Complement or substitute: Ethanol's uncertain relationship with gasoline under alternative petroleum price and policy scenarios

1. Introduction

Ethanol accounts for a larger share of global liquid fuels markets than ever before, but interactions between ethanol and fossil fuel sources are complicated by varying consumer uses and policy interventions. Since 2000, total energy consumption in the global transportation sector has been increasing 2% annually, and global ethanol production has risen from 28.5 billion liters in 2004 to 98 billion liters in 2015 [1]. In 2015, renewable energy use in the road transportation sector is estimated to be 4% of the total transportation fuel use and liquid biofuels, including ethanol, dominate among all other renewable fuels in this sector [1]. Ethanol is the most widely used biofuel that is blended with and displaces petroleum-based fossil fuel, leading to greenhouse gas emission (GHG) reductions [2]. While the recent increase has attracted attention, Brazil has been using ethanol as a fuel since 1925 [3]. In the U.S. and E.U., as in Brazil, government policies intervene in biofuel markets by setting minimum quantities or shares of domestic use, but these policies tend to be complex. For example, the U.S. Renewable Fuel Standard (RFS) sets a hierarchy of volume targets by biofuel type while allowing for waivers based, in part, on market conditions [4]. Ethanol use has grown in importance, but the interaction of demand and policy drivers is difficult to assess because this market has evolved so quickly and so recently in most countries.

The effect of petroleum price changes on ethanol markets and policies is uncertain yet important. The uncertainty relates to the sudden increase in this market and the nature of demand. As global ethanol use has more than doubled in just a decade, historical data might not represent current market conditions. Moreover, as shown later, demand is likely to be non-linear, ranging

from a complementary relationship with gasoline at very low volumes where it is used as a fuel additive to influence its physical properties, to a strong substituting relationship as fuels with high ethanol inclusion rate displace petroleum products. In addition, these relationships can be influenced by policies that set minimum use targets, particularly if a fixed blend is required. Estimates drawn from decades of U.S. data, for example, might span periods when the marginal use of ethanol was as an additive and periods when the marginal use was as a competing fuel source. Future interactions are uncertain.

The importance of these interactions is without doubt. Scientific assessment of supply chains and environmental impacts demonstrates the broad relevance of ethanol (e.g. [5, 6, 7]). Debates in the U.S. Congress, during the Presidential campaigns, and in the industry press about the details and very existence of the RFS show that the policy should be a subject of applied energy economics. The U.S. mandates affect markets and can cause billions of dollars in compliance costs for obligated parties, as discussed below. Looking ahead towards the legislated increases in the mandate and taking into account an uncertain petroleum price and its implications for ethanol demand, applied research has a role in outlining the potential market and policy cost impacts.

2. Background

Estimates over past data might not relate to market conditions in the future and, moreover, time series methods focusing on price series tend not to address the mandate compliance costs. The linkage between food and fuel markets has been discussed in the applied economic literature for many years. Serra and Zilberman [9] review time series studies of prices and find that, in general, energy prices tend to drive agricultural commodity prices historically. Serra et al. [10], Serra et al. [11], Whistance et al. [12], Whistance and Thompson [13], and Zhang et al. [14] use

time series analysis for both U.S. and Brazilian biofuel markets to estimate links between ethanol, petroleum-based fuels, and crop prices. They found that an increase in the petroleum prices results in an increase in the ethanol price and, consequently, an increase in the prices of corn in the U.S. and sugar in Brazil. However, very few of these studies rely primarily on recent data and also exploit information about U.S. mandate compliance [12, 13]. These studies argue that the linkage between food and fuel prices depends on the relationship between biofuels and gasoline. If biofuels complement petroleum products, as might be true in the case of fuels with a 10% ethanol inclusion rate (E10) in the U.S. (Fig. 1), then a high gasoline price will cause a decrease in biofuel use and can lower feedstock prices. Conversely, if biofuels and petroleum products are substitutes, as in the case of hydrous ethanol in Brazil (Fig. 2), then rising petroleum-based fuel prices increase biofuel demand and increase the prices of crops that are used as feedstocks. Demirbas [15] and Szklo et al. [16] point out that there are both complementary and substitute relationships between ethanol and gasoline. However, this line of work tends to be backward-looking, whereas future market conditions might differ if there are changes in petroleum price levels, mandated volumes or shares, or the relationship between ethanol and petroleum products at the margin. Moreover, studies that represent ethanol as either a complement to gasoline (Fig. 1) or a substitute (Fig. 2) could be completely incorrect about price relationships if the switch from one segment of demand to the other is not taken into account.

Structural modeling represents an alternative tool to time series that allows researchers to focus on current or anticipated market conditions. Many authors, including de Gorter and Just [17-19], Keeney and Hertel [20] and Tyner et al. [21], use structural models to study some of the consequences of policy on energy and agricultural markets. For example, Elobeid and Tokgoz [22] trace out the impact of removing the U.S. tax credit on ethanol markets using a multimarket

international ethanol model that consists of U.S., Brazil, and ROW (Rest of the World). Christensen and Siddiqui [23] pointed out the consequences of RFS implementation in the U.S. and world ethanol markets. However, RFS sub-mandates are not considered in many past studies. Many studies also represent aggregate demand for ethanol, without regard to the specific fuel choices that consumers make. Meyer and Thompson [24] and Whistance et al. [25, 26] examine several alternative mandate scenarios concerning the RFS sub-mandates and take into account relative prices of E10 and E85. These studies estimate that certain waiver scenarios that limit U.S. RFS expansion would result in a significant increase in the import of sugarcane-based ethanol, for example. To the best of our knowledge, studies do not consider the consequences for world ethanol markets of various options to waive the overall mandate and its components, identify sensitivity with respect to the petroleum price, and take into account the complexities of demand and mandate compliance.

We focus on (i) modeling the alternating complementary or substituting relationship between ethanol and gasoline simultaneously, (ii) waiver options for various RFS components that are currently under debate, and (iii) alternative future petroleum price levels. We use a structural economic model to consider the use of ethanol as a complement to gasoline in E10 and substitute at higher blends. Ethanol use in the U.S. and other key producing and consuming countries or regions, including Brazil is represented as elastic at a higher gasoline price relative to ethanol price to represent the dominance of the substitute effect and inelastic at a lower gasoline price relative to ethanol price to allow for a greater role of the complementary effect. The consequence is a non-linear, kinked ethanol demand curve with the petroleum price determining the location of the kink (Fig. 3). This representation of ethanol demand is part of a larger global partial equilibrium model of ethanol, ethanol feedstock, and related markets, including

agricultural commodity markets to represent additional complications such as slow adjustments to area allocation or livestock numbers that can also influence responses. This model builds on similar research using structural models by applying the ideas about ethanol demand drawn from the time series literature to the global ethanol market. This approach allows an examination of how petroleum price levels interact with the U.S. biofuel mandates and estimation of biofuel price and RFS compliance implications related to this key indicator of global energy markets.

The objectives of this study are to estimate the consequences of a lower and higher petroleum price on (a) the U.S. and global ethanol markets and (b) the U.S. biofuel mandate compliance costs. Our study expands on an economic partial equilibrium model for the world ethanol market, and related markets, breaking out the U.S., Brazil, and other key countries or regions. We introduced a kinked ethanol demand curve to represent the possibility of either a complementary or substituting relationship between ethanol and gasoline market. We find that these demand-side effects are suppressed in certain key markets, including Brazil, because of existing policies. We also find that a combination of factors, including U.S. domestic and export demands as well as mandate implementation, cause a higher petroleum price to have strong ethanol price impacts and to eliminate most of the U.S. mandate compliance costs.

2.1. U.S. Renewable Fuel Standard and its Implementation

The U.S. established the RFS in 2005. Two years later, the Energy Independence and Security Act (EISA) expanded the RFS mandate [4]. Another element of the new legislation was the definition of four separate components of the mandate: total renewable fuels, advanced biofuel, biomass-based diesel, and cellulosic and agricultural waste based (“cellulosic”) biofuel. The EISA nests some of these components as sub-mandates to others (Fig. 4). The total requirement is comprised of two categories: the sub-mandate for advanced biofuels and the

remaining “conventional” gap, most of which has been met with corn starch (i.e., “conventional”) ethanol. The advanced biofuel mandate has two sub-mandates of its own, namely the cellulosic biofuel and biomass-based biodiesel mandates, but can also be met by other advanced biofuels. Equation 1 shows that the advanced gap is the portion of the advanced biofuel mandate that can be met using biofuels other than biomass-based diesel or cellulosic biofuel. The advanced gap can be defined in terms of other EISA mandates as:

$$O = A - C - B \quad (1)$$

where O is the other advanced gap biofuel, A is the advanced renewable biofuel mandate, C is the cellulosic biofuel mandate, and B is the biomass-based biodiesel mandate in ethanol-equivalent gallons.

The RFS mandates, as laid out in EISA, call for the use of at least 36 billion gallons (136.3 billion liters) of total renewable biofuel by 2022, of which up to 15 billion gallons (57.8 billion liters) can be met using conventional ethanol from 2015 onwards. EISA also calls for the use of at least 16 billion gallons (60.6 billion liters) of cellulosic biofuel by 2022 starting from 500 million gallons (1.9 billion liters) of cellulosic biofuel in 2012. Biomass-based diesel is mandated to be at least 1 billion gallons (3.8 billion liters) from 2012 onwards [4].

The RFS is administered by the U.S. Environmental Protection Agency (EPA). The EPA has the responsibility to waive the RFS renewable fuel mandates, subject to criteria outlined in the law that generally relates to available supplies or market impacts in some way [24]. The EPA has reduced the cellulosic biofuel mandate every year at the time of writing. The hierarchy of sub-mandates suggests that a reduction in the cellulosic biofuel volume could necessitate greater use of other biofuels so that broader mandates can still be filled. For example, if only the cellulosic mandate was reduced, as in 2010-2013, then the use of biodiesel or other advanced biofuels

would have to offset the shortfall in cellulosic biofuel in order to comply with the advanced mandate. The EISA allows for the broader mandates to be reduced if the cellulosic mandate is waived, so other choices are possible. If cellulosic mandates continue to be waived in the future, then there could be offsetting increases in other biofuels to meet the mandate or not, depending on mandate implementation.

In May of 2016, the EPA released their proposed rules for 2017 [4]. The EPA used their cellulosic waiver authority to reduce the overall, advanced and cellulosic mandates below the original EISA levels. The 2017 requirements included some measure of growth relative to the final rules for 2016, but not at the same pace as EISA suggested. The proposed overall requirement rose from 18.1 billion gallons (68.5 billion liters) in 2016 to 18.8 billion gallons (71.2 billion liters) in 2017. Conventional ethanol in 2017 could account for 14.4 billion gallons (54.5 billion liters). Given the estimates of motor fuel use that were used, in part, to determine the proposed volumes, these requirements do not push much past the blend wall (i.e. the amount of fuel ethanol that can be consumed in 10% blends). The EPA also set the biomass-based diesel requirement to rise, starting from the actual use of 1.9 billion gallons (7.2 billion liters) in 2017 and climbing by 0.2 billion gallons (0.8 billion liters) per year to reach 2.1 billion gallons (7.9 billion liters) in 2018.

The EPA sets the requirements for each year as percentages of estimated fuel use. All obligated parties must demonstrate compliance by submitting a number of Renewable Identification Numbers (RINs) equal to those percentages multiplied by the volume of the fuels that they supply for domestic use. RINs are unique identifiers attached to each gallon of eligible renewable fuel as it is produced or imported. When that fuel has been blended with petroleum fuel

to be sold into the U.S. motor fuel market, those RINs can be separated and then bought, sold, or traded among obligated parties.

In theory, RIN prices reflect the degree to which the mandates are binding, as well as the hierarchical nature of mandates [13]. The petroleum price can affect RIN prices, setting aside for the moment the complications of ethanol demand (Fig. 5). The increase in crude oil price has the following consequences. First, overall motor fuel use in the U.S. decreases, so the product of the percentage and total motor fuel use also falls so the volume of biofuel required falls (mandate shift from M_E to M'_E). Second, there will be an increase in ethanol demand due to the substitution effect (demand shift from D_E to D'_E). This interaction can transform the RFS from binding to non-binding (Q_E to Q'_E) under certain circumstances and the given RIN price can fall to zero (from RIN_E to RIN'_E).

In 2014, the average ethanol inclusion rate in gasoline was 9.8%, which suggests that U.S. domestic ethanol consumption was approaching the blend wall [27]. In order to achieve the proposed higher mandates, more ethanol has to be used in high-blend fuels (e.g., E85) or through increased use of drop-in fuels that are not subject to blend limits. Unlike Brazil, where high-blend fuel infrastructure is more prevalent, E85 is available only at 2,677, or roughly 2.5% of, public gas stations in the U.S. so not all flex-fuel owners have the choice to fill their tank with E85 [28, 29]. Furthermore, in areas with access to E85, the fuel often is not priced competitively on an energy equivalent basis with E10, which makes it less likely to be used by flex-fuel vehicle drivers when they are given the choice [30].

3. International Ethanol Model

The starting point is a multi-market, multi-region, partial equilibrium model that has been used in some form for RFS and biofuel market analysis in the past [24, 31–33]. The U.S. biofuel

model has been described elsewhere [24-26, 30,33,34]. For this study, we develop an explicit international ethanol model¹[35-37]. Igos et al. [38], and Cai et al. [39] use a similar model to analyze the impact of energy policy. The major ethanol producing and consuming countries are modeled, including the U.S., Brazil, Argentina, Canada, E.U., and the aggregated rest of the world (ROW), which includes China, India, and other countries. Yu and Tao [40] mentioned that fuel ethanol is becoming an important component of China's strategy for diversifying their domestic energy mix and in alleviating environmental impacts of an expanding transportation sector. In our study, Chinese ethanol production, consumption, and trade are included in the ROW. In the case of Brazil and ROW, domestic use of ethanol is modeled as the sum of inelastic low-blend fuel (complement) and elastic high-blend fuel (substitute) use [15, 16]. The use of high-blend fuel is assumed to respond positively to increases in crude oil price. At high oil prices, we assume that there is still scope for expansion in overall use even though some part of high-blend fuel use will be in places where the low-blend fuel market is saturated.

A key point is that we expect aggregate consumer demand for ethanol will be kinked, with the kink occurring near the point where the price of ethanol is equivalent to the gasoline price per unit of energy. We assume the ethanol-gasoline price ratio at which consumer demand becomes more elastic is 0.70, which is the approximate energy equivalent level. A discount might be necessary to offset the costs of expanding the consumer and distribution infrastructure required for high-blend fuels. On the other hand, we model annual market prices aggregated over countries or even regions, so ethanol demand growth might very well expand in some places even if the ratio of broader price indices suggests otherwise. So, in general, at higher ethanol prices the ethanol demand curve is inelastic for lower blend fuels (E10) while it is elastic for higher blends (E85, E100) as the price of ethanol falls.

¹ Parameters used in the international ethanol model are listed in Appendix A.

As we mention above, the substitution effect between hydrous ethanol (E100) and gasoline C in Brazil is modeled at the level of ethanol-gasoline energy equivalence, which is about 0.70. In addition, there is the mandate-driven anhydrous ethanol use, which is assumed to be 27% of total gasoline use over the projection period. In the case of ROW, total fuel ethanol use is modeled as a kinked demand function similar to the one shown in Fig. 3 in which two different price elasticities, one less elastic than the other, are used to drive the total fuel ethanol use. The following equations explain the domestic ethanol use in Brazil and ROW:

$$Q^E = Q_L^E + Q_H^E \quad (2)$$

$$Q_L^E = \alpha - \beta \left(\frac{P_E}{P_G} \right) \quad \sigma < \left(\frac{P_E}{P_G} \right) \quad (3)$$

$$Q_H^E = \lambda - \rho \left(\frac{P_E}{P_G} \right) \quad \left(\frac{P_E}{P_G} \right) \leq \sigma \quad (4)$$

where Q^E is the total domestic ethanol use, including in lower blend, Q_L^E , and higher blend, Q_H^E , fuels. The low- and high- blend ethanol use equations represent ethanol demand based on relative prices of ethanol (P_E) to petroleum-based gasoline (P_G). Here, α and λ are the intercepts; and β and ρ are the price coefficients for lower blend and higher blend ethanol use. Low-blend demand is less elastic or even inelastic whereas high-blend demand is expected to be elastic, or in absolute value, $\beta > \rho$. A key point is that we expect consumer demand for low- or high- blend fuels will be kinked if the price of ethanol per unit of energy is equivalent to the gasoline price. The ratio of prices at which consumers switch from fuels with no ethanol or 10% ethanol to high-blend fuels is set to be at σ (in this study it is assumed to be 0.7).

On the supply side, for most of the countries, ethanol production is derived by multiplying ethanol industry capacity by the utilization rate of that capacity. Both the capacity and utilization equations are driven by the lagged price of ethanol as well as the price of the feedstocks used to

derive ethanol. We assume that, in the short term, the ethanol industry adjusts the production via the capacity utilization rate. In the longer term, we assume they are more likely to increase or decrease the overall capacity of their respective ethanol industry depending on the price of ethanol and feedstocks². Trade equations are included for both Brazil and U.S. while ethanol trade is considered as the residual of domestic production and consumption for other countries, including ROW. We also model the stocks of ethanol as a function of ethanol price and volume of ethanol production. Table 1 summarizes the literature on the country specific gasoline and ethanol demand elasticities and ethanol supply elasticities respectively. The demand and supply elasticities of our model are listed in Table 2.

4. Alternative Crude Oil Prices and High RFS Scenarios

We simulate the forward-looking global biofuel markets model under high RFS and two different crude oil price scenarios. One defining trait is two alternative projections for crude oil prices based on the low and high price scenarios of the 2016 Annual Energy Outlook, which was prepared by the U.S. Energy Information Administration (EIA) [49] (Fig. 6). These alternatives do not define the ranges of possibilities, but they serve to set two very different contexts for world biofuel markets. Biofuel markets can have rebound effects on petroleum markets [34,50,51]. In this study, the rebound effects of biofuels on the gasoline market are mostly excluded.

RFS assumptions are consistent with the final RFS rules for 2014-2016 and the proposed rules for 2017. The RFS is not represented as an absolute, fixed volume in our model. Instead, the RFS is set at a percent target of total fuel use, as suggested by our reading of the EPA rules.³ In

² The functional form of the equations used in the structural economic model representing the international ethanol market are listed in Appendix B.

³ Percent targets imply that the RFS volumes are determined endogenously. A high crude oil price that discourages motor fuel use would imply a low volumetric RFS requirement for a given percent requirement. However, we assume the conventional and advanced gaps in the requirement hierarchy cannot exceed the volumes implied in the EISA (i.e. the conventional gap is capped at 15 billion gallons). Under some conditions, this assumption will limit the overall and advanced volume requirements.

both high- and low crude oil price scenarios, we assume that the overall renewable mandate in U.S. will increase by 0.5 percentage points (e.g. 10.1% to 10.6%) per year, the advanced mandate will increase by 0.15 percentage points per year, the biomass-based diesel will increase by 0.1 percentage points per year and cellulosic biofuels will increase by 0.02 percentage points per year. We map these percentages to volumes here to facilitate comparisons to other volumes, including EISA levels.

In total, we analyze two crude oil price scenarios, high and low, under an RFS percent requirement assumption that expands fairly rapidly over the simulated period. As noted above, the combination of fixed percent RFS requirements and varying petroleum prices maps to a different set of RFS volumes in each scenario.

5. Scenario Analysis and Results

Table 3 compares the projected U.S. and Brazilian ethanol and gasoline prices and U.S. RIN prices obtained from solving the global biofuel model under two alternative crude oil price scenarios and with the assumption of U.S. high RFS. In the low crude oil price scenario, we estimate the 2023–25 average U.S. Omaha rack price to be \$0.54 per liter and the Brazilian anhydrous ethanol price to be \$0.53 per liter. The estimated average retail gasoline prices in the U.S. and Brazil are \$0.48 per liter and \$0.83 per liter respectively. Under the high crude oil price scenario, the estimated ethanol prices for the U.S. rack and Brazil anhydrous increase to \$0.62 per liter and 0.60 per liter respectively, and gasoline price is estimated to be \$1.74 per liter in the U.S. and \$1.02 per liter in Brazil. The U.S. gasoline price is more sensitive to the changes in the world crude oil price relative to the Brazilian gasoline price. In Brazil, the gasoline C price is influenced by policy in addition to variations in global petroleum and petroleum product market conditions and prices. This pattern is assumed to continue during the simulation period: the global crude oil

price has less effect on the Brazilian gasoline C price than on the U.S. retail price. However, the changes in ethanol price across both the countries are quite similar in magnitude.

With the increase in crude oil price, the U.S. RFS is not binding whereas the RFS is binding in the low crude oil price case (as demonstrated in Fig. 5). The conventional RIN price falls to zero in the high crude oil price scenario compared to \$0.34 per RIN-liter in the low crude oil price case (Table 3). Moving from the low crude oil price scenario to the high price scenario, the RIN values attached to other advanced biofuel and biomass-based diesel⁴ also fall to zero, implying that these components of the mandate also cease to be binding.

U.S. RIN generation under the two alternative crude oil prices is shown in Table 4. The substitution effect under the high crude oil price scenario drives an increase in both the ethanol demand, which leads to an increase in conventional RINs generation from 15 to 19.1 billion RINs. The RINs generated from other advanced biofuel decrease from 0.9 billion RINs to 0.5 billion RINs, while the RINs generated from biomass-based diesel and cellulosic biofuel remain flat between the low and high crude oil prices scenarios. The main reason behind the decrease in the number of other advanced biofuel RINs is the decrease in the total volume of the corresponding mandate requirements even though the percentage requirements remain identical in both cases. With the decrease in total mandated volumes from the low crude oil price scenario to the high crude oil price scenario, the use of RINs for overall RFS compliance in the U.S. decreases from 21.7 billion RINs to 16.4 billion RINs.

Table 5 shows the differences in domestic production, fuel use and net trade of ethanol by major ethanol producing and consuming countries between the low crude oil price and high crude oil price scenarios under the U.S. high RFS mandate assumption. The increasing crude oil price

⁴ The model represents all components of the mandate and the related biofuel markets. However, the focus of this study is on ethanol markets, not biomass-based diesel.

drives higher consumer demand for ethanol, although the degree of the impact can vary widely among countries depending on the level of use relative to the blend wall. Higher consumer demand causes an increase in the ethanol price (Table 3) which, in turn, leads to an increase in ethanol production worldwide (Table 5). In Brazil, ethanol consumption increases by 2.7% in the high crude oil price case relative to the low crude oil price case. This is less than expected given that the availability of hydrous ethanol (E100) at the retail level implies consumers can quickly switch between petroleum-based fuel and ethanol depending on the relative prices (Fig. 2). However, the results are consistent with the assumption that the Brazilian gasoline price is controlled, in part, by policy. The increase in ethanol production leads to an increase in the Brazilian net ethanol exports by around 2.2 billion liters.

Comparing the low crude oil price to the high crude oil price scenario, ROW ethanol production increases by 95 million liters while consumption increases by 5.7 billion liters. These changes lead to an increase in net imports by 5.5 billion liters from the international market. ROW production and consumption response are uncertain given the array of countries and regions represented, but it is possible that rising petroleum prices increase ethanol demand in countries that have not played a large role in the world ethanol market in the past and that these countries consequently increase imports, at least over a medium-term projection.

In the U.S., the high crude oil prices, and subsequently high gasoline prices, increase the domestic fuel ethanol use by 25.2% and production by 29.5% (Table 5). The results in table 5 show that, regardless of the crude oil price level, the U.S. is a major exporter of ethanol to the world market. However, with a high crude oil price both the U.S. and Brazil see an expansion in their net exports to the global ethanol market.

The per capita simulated ROW ethanol use over the projection period is shown in Fig. 7. In the case of a low crude oil price path, ethanol demand might be expected to be inelastic. Demand for ethanol as a substitute would be low; the marginal use would often be as a complement – unless the policy of a particular country or jurisdiction requires greater use beyond the blend wall. The per capita ethanol use is expected to be very elastic when the crude oil price is \$220 per barrel. The demands traced out by our simulation results are consistent across low and high crude oil prices and ROW (Fig. 7) and are conceivably extensions of recent data (Figs. 1 and 2). The time series effects of the net ethanol trade among the major ethanol importing and exporting countries are traced in Fig. 8, which shows that with the increase in crude oil price (Fig. 6) the consumption in ROW increases resulting in increasing imports, mostly from the U.S and Brazil.

5.1 *Sensitivity to RFS waiver*

The responsiveness of ethanol use in the U.S. depends in part on the mandates. We assume a fairly constant percent requirement, as suggested by recent implementation decisions. However, it might be the case that the RFS targets are also adjusted. To test the sensitivity of results to the mandate, we test the impacts of a reduction in the mandate in the low crude oil price case.

Relaxing the mandate in the low crude oil price case allows the conventional RIN price to fall, dropping by less than a third in this experiment. Domestic ethanol use in the U.S. contracts, as expected, given the combination of weak demand for ethanol as a substitute, beyond the blend wall, and less required use to satisfy policy requirements. Of the 1.5 billion liters less domestic use in this experiment, about half is exported, with reduced U.S. ethanol production accounting for the other half. Greater U.S. ethanol exports tend to displace Brazilian exports in the low crude oil price case, with global ethanol demand mostly inelastic.

This experiment shows that results can be sensitive to the mandate. The potential for U.S. to respond to changes in world ethanol market conditions caused by crude oil price changes can vary if the mandate is set more or less aggressively. Moreover, results suggest that, because of their competition in international markets and particularly in the context of inelastic global ethanol demand, changes in U.S. ethanol trade tend to cause offsetting effects in Brazilian trade.

6. Conclusions and Policy Implications

Whereas scientific assessment of how petroleum price and the RFS interact does not consistently exploit information about current and future ethanol demand, we develop a representation that allows us to explore the interaction of petroleum prices and the RFS in a forward-looking context that reflects the current realities of global ethanol markets. Our work is important for policy makers who decide the future of the RFS, regulators who implement these mandates, and to industry, public, and scientific communities because of the relationship to compliance costs and broader implications relating to market effects, food security, and GHGs. Studies based on historical price data or a historical base period might relate to a time of rising RFS biofuel use that was still below the blend wall in the U.S. or might not take into account the potential for similar non-linear ethanol demand responses in other countries. The findings of this study are critical as, with the U.S. E10 market saturated and the future crude oil price a source of great uncertainty, the potential interactions of future RFS implementation and ethanol demand, in the U.S. and elsewhere, the potential mandate impacts are unknown to policymakers, regulators, industry representatives, and others.

In this paper, a structural economic model of biofuel and related markets is expanded and used to estimate the impacts of crude oil prices taking into account U.S. biofuel mandates and the varying nature of the gasoline-ethanol relationship. We exploit a widely used structural model

([24-26, 30, 33, 34, 52] and develop further the representation of ethanol demand to reflect new-found complications in demand that indicate the potential for a regime change between complementary and substituting relationships ([12, 13], Figs. 1 and 2). The RFS is represented based on how it is implemented now, namely as slowly rising percentage of total U.S. fuel use, rather than as fixed volume targets. The petroleum price can have complicated effects through (a) the overall level of fuel demand in the U.S. and consequently the effective mandate as implemented, (b) the demand for ethanol based on relative fuel prices in the U.S., and (c) world demand for ethanol to the extent that the marginal use is as a substitute for petroleum products. As historical data can represent a different market structure, we believe that forward-looking analysis of these complicated petroleum price effects requires a structural model of the type we apply here.

We find that a crude oil price of around \$50 per barrel implies a market condition in which ethanol use is often complementary to gasoline, with only limited substitution potential at the margin. The lower and less elastic ethanol demand leads to more binding U.S. mandates and lower U.S. exports but also depressed global ethanol trade more generally. In contrast, a crude oil price of around \$220 per barrel – a level that is consistent with EIA high crude oil price projection – implies a very different setting for global ethanol markets. This high crude oil price implies far more potential to substitute from gasoline to ethanol globally and greater global trade. Moreover, this high price level depresses total U.S. fuel demand, so the U.S. mandate percentage is mapped to a lower absolute level and is more easily filled. Global ethanol trade can become lively if crude oil prices recover to their old levels and keep rising from there. That said, we find important distinctions between responses in countries where the changing relative prices can move ethanol

demand into a substituting relationship as compared to countries, such as the U.S. and Brazil, where demand is tied to mandates or is at some limit, like the blend wall.

Our research also raises certain concerns that might be addressed in other studies. If the blend wall proves a persistent barrier to domestic ethanol use, then researchers who investigate the RFS might add information by recognizing two different contexts, namely the complementary or substituting relationship between gasoline and ethanol at the margin. Studies of how mandate implementation affects the domestic market, and imports and exports of the U.S., as well as the effects in Brazil and other parts of the world, might be quite sensitive to the exact crude oil price path. The nature of global ethanol demand is uncertain and research is scarce on what could be an increasingly important issue for biofuel producers, biofuel and climate change mitigation policies, and by agricultural producers that provide the inputs to biofuel markets. The potential for non-linear ethanol demand and asymmetric responses that vary with petroleum price have serious implications. As shown here, mandate compliance costs can vary with market conditions, implying that the costs of any results of the RFS pertaining to GHG reduction targets or energy security, with consequences for any cost-benefit assessment of this policy. Scientific assessments of the ethanol market or supply chains ([24-26, 30, 33, 34, 52]) or environmental impacts ([53–55]) might generate results that are specific at a certain petroleum price or a particular point in time historically, with limited ability for extrapolation to current or future market conditions. Our work supports greater efforts by researchers to confirm results for different market contexts and different segments of ethanol demand. We also caution readers who would apply findings of past ethanol studies to verify that the ethanol demand representation of a simulation model or the nature of demand during a historical estimation period is a realistic representation of ethanol

demand response at the time relevant to the decisions of policy makers, regulators, investors, or others whom researchers wish to inform.

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Table 1. Summary of published country specific ethanol and gasoline demand and supply elasticities.

Previous Study		Elasticities				
Authors	Ref.	Country	Commodity	Own Price	Cross Price	Income
Demand side						
Elobeid and Tokgoz	[22]	U.S.	Ethanol	-0.43		0.11
			Anhydrous			
		Brazil	Ethanol	-0.10		0.13
		Brazil	Hydrous Ethanol	-0.30		0.13
Tokgoz	[41]	E.U.	Ethanol	-0.55	0.51	
			Gasoline	-0.77		0.10
Anderson	[42]	U.S.	Ethanol		2.50 to 3.00	
Santos and Colomer	[43]	Brazil	Ethanol	-0.48	1.42	
Golub et al.	[44]	Brazil	Biofuels		1.35	
		E.U.	Biofuels		1.65	
		U.S.	Biofuels		3.95	
Sukati	[45]	E.U.	Ethanol	-0.03 to -0.06		
Jianping and Yalin	[46]	China	Ethanol		0.10 to 5.00	
Chisari et al.	[47]	Argentina	Biofuels		2.00	
Santos	[48]	Brazil	Gasoline	-0.78	1.56	0.28
			Ethanol	-1.53	1.18	0.54
Supply side						
Elobeid and Tokgoz	[22]	U.S.	Ethanol	0.65		
		Brazil	Ethanol	0.20		
Tokgoz	[41]	E.U.	Ethanol	0.79		

Source: Elasticities are drawn from referenced studies as listed above.

Table 2. Ethanol and gasoline demand and supply elasticities used in this study

Country	Commodity	Price Elasticity	Income Elasticity
Demand Side			
U.S	Gasoline	-0.07	0.11
	Ethanol (E10)	-5.85	na
Brazil	Gasoline	-0.10	0.30
	Ethanol	-0.50	0.10
E.U.	Gasoline	-0.10	0.50
	Ethanol	-0.03	0.30
Argentina	Ethanol	-0.05	0.10
Canada	Ethanol	-0.03	0.40
ROW	Ethanol	-0.20	0.10
Supply Side*			
U.S	Ethanol	1.13	na
Brazil	Ethanol	0.80	na
E.U.	Ethanol	0.10	na
Argentina	Ethanol	0.20	na
Canada	Ethanol	0.70	na
ROW	Ethanol	0.60	na

*Ethanol supply, we employ linear capacity and logistic capacity-utilization rate equations. Here, we show the percent changes in utilization rates that occur given a 1% increase in the ratio of ethanol to gasoline prices. They are not elasticities in the strictest sense, but they give the reader an idea of the responsiveness of these utilization rates.

Source: Authors' calculation.

Table 3. Ethanol and RIN prices (\$/liter)*

	Low Oil Price	High Oil Price
Ethanol		
U.S. Omaha Rack	0.54	0.62
Brazilian Anhydrous (F.O.B)	0.53	0.60
Gasoline Price**		
U.S.	0.48	1.74
Brazil	0.83	1.02
Renewable Identification Numbers (RIN)		
Conventional	0.34	0.00
Advanced	0.34	0.00
Biomass-based Diesel	0.50	0.00

*Average of the last three years of the projection 2023-2025

**Domestic retail gasoline price

Source: Authors' calculation.

Table 4. RIN generation in U.S. under alternative oil price scenarios (million RINs)*

	Low Oil Price	High Oil Price
Production	21,759	25,404
Total Advanced	6,713	6,319
Biomass-based Diesel**	5,490	5,552
Cellulosic	277	277
Other Advanced	946	490
Conventional	15,046	19,085
Use for RFS compliance**	21,694	16,391

* Average of the last three years of the projection (2023-2025)

** Stated in ethanol equivalent terms

Source: Authors' calculation.

Table 5. Changes in ethanol production, fuel use and net trade by country, low and high crude oil prices (million liters)*

	Low Oil Price	High Oil Price	Absolute Changes	Percentage Changes
United States				
Production	60,079	77,782	17,703	29.5%
Domestic Fuel Use	56,944	71,266	14,322	25.2%
Net Export	1,504	4,803	3,299	
Brazil				
Production	28,682	31,686	3,004	10.5%
Domestic Fuel Use	26,089	26,784	695	2.7%
Net Export	718	2,887	2,169	
European Union				
Production	7,955	7,967	12	0.2%
Domestic Fuel Use	5,236	5,269	33	0.6%
Net Export	207	183	-24	-11.6%
Canada				
Production	2,064	2,099	35	1.7%
Domestic Fuel Use	2,818	2,823	5	0.2%
Net Import	964	935	-29	-3.0%
Argentina				
Production	1,277	1,279	2	0.1%
Domestic Fuel Use	1,176	1,177	1	0.1%
Net Import	49	48	-1	-2.0%
Rest of the World				
Production	20,928	21,023	95	0.5%
Domestic Fuel Use	8,897	14,599	5,702	64.1%
Net Import	75	5,550	5,475	

*Average of the last three years of the projection 2023-2025.

Source: Authors' calculation.

Note: Global net trade data do not balance historically because of discrepancies in the raw data and we assume that this error is constant in the period and in both scenarios. Domestic non-fuel use is not mentioned in the table. It is assumed to be exogenous and does not change between scenarios.

Figure 1

Figure 1. The ratio of the ethanol use to gasoline use plotted against the ratio of the ethanol retail price to gasoline retail price in the U.S., suggesting complementarity.

Source: Ethanol and motor fuel use data are from EIA [27]; U.S. ethanol retail price in energy equivalent terms is calculated based on Nebraska monthly ethanol price [56], assumed margins, and RIN price data from OPIS [57]; and U.S. gasoline retail price is from Consumer Price Index, Department of Labor [58].

Note: Data represent the period from January 2010 to February 2015.

Figure 2

Figure 2. The ratio of ethanol and gasoline C sales plotted against the ratio of the ethanol retail price to gasoline C retail price in Brazil, suggesting substitution.

Source: Brazil ethanol and gasoline price and domestic sales data are obtained from National Agency of Petroleum, Natural Gas and Biofuels (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis) [59, 60].

Note: Data represent the period from January 2010 to February 2015.

Figure 3

Figure 3. Kinked ethanol demand curve.

Figure 4

Figure 4. Venn diagram of different categories of biofuels nested under the total renewable fuels according to EISA 2007.

Figure 5

Figure 5. Schematic representation of the U.S. RINs market values under low and high gasoline price.

Figure 6

Figure 6. West Texas Intermediate (WTI) crude oil price path assumptions: (i) low crude oil price, and (ii) high crude oil price.

Source: 2016 Annual Energy Outlook [49].

Figure 7

Figure 7. Simulated per capita quantity demand for ethanol in rest of world (ROW).

Note: We use the ratio of crude oil price and Brazilian anhydrous ethanol price as the representative of the world ethanol price.

Figure 8

Figure 8. Absolute changes in country specific ethanol trade from low crude oil price scenario to high crude oil price scenario.