⟩ (accessed 20.04.15.).
California Air Resources Board, 2011. California Cap and Trade System [WWW Document]. URL ⟨http://arb.ca.gov/cc/capandtrade/capandtrade.htm⟩.
California Air Resources Board, 2009. Low Carbon Fuel Standard Program [WWW Document]. URL ⟨http://www.arb.ca.gov/fuels/lcfs/lcfs.htm⟩ (accessed 07.04.15.).
Carriquiry, M.A., Du, X., Timilsina, G.R., 2011. Second generation biofuels: economics and policies. Energy Policy 39, 4222–4234. http://dx.doi.org/10.1016/j.enpol.2011.04.036.
Christensen, A., Lausten, C., 2014. Fundamental inconsistencies between federal biofuels policy and their implications. Environ. Law Rev. 44, 10395–10412.
Christensen, A., Siddiqui, S., 2015. A mixed complementarity model for the US Biofuel Market with Federal Policy Interventions, Biofuels, Bioproducts and Biorefining 9 (4), 397–411. http://dx.doi.org/10.1002/bbb.1545.
Decker, C., Wohar, M., 2007. Do increases in petroleum product prices put the incumbent party at risk in US presidential elections? Appl. Econ. 39, 7270737.
Department of Energy, 2014a. Minnesota Biofuel Blend Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6093⟩.
Department of Energy, 2014b. Oregon Renewable Fuels Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6274⟩.
Department of Energy, 2014c. Montana Ethanol Blend Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6168⟩.
Department of Energy, 2014d. Hawai'i Ethanol Fuel Blend Standard [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6080⟩.
Department of Energy, 2014e. Missouri Ethanol Blend Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6083⟩.
Department of Energy, 2014f. Minnesota Biodiesel Blend Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/5452⟩.
Department of Energy, 2014g. New Mexico Biodiesel Blend Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6181⟩.
Department of Energy, 2014h. Louisiana Renewable Fuel Standard [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6103⟩.
Department of Energy, 2014i. Pennsylvania Renewable Fuels Mandate [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6486⟩.
Department of Energy, 2014j. Washington Biodiesel Use Requirement [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws/6041⟩.
Department of Energy-EERE, 2015. Alternative Fuels Data Center-Federal and State Laws and Incentives [WWW Document]. URL ⟨http://www.afdc.energy.gov/laws⟩ (accessed 07.04.15.).
Energy Independence and Security Act of 2007, n.d.
Energy Information Administration, 2015a. Annual Energy Outlook 2015 [WWW Document]. URL ⟨http://www.eia.gov/forecasts/aeo/⟩ (accessed 27.04.15.).
Energy Information Administration, 2015b. Electricity-Average Retail Price of Electricity By End-Use Sector [WWW Document]. URL ⟨http://www.eia.gov/forecasts/aeo/⟩ (accessed 02.04.15.).
Energy Information Administration, 2015c. Natural Gas Prices-Industrial Price [WWW Document]. URL ⟨http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm⟩ (accessed 02.04.15.).
Energy Information Administration, 2015d. Petroleum and Other Liquids-Mont Belvieu, TX Propane Spot Price [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epllpa_pf4_y44mb_dpg&f=d⟩ (accessed 02.04.15.).
Energy Information Administration, 2015e. Natural Gas Prices-Exports Price [WWW Document]. URL ⟨http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm⟩ (accessed 02.04.15.).
Energy Information Administration, 2015f. Petroleum and Other Liquids-Spot Prices [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm⟩ (accessed 02.04.15.).
Energy Information Administration, 2015g. Petroleum and Other Liquids-US Gulf Coast Kerosene-Type Jet Fuel Spot Price [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epjk_pf4_rgc_dpg&f=d⟩ (accessed 02.04.15.).
Energy Information Administration, 2015h. Refiner Petroleum Product Prices by Sales Type [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/pet_pri_refoth_dcu_nus_m.htm⟩ (accessed 16.04.15.).
Energy Information Administration, 2014a. Refinery Utilization and Capacity [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/pet_pnp_unc_dcu_nus_m.htm⟩.
Energy Information Administration, 2014b. US Imports of Finished Motor Gasoline by Country of Orgin [WWW Document]. URL ⟨http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_epm0f_im0_mbbl_a.htm⟩.
Energy Information Administration, 2014c. US Imports of Distillate Fuel Oil 15 ppm

and Under (Sulfur) by Country of Orgin [WWW Document]. URL 〈http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_EPDXL0_im0_mbbl_a.htm〉.
Energy Information Administration, 2014d. Weekly Retail Gasoline and Diesel Prices [WWW Document]. URL 〈http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_w.htm〉.
Energy Information Administration, 2014e. Company Level Imports [WWW Document]. URL 〈http://www.eia.gov/petroleum/imports/companylevel/〉 (accessed 20.03.15.).
Energy Information Administration, 2013a. Annual Energy Outlook 2013-Table 58 Light-Duty Vehicle Stock by Technology Type [WWW Document]. URL 〈http://www.eia.gov/forecasts/aeo/supplement/suptab_58.xlsx〉.
Energy Information Administration, 2013b. Liquid Fuels Market Module [WWW Document]. URL 〈http://www.eia.gov/forecasts/aeo/assumptions/pdf/liquidfuels.pdf〉.
Energy Information Administration, 2012. Biofuels Issues and Trends [WWW Document]. URL 〈http://www.eia.gov/biofuels/issuestrends/〉.
Environmental Protection Agency, 2015. Renewable Fuel Standard Program: Standards for 2014, 2015 and 2016 and Biomass-Based Diesel Volume for 2017, Docket #: EPA-HQ-OAR-2015-0111.
Environmental Protection Agency, 2014a. Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards, 79 Fed. Reg. 23414.
Environmental Protection Agency, 2014b. RFS EMTS Information Data [WWW Document]. URL 〈http://www.epa.gov/otaq/fuels/rfsdata/index.htm〉.
Environmental Protection Agency, 2014c. Notice of Delay in Issuing 2014 Standards for the Renewable Fuel Standard Program [WWW Document]. URL 〈http://www.epa.gov/otaq/fuels/renewablefuels/documents/fr-notice-2014-rf-standards.pdf〉.
Environmental Protection Agency, 2014d. Response to Petitions for Reconsideration of the 2013 Cellulosic Biofuel Standard-American Petroleum Institute [WWW Document]. URL 〈http://www.epa.gov/otaq/fuels/renewablefuels/documents/api-01232014.pdf〉.
Environmental Protection Agency, 2014e. Response to Petitions for Reconsideration of the 2013 Cellulosic Biofuel Standard-American Fuel and Petrochemical Manufacturers [WWW Document]. URL 〈http://www.epa.gov/otaq/fuels/renewablefuels/documents/afpm-01232014.pdf〉.
Environmental Protection Agency, 2013. 2014 Standards for the Renewable Fuel Standard Program, 78 Fed. Reg. 71732.
Environmental Protection Agency, 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis [WWW Document]. URL 〈http://www.epa.gov/otaq/renewablefuels/420r10006.pdf〉.
Environmental Protection Agency, 2007. EPA Finalized Regulations for a Renewable Fuel Standard (RFS) Program for 2007 and Beyond, 72 Fed. Reg. 23900.
Federation of Tax Administrators, 2014. State Motor Fuel Tax Rates.
Government Accountability Office, 2004. Energy Markets-Effects of Mergers and Market Concentration in the US Petroleum Industry (No. 04-96).
Governor Schwarzenegger, 2007. Executive Order S-01-07 [WWW Document]. URL 〈http://www.arb.ca.gov/fuels/lcfs/eos0107.pdf〉 (accessed 07.04.15.).
Greene, D., 2008. Vehicles and E85 Stations Needed to Achieve Ethanol Goals. National Academies, Transportation Research Board, http://trrjournalonline.trb.org/doi/10.3141/2058-21.
Hassett, K.A., Mathur, A., Metcalf, G.E., 2007. The Incidence of a US Carbon Tax: A Lifetime and Regional Analysis. National Bureau of Economic Research, http://www.nber.org/papers/w13554.
House of Representatives-Committee on Energy and Commerce, 2013a. Overview of the Renewable Fuel Standard: Government Perspectives. Washington, DC.
House of Representatives-Committee on Energy and Commerce, 2013b. Overview of the Renewable Fuel Standard: Stakeholder Perspectives. Washington, DC.
Liu, C., Greene, D., 2013. Modeling the Demand for E85 in the United States (No. ORNL/TM-2013/369). Oak Ridge National Laboratory, http://info.ornl.gov/sites/publications/files/Pub45616.pdf.
Mansur E.T., 2010. Upstream Versus Downstream Implementation of Climate Policy. National Bureau of Economic Research Working Paper Series no. 16116. doi:10.3386/w16116.
McPhail, L.L., 2012. A structural VAR approach to disentangle RIN prices. Environ. Econ. 3, 8–16.
McPhail, L., Westcott, P., Lutman, H., 2011. The Renewable Identification Number System and US Biofuel Mandates. USDA, ERS Report BIO-03, http://www.ers.usda.gov/media/138383/bio03.pdf.
Methanex, 2015. Methanex Methanol Price History [WWW Document]. URL 〈https://www.methanex.com/sites/default/files/methanol-price/MxAvgPrice_Mar%2027%202015.pdf〉 (accessed 14.04.15.).
Meyer, S., Thompson, W., 2010. FAPRI-MU US Biofuels, Corn Processing, Distillers Grains, Fats, Switchgrass, and Corn Stover Model Documentation. University of Missouri, Columbia (No. FAPRI-MU Report #09-10).
Milbrandt A., Kinchin C., McCormick R., 2013. The Feasibility of Producing and Using Biomass-Based Diesel and Jet Fuel in the United States (No. NREL/TP-6A20-58015).
Miller, N., Christensen, A., Park, J.E., Baral, A., Malins, C., Searle, S., 2013. Measuring and Addressing Investment Risk in the Second-generation Biofuels Industry. International Council on Clean Transportation http://www.theicct.org/sites/default/files/publications/ICCT_AdvancedBiofuelsInvestmentRisk_Dec2013.pdf.
National Biodiesel Board, 2015. OEM Information [WWW Document]. URL 〈http://biodiesel.org/using-biodiesel/oem-information〉 (accessed 07.04.15.).
National Biodiesel Board, 2014. National Biodiesel Board Member Plants [WWW Document]. URL 〈http://biodiesel.org/production/plants〉.
National Biodiesel Board, 2008. Comprehensive Survey on Energy Use for Biodiesel Production [WWW Document]. URL 〈http://www.biodiesel.org/docs/ffs-production/comprehensive-survey-on-energy-use-for-biodiesel-production.pdf?sfvrsn=4〉.
Parry, I.W., Williams III, R.C., Goulder, L.H., 1999. When can carbon abatement policies increase welfare? The fundamental role of distorted factor markets. J. Environ. Econ. Manag. 37, 52–84.
Pearlson, M.N., 2011. A Techno-economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels. Massachusetts Institute of Technology http://dspace.mit.edu/handle/1721.1/65508.
Peterka, A., 2014. White House Urged EPA Restraint on 2014 RFS Targets. Greenwire-E&E News, http://www.eenews.net/stories/1059992426.
Pouliot S., 2013. Arbitrage between ethanol and gasoline: evidence from motor fuel consumption in Brazil. Presented at the Agricultural & Applied Economics Association Annual Meeting, Washington, DC.
Renewable Fuels Association, n.d. Industry Stastistics [WWW Document]. URL 〈http://ethanolrfa.org/pages/statistics〉.
Searle, S., Christensen, A., 2014. How the Renewable Fuel Standard Works. International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCTBriefing_RFS2_20140211.pdf.
Searle, S., Sanchez, F.P., Malins, C., German, J., 2014. Technical Barriers to the Consumption of Higher Blends of Ethanol. International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/ICCT_ethanol_revised_02_03_format.pdf.
Strogen, B., Horvath, A., McKone, T.E., 2012. Fuel miles and the blend wall: costs and emissions from ethanol distribution in the United States. Environ. Sci. Technol. 46, 5285–5293.
Thompson, W., Meyer, S., Westhoff, P., 2010. The new markets for renewable identification numbers. Appl. Econ. Perspect. Policy 32, 588–603. http://dx.doi.org/10.1093/aepp/ppq021.
Thompson, W., Whistance, J., Meyer, S., 2011. Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions. Energy Policy 39, 5509–5518. http://dx.doi.org/10.1016/j.enpol.2011.05.011.
UNICA-Brazilian Sugarcane Industry Association, 2015. UNICA Data [WWW Document]. URL 〈http://www.unicadata.com.br/index.php?idioma=2〉 (accessed 15.04.15.).
United States Department of Agriculture, 2015. USDA National Agricultural Statistics Service-Agricultural Prices [WWW Document]. URL 〈http://www.nass.usda.gov/Statistics_by_Subject/Economics_and_Prices/index.asp〉 (accessed 14.04.15.).
Whistance, J., Thompson, W., 2014a. The role of CAFE standards and alternative-fuel vehicle production credits in U.S. biofuels markets. Energy Policy 74, 147. http://dx.doi.org/10.1016/j.enpol.2014.09.004.
Whistance, J., Thompson, W., 2014b. A critical assessment of RIN price behavior and the implications for corn, ethanol, and gasoline price relationships. Appl. Econ. Perspect. Policy 36, 623–642.
Whistance, J., Thompson, W., 2014c. FAPRI-MU US Biofuels, Corn Processing, Biomass-based Diesel, and Cellulosic Biomass. University of Missouri, Columbia (No. FAPRI-MU Report #03-14).
Wu, M., 2008. Analysis of the Efficiency of the US Ethanol Industry 2007. Argonne National Laboratory, http://www.energy.gov/eere/bioenergy/downloads/analysis-efficiency-us-ethanol-industry.