THREE ESSAYS ON THE LINKS BETWEEN AGRICULTURE AND ENERGY POLICIES IN THE U.S.

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And hereby certify that, in their opinion, it is worthy of acceptance.

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A very special thank you to my family and, of course, Erin…I truly appreciate all the
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ABSTRACT

The first essay develops and applies a structural, partial equilibrium model of United States biomass supply and demand. The aim is to examine the biomass price and expenditure effects of domestic biofuel policies. The results indicate that the cellulosic biofuel sub-mandate alone could increase biomass prices by an average of 50% to 100% over the baseline values. Biomass expenditures by sectors competing with biofuel producers increase by an average of 26% relative to the baseline suggesting those sectors cannot fully shift away from biomass energy sources. A sensitivity analysis focusing on supply response indicates that the results are not very sensitive to the supply elasticity. This study contributes to the literature by providing policymakers and other energy policy stakeholders with a forward looking analysis of potential policy effects on the U.S. biomass market.

The second essay develops a similar type of model applied toward the domestic and international petroleum and petroleum products markets as well as the domestic biofuel market and the domestic light-duty vehicle sector. The goal is to investigate the impact of CAFE standards and alternative-fuel vehicle production incentives on the biofuel market and RFS compliance, in particular. The results suggest that holding CAFE standards at the 2010 level could significantly reduce the blendwall problem in the U.S. ethanol market. Furthermore, the alternative fuel production incentives appear to have only minimal effects. However, there is much uncertainty surrounding the appropriate level of automaker response to those incentives, and a sensitivity analysis indicates the model is fairly sensitive to the assumed level of response.

The third essay highlights a few of the theories put forth regarding the expected price behavior of Renewable Identification Numbers (RINs). The theories are tested both observationally and empirically with a dataset containing daily RIN price observations going back to January 2009. The behavior does not always match expectations, although the exact causes remain uncertain. In addition, the information provided by RIN prices is used to test the implications of a binding renewable fuel standard (RFS) versus a non-binding RFS on the ethanol-gasoline price relationship. Cointegration tests provide some evidence that the relationship between conventional ethanol and gasoline prices at the wholesale level is weaker in the presence of a binding RFS.

DOMESTIC ENERGY POLICY EFFECTS ON THE U.S. BIOMASS MARKET[1]

1. Introduction

Energy derived from cellulosic biomass is not a new concept. However, environmental goals regarding greenhouse gas emissions and climate change as well as energy security concerns resulting from rising petroleum prices have brought all forms of biomass-based energy to the forefront of the renewable energy discussion. Although there are skeptics, bioenergy is seen by many people as the best way to move beyond a fossil fuel based society. Bioenergy will continue to play a role in meeting human energy needs in the United States and around the globe, and the size of that role could have important implications for energy prices and expenditures.

Policymakers in the U.S. are among the many who support the idea of a larger bioenergy sector. Two of the most recent energy bills passed by the U.S. legislature, the Energy Policy Act (EPACT) of 2005 and the Energy Independence and Security Act (EISA) of 2007 , most well-known for the renewable fuel standard (RFS) provisions, specifically call for an increasing presence of bioenergy production in the U.S. energy portfolio. The American Clean Energy and Security (ACES) Act , which called for a 20% renewable portfolio standard (RPS) among other provisions, was passed by the U.S. House of Representatives in 2009 but failed to become law when it did not pass the U.S. Senate.

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[1] NOTICE: this is the author's version of a work that was accepted for publication in *Biomass and Bioenergy*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in *Biomass and Bioenergy*, [46, (2012), pp. 133-44] http://dx.doi.org/10.1016/j.biombioe.2012.09.013

There is a large and growing line of research that investigates the consequences of energy policies. One research thread, in particular, asks how corn-ethanol mandates affect prices in other energy markets. Some of the studies focus more narrowly on motor fuel prices (Du and Hayes 2009; Wang 2008) while others focus on broader sectors and markets (Whistance and Thompson 2010; Whistance, Thompson, and Meyer 2010). Du and Hayes (2009) and Wang (2008) both found that the ethanol mandates could have moderate consumer price effects in the motor fuel market, and Whistance and Thompson (2010) and Whistance et al. (2010) found that the same mandates could have smaller, but not necessarily insignificant, effects on natural gas prices and expenditures at the sector level.

This study extends that line of research by asking how the cellulosic biofuel mandate as laid out in EISA 2007 and the RPS as proposed in ACES 2009 might affect prices and expenditures in the U.S. biomass market. In addition, this study performs a sensitivity analysis in which the supply elasticity is varied over a plausible range of values. A structural, partial equilibrium model of U.S. biomass supply and demand is developed and utilized, and a baseline projection is obtained. The potential effects of the policy scenarios are determined by introducing demand shocks to the model, simulating new outcomes, and comparing the outcomes to the reference baseline.

This study is important because it looks at the whole biomass market in a forward looking manner. The results are useful to policymakers and others who are interested in the potential market effects of increased biomass use stemming from current and potential, domestic energy policies.

2. Background

In this study, the term “biomass” includes agricultural residues (corn stover, wheat straw, etc.), energy crops (switchgrass, miscanthus, etc.), short rotation woody crops like hybrid poplar, forest resources including fuelwood and logging residues, mill residues, and municipal solid wastes.

In recent years, there have been many studies attempting to determine the cellulosic biomass potential in the U.S. and in countries abroad. The so-called “Billion Ton Study” (BTS) (Perlack et al. 2005) was conducted in 2005 by the U.S. Department of Agriculture (USDA) in conjunction with the U.S. Department of Energy (DOE). The aim of the BTS was to determine the ability of the U.S. to produce enough biomass from feedstocks such as corn stover, wheat straw, and logging/mill residues to displace 30% of petroleum consumption. The authors found that the U.S. could sustainably produce that level of biomass. However, their conclusions were based on a number of key assumptions such as excluding inaccessible forests and environmentally sensitive areas as well as assuming 100% no-till adoption and allowing 75% of crop residues to be removed. An update to the 2005 BTS was released in 2011 (Perlack and Stokes (Leads) 2011). The assumptions were revised to be more in line with current expectations regarding tilling practices, residue removal, etc. Still, the results were quite similar to the earlier version. The report suggests that just less than 1 billion metric tons (mt) of biomass could potentially be available by 2030 at a price of $66/ dry mt.

Also in 2005, Milbrandt (2005) performed an analysis similar to the BTS for the National Renewable Energy Laboratory (NREL). Under a set of more restrictive assumptions (e.g. a crop residue removal rate of 35% as opposed to 75%), Milbrandt found a biomass potential slightly lower than 400 million mt.

Studies such as Perlack et al. (2005) and Milbrandt (2005) estimate the potentially available quantities of the feedstocks they analyzed under their given assumptions. They do not, however, consider at what price those quantities would be supplied to the market. Until we have an idea of the costs associated with biomass production, processing and transportation, we will be uncertain about the actual biomass supply curve. In 2007, Gan (2007) derived supply curves for logging residues based on the costs of delivered feedstock to electricity generation plants. Gan estimated approximately 32 million dry mt of logging residues would be available at a median delivered cost of $44/dry mt. Walsh (2008) used the POLYSYS model to estimate biomass availability by U.S. county for the 2005-2030 time period at prices ranging from $22 to $110/dry mt. Walsh focused on forest residues, mill residues, urban wood waste, corn stover, wheat straw, and switchgrass. Overall, Walsh's results seem to agree with Milbrandt (2005) and Gan (2007). Walsh estimated 350 million mt of biomass, of which forest residues were estimated to be 37 million mt, would be available in 2020 at $44/dry mt. Kumarappan et al. (2009) estimated biomass supply curves for both the U.S. and Canada using a similar cost approach. Their estimates were also very similar to the prior studies. For example, they estimated that 315 million dry mt of total biomass would be supplied at a price of $40/dry mt and forest/mill residues accounted for 80 million mt. More recently, LaTourrette et al. (2011) focused exclusively on the costs of supplying biomass to an individual electricity provider co-firing coal and biomass. They estimated marginal production costs ranging from $84/mt, at which point biomass supply is zero, to $100/mt, at which point biomass supply reaches 3.3 million mt. All of these studies are valuable because they give us an idea of what biomass supplies might look like in the future, but they lack an important feature. They do not reveal the allocation of those supplies to competing uses such as electricity generation or biofuel production.

In 2006, English et al. (2006) addressed that issue by using the POLYSYS model along with IMPLAN, an input-output model, to analyze the effects of two “25 by 25” scenarios. In the first scenario, 25% of the U.S. energy mix would be derived from renewable energy by the year 2025 while in the second scenario the 25% requirement would apply only to electric power and transportation fuels. The goals of this study were twofold. First, the authors were interested in whether or not the U.S. agriculture sector could provide enough biomass to meet those energy requirements with limited impacts on food and feed prices. Second, they wanted to show how the biopower and biofuel industries compete for biomass supplies. Their assumptions regarding the proliferation of cellulosic ethanol technology and dedicated energy crops seem optimistic by today’s standards, but they show domestically produced biomass has the potential to meet such significant energy goals (English et al. 2006). In addition, the results of their simulation indicated that biomass feedstocks dominated the ethanol production industry by 2025. The following year, de la Torre Ugarte et al. (2007) made a further extension by including bioproduct uses of biomass (e.g. levulinic acid, succinic acid, etc.) in their allocation of biomass supplies. Their analysis focused on bioenergy goals targeting 5% of electrical power and 10% of transportation fuels. They reached the same general conclusion as English et al. (2006) using similar methods.

In 2007, the Energy Information Administration (EIA) used their National Energy Modeling System to analyze the potential effects of a 25% RFS combined with a 25% RPS fully implemented by 2025 (U.S. Energy Information Administration 2007). They found that, in order to meet those requirements, biomass consumption must increase substantially in both the electric power and transportation demand sectors leading to increased competition for limited supplies. The increased competition leads to biomass prices that are more than three times higher in 2025 relative to their reference case (U.S. Energy Information Administration 2007).

Government energy policies have often attempted to stimulate both biomass supply and demand. A few of the key provisions of EPACT 2005 were summarized in Holt and Glover (2006). Title IX and Title XV were particularly important. Title IX established federally funded research and development programs, including grants and other incentives, to encourage innovations in the areas of cellulosic biomass preprocessing and harvesting as well as cellulosic biofuel production. Title XV established the nation's first RFS which called for 28 billion liters of renewable fuel by 2012.

Two years later, EISA 2007 was passed to further encourage the use domestically produced clean energy. Sissine (2007) summarized the key provisions from this act. Title II of EISA 2007 revised and extended the earlier RFS. Specifically, it is a mandate for the use of renewable fuels with at least 20% fewer life-cycle greenhouse gas (GHG) emissions relative to the 2005 baseline level of emissions by the motor fuel they are replacing. The mandate requirement increases each year and reaches 136 billion liters by 2022. Conventional, or corn-starch, ethanol that meets the 20% GHG reduction can only account for 57 billion liters. The rest must come from advanced biofuels including a 61 billion liter requirement for cellulosic ethanol with a 60% GHG reduction or biodiesel with at least 50% fewer GHG emissions, both of which may be derived from biomass feedstocks. Title II also authorized more federal funding to support biofuel related research and development as well as biofuel infrastructure development.

3. Method and data

The current study develops and employs a model of U.S. biomass supply and demand. It follows the approach used by many of the previously cited studies that develop and employ their models in a similar fashion. The model in this study mimics the structure of the biomass market in the U.S. Figure 1 is a graphical representation of the model. Biomass supply, which includes biomass production and imports, is depicted on the top. Biomass demand is on the bottom and includes consumption by five domestic sectors of the economy as well as export demand. The equilibrium market price is jointly determined and occurs at the point where supply and demand balance. However, this model is a partial-equilibrium model, so it focuses on this particular market while other markets are exogenous. Biomass supply and demand quantities are expected to rise rapidly in the future relative to their historical levels, so this approach focuses on ensuring the structure of the system is correct in order to obtain more accurate projections.

The equations of this model are estimated over the historical period ranging from 1971 to 2009. The starting point of the reference baseline is the year 2009, and the values for the simulated period are calibrated to the Reference Case of the EIA’s 2011 Annual Energy Outlook (U.S. Energy Information Administration 2011a). An error term, equal to the difference between the values estimated by this model and values taken from the

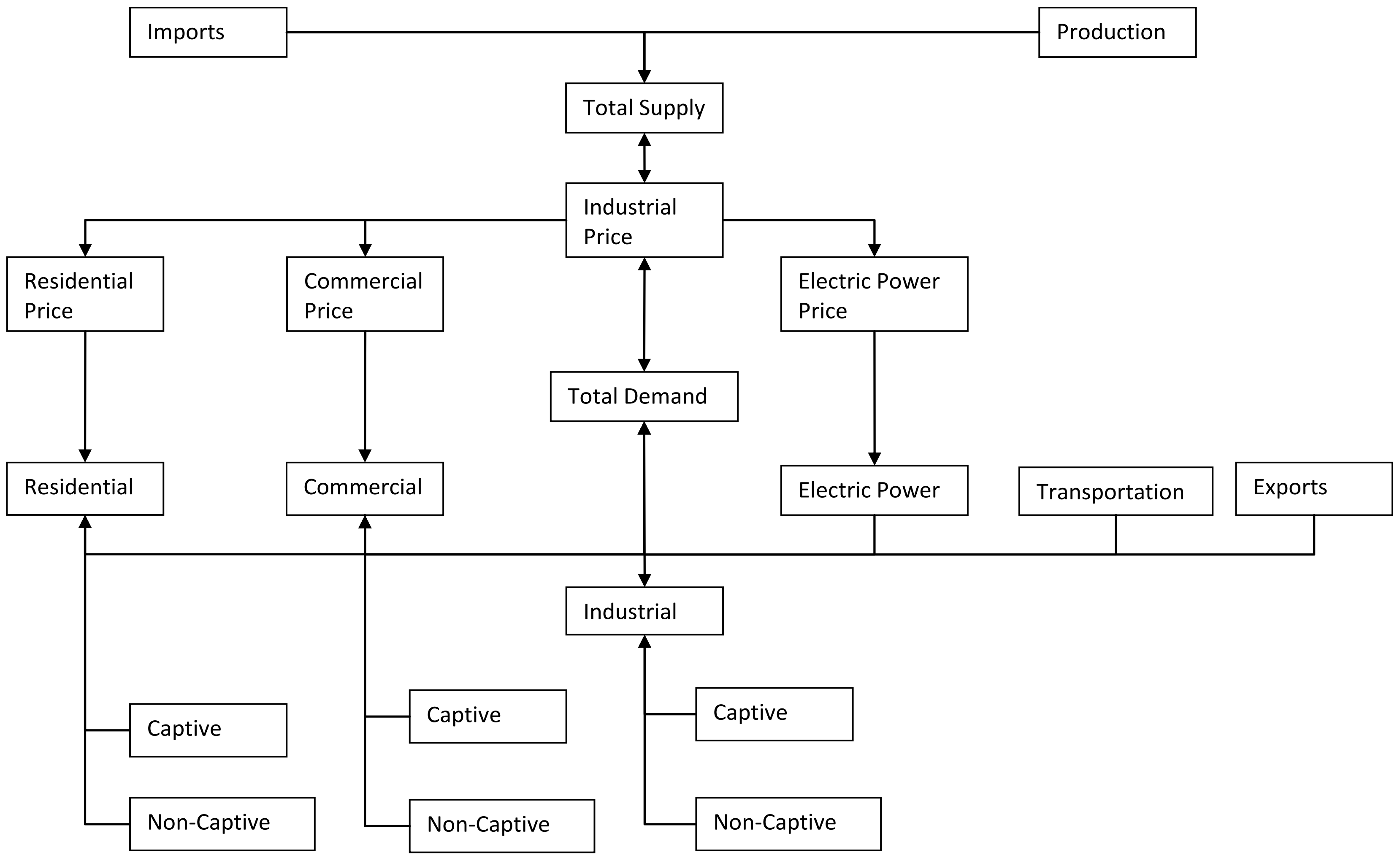

Figure 1. Flowchart depicting US biomass supply and demand

outlook, is added back to the equation for that particular year to calibrate the model. The error terms are carried forward and are included also in the policy scenario simulations. The simulations occur over a long term, 22-year projection period extending from 2009 to 2030. The policy scenarios represent demand shocks that are applied to the model independently. In each scenario, the model is simulated again with the shocks in place which results in a different projection path. The results are compared to the reference baseline to determine both the short- and long-run effects of the given shock. In addition to the policy scenario analyses, a supply elasticity sensitivity analysis is also performed by varying the supply elasticity over a plausible range of values and comparing the results to the reference baseline. The following sub-sections provide a general overview of the structure of this model. For a detailed listing of equations and parameter estimates, refer to the Appendix.

3.1. Data

The data for this study were gathered primarily from the State Energy Demand System (SEDS) maintained by the EIA. They cover the period ranging from 1970 to 2009. According to the SEDS documentation, the definition of the “wood and waste” used by the EIA was made more restrictive in 2001 (U.S. Energy Information Administration 2009b). To account for that change, a variable equal to 1 for the years 2001 and beyond, zero otherwise, is used in the estimations described below. Wood pellet imports and exports were obtained from the U.S. International Trade Commission for the period extending from 1993 to 2010. Table A.1 in the Appendix provides the variable names, units and sources and table A.2 summarizes the historical data.

3.2. Biomass supply

In many previous studies, potential biomass supplies were estimated for given ranges of production costs. The supply measures in those studies are akin to biomass inventories that would be available at a certain cost level but not necessarily the quantities that would be supplied to the market. The SEDS does not provide an explicit measure of biomass production. Here, biomass production is calculated as the sum of total biomass demand including exports. It is assumed that there are no stocks of biomass supplies being held by producers. This assumption may not be the most accurate, but data availability is an issue. Total biomass supply is the sum of domestic production and imports.

Biomass supplies are likely to come from two main sources: dedicated energy crops and agricultural/forestry residues. Supplies from energy crops will depend on both the expected prices for biomass and the expected returns to crops that compete for the same land. Residues are co-products with other agricultural crop or forestry production, and their supplies will depend also on expected returns. The SEDS data do not differentiate between biomass from dedicated energy crops or residues, so the supply equation must cover both. This study assumes producers expect future returns and current returns to be equal. The quantity of biomass supplied in a given year is a function of current biomass prices as well as the expected net returns for competing land uses.

3.3. Biomass demand

To estimate biomass demand, this study follows the EIA's convention of modeling demands at the sector level. There are four endogenous demand sectors: residential, commercial, industrial, and electric power. There are two exogenous demand sectors: transportation and biomass exports. The transportation sector accounts for biomass consumed as an input to cellulosic biofuel production, and it is necessary for the scenario analyses discussed in more detail later. The residential, commercial and industrial sector demands have been split into quantities that are consumed at no cost, or "captive", and those that are consumed at a cost, or "non-captive"[2]. The distinction is important as it allows some, but not necessarily all, of the demands in a particular sector to be bid away by other sectors. This study assumes that all biomass quantities used for electric power generation are non-captive. The captive shares of biomass demand were unchanged from 2004 to 2009 at roughly 55%, 45%, and 35% for the residential, commercial, and industrial sectors respectively.

The overall consumption of biomass has been increasing over time, although current levels of consumption are somewhat lower than they were for most of the 1980's and 1990's. Historically, biomass consumption has been dominated by the industrial sector. This is due, in part, to the fact that energy needs within, for example, the paper and pulping industries have often been met with co-generated biomass residues. The industrial sector accounted for around 60% of total consumption in 2009. The residential sector accounted for a large share historically as well, but it has since lost a sizeable portion of its share. At the same time, the electric power sector increased its share of biomass demand. Together the shares of the residential and electric power sectors have each converged to about 18% of total consumption in 2009. Captive demands trended up early in the historical period but have shown a general downward

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[2] According to the EIA (U.S. Energy Information Administration 2011c), the "captive [biomass] market pertains to users with dedicated biomass supplies that obtain energy by burning biomass byproducts resulting from the manufacturing process (i.e. the pulp and paper and forest products industries)." Whereas, the non-captive market "include[s] the electric utility sectors, the ethanol production sector, and the resources marketed in the industrial sector…[and] residential and commercial uses of biomass." (pp 99-100) Note that in this study "captive" and "non-captive" refer only to whether or not the biomass was marketed not just the sector in which it was consumed.

trend since then. The upward trend in non-captive demands, especially for the industrial and electric power sectors, has buoyed the overall consumption level.

Another convention borrowed from the EIA is the use of sector prices for biomass. Different sectors are charged different prices for the biomass they consume owing to factors such as transportation costs and differences in their ability to utilize certain forms of biomass. For instance, the residential sector is unlikely to utilize mill residues directly. However, if they use wood pellets derived from mill residues the price they face would reflect the additional transportation, processing and marketing costs. The non-captive demands for the four endogenous sectors respond primarily to the appropriate sector biomass prices as well as the prices for competing sources of energy within that sector. In the residential, commercial and industrial sectors, competing prices would include those for electricity and natural gas, and possibly coal. Heating oil and propane could also compete with biomass in the residential sector. These two sources were not included in this study after the Residential Energy Consumption Survey carried out by the EIA indicated electricity and natural gas were still the dominant competing energy sources (U.S. Energy Information Administration 2009a). In the electric power sector, the coal price is the main competing energy input. In each case, the captive demands are determined by their historical trend.

The trend in biomass prices is marked by an early sharp rise, a period of gradual decline, and another period of sharply rising prices that continues to 2008. In this model, the industrial biomass price is taken to be the price that motivates biomass supply and is used in the equation estimating supply. The biomass prices for the residential, commercial and electric power sector are estimated as functions of the industrial price.

4. Results and discussion

The equations for supply, demand, and biomass prices were estimated by ordinary least squares using historical data through the year 2009. (See table A.3 in the Appendix for a full listing of parameter estimates). In an econometric model such as this, the coefficient estimates are used to calculate supply and demand elasticities. Price elasticities measure the percentage change in either supply or demand that results from a one percent change in the value of the given price variable. In most cases, the estimated parameters were consistent with economic theory. However, the own-price coefficients for the residential and industrial biomass demands were estimated to be positive although efforts were taken to correct for any potential biases. This is problematic as it would seem to indicate an increase in biomass prices would increase demand, which does not follow economic theory. The own-price elasticity of supply was estimated correctly in terms of direction, but the magnitude was much more inelastic in nature (i.e. supply was less responsive to price movements) than the literature seemed to indicate. The own-price residential demand, industrial demand, and biomass supply coefficients were restricted to give short-run elasticity values of -0.12, -0.30, and 0.08, respectively, to be are more in line with theory and previous literature. The other own-price demand elasticities were estimated to be fairly inelastic in the short-run (see table A.4 in the Appendix). The elasticities varied from -0.12 for the electric power sector to -0.30 for the industrial sector. Long-run elasticities varied between -0.57 for the residential sector and -0.72 for the industrial sector. Competing energies such as natural gas, coal, and electricity substitute for biomass in heating and power generating activities, so cross-price elasticities are expected to be positive. This occurred for the commercial and electric power sectors, but restrictions were necessary for the residential and industrial sectors.

Durbin-Watson and Godfrey tests indicated that most of the equations do not suffer the variance-inflating effects of serial correlation. The equations most affected were the captive demand and sector price equations. An autocorrelation consistent covariance matrix was used to correct the standard errors. As a simple validity test for the model, an in-sample projection for the period 1993-2007 was estimated and the percent root mean square errors (%RMSE) were calculated. The %RMSEs are a measure of the forecasting accuracy of the model. Higher values indicate larger forecasting errors and less accuracy. The %RMSEs for this model were a little high in a few cases, but given the limited historical data that is not surprising. The emphasis of this study is on obtaining plausible economic responses through the model structure and elasticities. The aim is to show the changes that could occur relative to a baseline under different scenarios while recognizing the limitations of the model and the uncertainty of the future.

4.1. Scenario 1: Binding and enforced cellulosic biofuel sub-mandate

Under the Renewable Fuel Standard detailed in EISA 2007, cellulosic biofuel quantities were to rise from an initial 2 billion liters in 2010 to 61 billion liters by 2022 (figure 2). The Environmental Protection Agency (EPA) has waived this particular sub-mandate for the past three years. The baseline in this study was projected under the assumption that the EPA would continue to waive the cellulosic mandate through 2022. This scenario depicts the potential changes relative to the baseline path assuming the mandates are binding and enforced by the EPA beginning in 2012 and lasting through 2022. Beyond 2022, it is assumed that cellulosic ethanol use continues to climb at the same rate of growth as total motor fuels (U.S. Energy Information Administration 2011b).

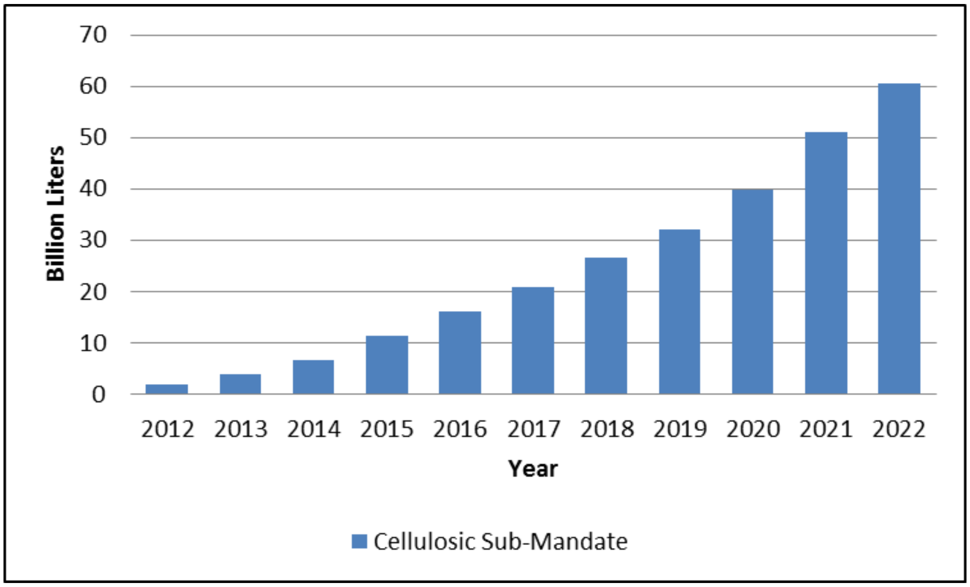

Figure 2. Cellulosic biofuel mandate requirements as defined in the Energy Information and Security Act of 2007. Source: Public Law 110-140 (2007)

To implement the shock, the first step is to determine the quantities of biomass input necessary to produce enough cellulosic ethanol to meet the cellulosic biofuel sub-mandate. An average cellulosic ethanol yield of 101 gallons per dry ton[3] of feedstock is calculated using the following inputs: corn stover, straw, switchgrass, forest residues, sawdust, and mixed paper. The EERE theoretical yield calculator (Office of Energy Efficiency and Renewable Energy 2012) provided the theoretical ethanol yields for those components. The EERE's Biomass Energy Databook (Office of Energy Efficiency and Renewable Energy 2011) and the Phyllis database (Energy Research Centre of the Netherlands) were used to determine the biomass input on an energy basis, which would allow it to be comparable to the other biomass quantities in the model. The input requirements represent a lower bound in that ethanol production inefficiencies will result

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[3] Individual theoretical ethanol yields were: Corn stover (113 gal/dt); Wheat straw (96.4 gal/dt); Switchgrass (96.7 gal/dt); Forest residue (81.5 gal/dt); Sawdust (100.8 gal/dt); Mixed paper (116.2 gal/dt).

in yields lower than those provided by EERE (Office of Energy Efficiency and Renewable Energy), so greater input quantities than those in this study will likely be required to meet the mandated amounts. Those efficiency losses, as they apply to different feedstocks and production processes, are uncertain. The biomass input requirements in this scenario are represented in the model as exogenous increases in cellulosic biomass demand by the transportation sector. The model is solved over the projection period with the new demands in place.

Figures 3 and 4 detail the baseline biomass price and expenditure paths by sector. The sector price and explicit expenditure effects are presented in table 1. Differences relative to the estimated baseline are presented in both level and percentage terms. The path of biomass prices in the scenario is higher than the baseline price path throughout the period. In the early years of the period, the cellulosic sub-mandate remains quite small, so the effect on biomass prices remains fairly small as well. Of course, the

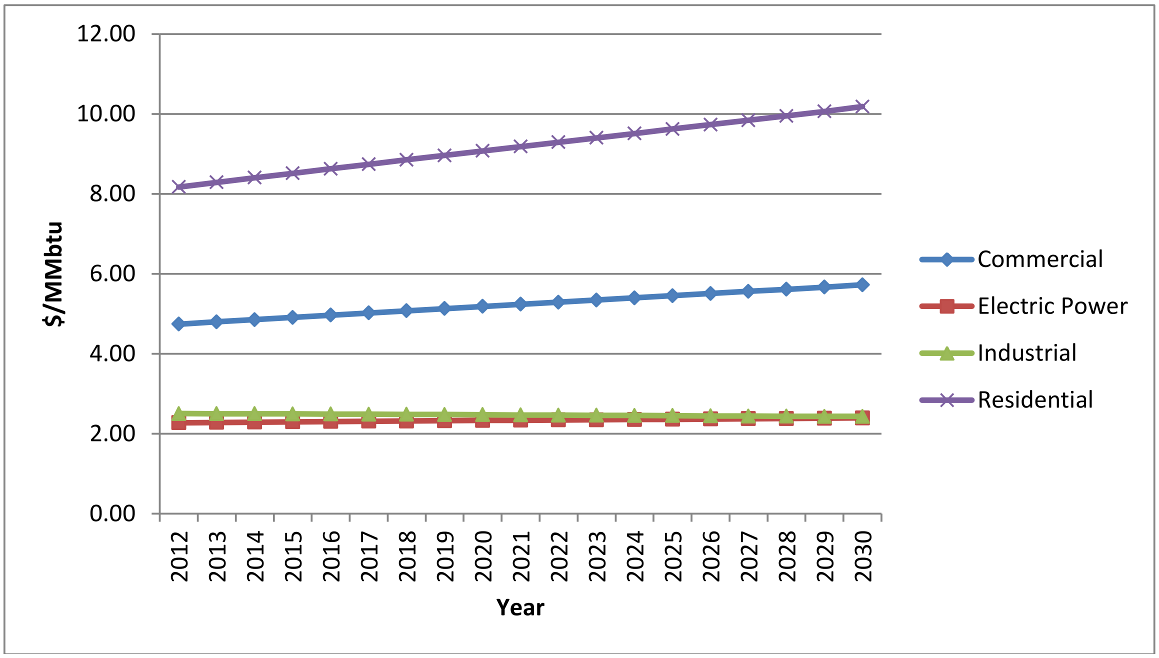

Figure 3. Baseline biomass prices by sector, 2012-2030. Source: Calculated

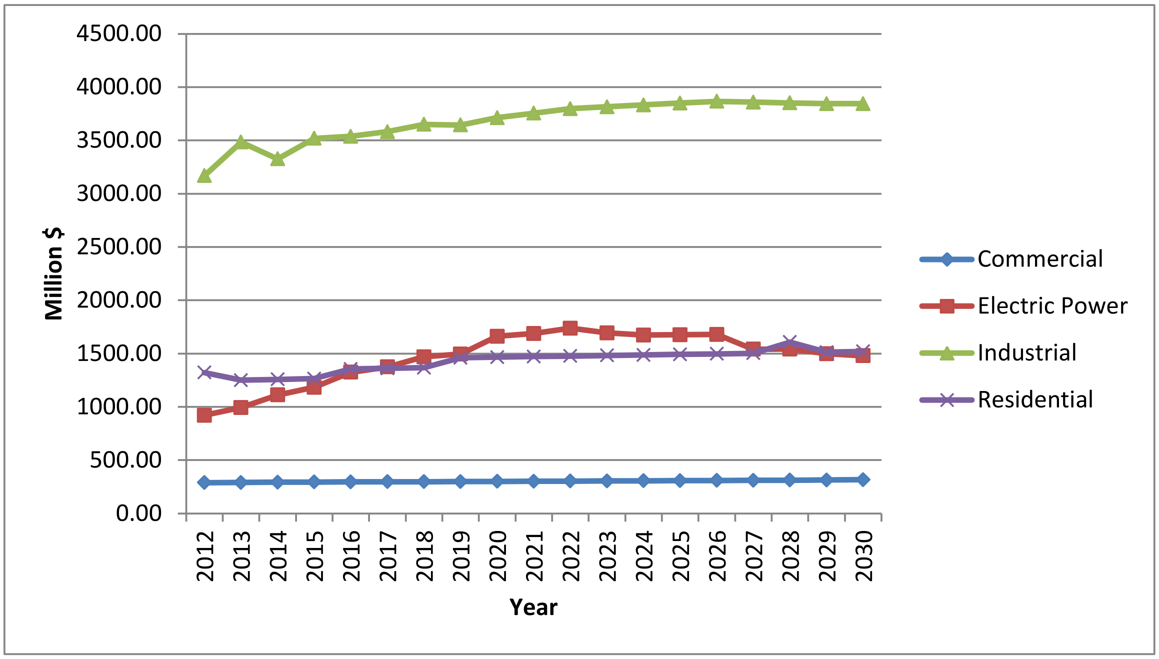

Figure 4. Baseline biomass expenditures by sector, 2012-2030. Source : Calibrated to the EIA's 2011 Annual Energy Outlook .

mandate requirements grow quite rapidly over time. As the biomass quantities necessary for cellulosic ethanol production increase, there is less remaining for the other sectors to consume. The increased competition between the other four sectors drives up the biomass prices they all face. In 2022, the projected prices for the industrial and electric power sector are 150%-180% higher than their baseline counterparts while the prices in the residential and commercial sectors are 80%-90% higher.[5] The projection period up to that point could be viewed as a transition period from very low cellulosic biofuel use to very high. Beyond that, cellulosic biofuel use grows at a slower pace and the players in the market have more time to adjust. Thus, the biomass price effects become slightly more moderate by the final year of the simulation.

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[5] If we assume cellulosic ethanol yields are 75% of the theoretical value, the average price effects are 15-33 percentage points higher. The average expenditure effects are 3-9 percentage points lower for residential, industrial, and commercial sectors, and 7 percentage points higher for the electric power sector.

The explicit biomass expenditure effects depend, in large part, on the non-captive demand elasticities. The expenditure effects are mixed throughout the period. Like the price effects, the expenditure effects are fairly small and positive relative to the baseline in the early years of the period. This is a reflection of the inelasticity of demand in the short run. Although biomass prices are slightly higher and demands slightly lower than the baseline values, expenditures are slightly higher. The results of this simulation suggest residential consumers are able to adjust more fully in the long run as the mandated quantities of cellulosic biofuel climb. As residential demands continue to fall relative to the baseline so do the residential biomass expenditures. The other three sectors cannot adjust their demand to that extent, so their biomass expenditures remain higher than the baseline levels. The last column of table 1 gives the present value of the expenditure effects. The streams of expenditure changes relative to the baseline were discounted using a rate of 3%, which is a Congressional Budget Office estimate of the real interest rate for the time period (U.S. Congressional Budget Office 2011). According to those calculations, the present value of all the differences in biomass expenditures by sector roughly totals $131 billion.Consumers representing captive biomass demand, while not charged explicitly for the biomass they consume, face opportunity costs equal to the amount they would receive by selling that biomass in the market. Such opportunity costs could be thought of as implicit expenditures that, in the scenario, rise at nearly the same rate as the biomass prices within each sector. The present value of the increase in total implicit expenditures relative to the baseline is $27 billion. Although it does not occur in this study, one would expect captive demands to diminish and, perhaps, cease if the biomass prices were high enough. In that case, the increase in supply would reduce

Table 1. Biomass price and expenditure differences under a binding cellulosic biofuel mandate relative to the baseline.

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Price effects														
Residential	US $ / GJ	0.53	0.70	1.15	1.98	2.41	2.85	3.59	4.13	5.30	7.32	7.86	5.71	5.75
	Percent	*7%*	*9%*	*14%*	*25%*	*30%*	*34%*	*43%*	*49%*	*62%*	*84%*	*89%*	*64%*	*64%*
Industrial	US $ / GJ	0.23	0.31	0.50	0.87	1.05	1.25	1.57	1.80	2.32	3.20	3.43	2.49	2.51
	Percent	*10%*	*13%*	*21%*	*37%*	*45%*	*53%*	*67%*	*77%*	*99%*	*137%*	*147%*	*107%*	*108%*
Commercial	US $ / GJ	0.28	0.36	0.60	1.03	1.25	1.48	1.86	2.13	2.74	3.79	4.06	2.95	2.97
	Percent	*6%*	*8%*	*13%*	*22%*	*27%*	*31%*	*39%*	*44%*	*56%*	*76%*	*81%*	*58%*	*58%*
Electric Power	US $/ GJ	0.27	0.35	0.57	0.99	1.20	1.42	1.79	2.06	2.64	3.65	3.91	2.84	2.86
	Percent	*12%*	*16%*	*26%*	*45%*	*55%*	*65%*	*81%*	*93%*	*120%*	*165%*	*176%*	*128%*	*128%*
Expenditure effects														
Residential	Million US $	74	76	113	178	198	189	197	209	221	230	66	-178	-211
	Percent	*6%*	*6%*	*9%*	*14%*	*15%*	*14%*	*14%*	*14%*	*15%*	*16%*	*5%*	*-12%*	*-14%*
Industrial	Million US $	228	292	417	740	786	851	1,025	1,037	1,259	1,453	1,165	643	859
	Percent	*7%*	*8%*	*13%*	*21%*	*22%*	*24%*	*28%*	*28%*	*34%*	*39%*	*31%*	*17%*	*22%*
Commercial	Million US $	14	17	25	41	44	45	52	51	59	72	51	5	5
	Percent	*5%*	*6%*	*9%*	*14%*	*15%*	*15%*	*17%*	*17%*	*20%*	*24%*	*17%*	*2%*	*1%*
Electric Power	Million US $	101	134	240	428	558	650	851	941	1,341	1,782	1,814	1,085	1,027
	Percent	*11%*	*13%*	*22%*	*36%*	*42%*	*47%*	*58%*	*63%*	*81%*	*106%*	*104%*	*64%*	*61%*
Transportation	Million US $	206	424	796	1,536	2,301	3,142	4,352	5,595	7,757	11,853	14,630	12,316	12,426
Total	Million US $	624	943	1,592	2,923	3,887	4,876	6,477	7,833	10,638	15,389	17,726	13,871	14,106
	Percent	11%	16%	27%	47%	60%	74%	95%	114%	149%	213%	242%	190%	193%

Table 1 (continued)

		2025	2026	2027	2028	2029	2030	2012-2030 Average	
Price effects									
Residential	US $ / GJ	5.80	5.90	6.00	6.12	6.26	6.26	4.51	
	Percent	*64%*	*64%*	*64%*	*65%*	*66%*	*65%*	*51%*	
Industrial	US $ / GJ	2.53	2.58	2.62	2.68	2.73	2.73	1.97	
	Percent	*109%*	*111%*	*113%*	*116%*	*119%*	*119%*	*84%*	
Commercial	US $ / GJ	3.00	3.05	3.10	3.17	3.24	3.24	2.33	
	Percent	*58%*	*58%*	*59%*	*59%*	*60%*	*60%*	*46%*	
Electric Power	US $/ GJ	2.89	2.94	2.99	3.05	3.12	3.12	2.24	
	Percent	*129%*	*131%*	*133%*	*135%*	*138%*	*137%*	*101%*	
Expenditure effects									2012-2030 Present Value
Residential	Million US $	-237	-257	-274	-226	-307	-329	-14	182
	Percent	*-16%*	*-17%*	*-18%*	*-14%*	*-20%*	*-22%*	*-0%*	
Industrial	Million US $	1,027	1,181	1,283	1,384	1,479	1,459	977	13,275
	Percent	*27%*	*31%*	*33%*	*36%*	*38%*	*38%*	*26%*	
Commercial	Million US $	4	4	5	5	7	6	27	409
	Percent	*1%*	*1%*	*2%*	*2%*	*2%*	*2%*	*9%*	
Electric Power	Million US $	1,012	1,014	832	846	799	761	853	11,662
	Percent	*60%*	*60%*	*54%*	*55%*	*53%*	*51%*	*55%*	
Transportation	Million US $	12,561	12,742	12,930	13,148	13,379	13,469	8,187	105,734
Total	Million US $	14,367	14,685	14,775	15,158	15,356	15,367	10,031	131,264
	Percent	196%	200%	205%	207%	214%	215%	140%	

Note(s): Present values are calculated as streams of expenditure differences discounted at a rate of 3%. They do not include the government outlays, changes in tax revenue, or implementation costs necessary for a complete Net Present Value calculation.

On a Btu basis, the magnitudes of the level terms are slightly larger. Conversion: 1$/GJ = 0.95$/MMBtu prices slightly from the levels shown in this scenario while explicit expenditures would increase slightly over the levels shown as non-captive consumers purchase the formerly captive biomass.

4.2. Scenario 2: Binding and enforced cellulosic biofuel sub-mandate with renewable portfolio standard

In the near term, a renewable portfolio standard enacted by the federal government is probably unlikely. However, an interesting application of this model would be to ask how such a policy might interact with the current RFS and what the combined effects might be for the U.S. biomass market.

The demand for biomass by the cellulosic ethanol industry is assumed to expand as it did in Scenario 1, and the additional demand for biomass by the electric power sector is assumed to expand based on the RPS requirements as proposed by ACES 2009. The renewable electricity requirements in that Act were set to grow from 6% in 2012 to 20% by 2020 and remain at that level. Total electricity demand projections were taken from the EIA’s 2011Annual Energy Outlook (U.S. Energy Information Administration 2011a). The RPS requirements were used to calculate how much electricity would be derived from renewable, and biomass was assumed to provide 30% of that total.

Table 2 presents the results of this scenario. The RPS places a bigger burden on biomass supplies as the competition intensifies between electricity providers and cellulosic ethanol producers. This leads to much stronger price effects. In 2022, all the projected biomass prices are at least 100% higher than the baseline values. As before, the price effects moderate slightly in the long run.

Table 2. Biomass price and expenditure differences under binding cellulosic biofuel mandate and renewable portfolio standard relative to the baseline.

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Price effects														
Residential	US $ / GJ	3.03	1.33	4.97	3.60	7.35	5.55	9.97	8.13	12.91	12.72	13.30	11.47	11.61
	Percent	*39%*	*17%*	*62%*	*45%*	*90%*	*67%*	*119%*	*96%*	*150%*	*146%*	*151%*	*129%*	*129%*
Industrial	US $ / GJ	1.32	0.58	2.17	1.57	3.21	2.42	4.35	3.55	5.64	5.56	5.81	5.01	5.07
	Percent	*56%*	*25%*	*92%*	*67%*	*136%*	*103%*	*185%*	*151%*	*240%*	*237%*	*249%*	*215%*	*218%*
Commercial	US $ / GJ	1.57	0.69	2.57	1.86	3.80	2.87	5.15	4.21	6.67	6.57	6.88	5.93	6.00
	Percent	*35%*	*15%*	*56%*	*40%*	*81%*	*60%*	*107%*	*86%*	*136%*	*132%*	*137%*	*117%*	*117%*
Electric Power	US $/ GJ	1.51	0.66	2.47	1.80	3.66	2.76	4.97	4.05	6.43	6.33	6.63	5.71	5.78
	Percent	*70%*	*31%*	*114%*	*82%*	*168%*	*126%*	*226%*	*184%*	*291%*	*286%*	*298%*	*257%*	*259%*
Expenditure effects														
Residential	Million US $	394	85	404	142	365	43	75	-169	-331	-731	-1,062	-1,219	-1,317
	Percent	*30%*	*7%*	*32%*	*11%*	*27%*	*3%*	*5%*	*-12%*	*-23%*	*-50%*	*-72%*	*-82%*	*-89%*
Industrial	Million US $	1,094	315	1,265	651	1,152	428	544	-159	-783	-1,647	-2,110	-1,804	-1,437
	Percent	*35%*	*9%*	*38%*	*18%*	*33%*	*12%*	*15%*	*-4%*	*-21%*	*-44%*	*-56%*	*-47%*	*-38%*
Commercial	Million US $	77	21	96	45	97	38	74	14	18	-40	-80	-106	-112
	Percent	*27%*	*7%*	*33%*	*15%*	*33%*	*13%*	*25%*	*5%*	*6%*	*-13%*	*-26%*	*-35%*	*-36%*
Electric Power	Million US $	1,895	1,202	4,613	3,764	8,724	7,214	14,442	12,534	22,059	21,984	22,994	20,740	21,219
	Percent	*206%*	*121%*	*415%*	*318%*	*659%*	*525%*	*983%*	*838%*	*1328%*	*1303%*	*1323%*	*1224%*	*1268%*
Transportation	Million US $	293	468	1,258	1,873	3,754	4,168	7,443	7,952	13,288	16,895	20,660	18,736	19,002
Total	Million US $	3,752	2,090	7,637	6,475	14,092	11,891	22,578	20,172	34,251	36,462	40,402	36,346	37,356
	Percent	66%	35%	128%	103%	216%	180%	333%	292%	480%	505%	552%	498%	512%

Table 2 (continued)

		2025	2026	2027	2028	2029	2030	2012-2030 Average	2012-2030 Present Value
Price effects									
Residential	US $ / GJ	11.71	11.97	12.81	12.71	13.20	13.23	9.56	
	Percent	*128%*	*130%*	*137%*	*135%*	*138%*	*137%*	*108%*	
Industrial	US $ / GJ	5.12	5.23	5.60	5.55	5.77	5.78	4.17	
	Percent	*220%*	*225%*	*242%*	*240%*	*250%*	*251%*	*179%*	
Commercial	US $ / GJ	6.06	6.19	6.62	6.57	6.82	6.84	4.94	
	Percent	*117%*	*119%*	*126%*	*123%*	*127%*	*126%*	*98%*	
Electric Power	US $/ GJ	5.83	5.96	6.38	6.33	6.57	6.59	4.76	
	Percent	*261%*	*266%*	*284%*	*281%*	*291%*	*290%*	*214%*	
Expenditure effects									
Residential	Million US $	-1,398	-1,474	-1,503	-1,530	-1,513	-1,520	-645	-7,569
	Percent	*-94%*	*-98%*	*-100%*	*-95%*	*-100%*	*-100%*	*-42%*	
Industrial	Million US $	-1,145	-891	-843	-759	-659	-790	-399	-3,982
	Percent	*-30%*	*-23%*	*-22%*	*-20%*	*-17%*	*-21%*	*-10%*	
Commercial	Million US $	-116	-120	-125	-132	-135	-138	-33	-285
	Percent	*-38%*	*-39%*	*-40%*	*-42%*	*-43%*	*-44%*	*-10%*	
Electric Power	Million US $	21,624	22,253	23,881	24,012	25,050	25,455	16,087	211,834
	Percent	*1290%*	*1325%*	*1551%*	*1556%*	*1673%*	*1721%*	*1033%*	
Transportation	Million US $	19,239	19,646	20,728	20,734	21,426	21,602	12,588	162,057
Total	Million US $	38,203	39,414	42,139	42,324	44,168	44,610	27,598	362,058
	Percent	521%	536%	584%	579%	616%	623%	387%	

Note: Present values are calculated as streams of expenditure differences discounted at a rate of 3%. They do not include the government outlays, changes in tax revenue, or implementation costs necessary for a complete Net Present Value calculation.

On a Btu basis, the magnitudes of the level terms are slightly larger. Conversion: 1$/GJ = 0.95$/MMBtu

The biomass expenditure effects are a little more interesting. In the face of much higher biomass prices, residential, industrial, and commercial consumers reduce their demand enough to lower their overall expenditures. For a few of the later years the simulation suggests, somewhat implausibly, that residential biomass consumers are priced out of the market entirely. Biomass expenditures by the electric power sector are much higher than before as a result of the RPS requirements. [6]

4.3. Supply elasticity sensitivity analysis

The results of any shock to this particular model may be very dependent on how quickly biomass supply can adjust to the price signals. One of the key assumptions in this study relates to the short- and long-run own-price elasticity of biomass supply. For the baseline projection and the previous scenario analysis, a short-run supply elasticity of 0.08 and a long-run elasticity of 0.8 have been assumed. Intuitively, it seems that biomass supply would be inelastic in the short-run as energy crop acres would be fixed in a given year and the time to collect and process other forms of biomass could be lengthy. In the long-run, however, the supply should be relatively more elastic. Quantities of biomass supplied should be more responsive to price signals when producers are given enough time to adjust energy crop planting and biomass collection decisions. There are few examples in the literature of estimated biomass supply elasticities. The uncertainty regarding the appropriate magnitude of supply elasticities assumed in this study implies an uncertainty in the price and expenditure effects that are estimated. A sensitivity analysis, in which the supply elasticities are varied over a range of plausible levels and

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[6] Again assuming cellulosic ethanol yields are 75% of the theoretical value, the average price effects are 17-36 percentage points higher. The average expenditure effects are 7-14 percentage points lower for residential, industrial, and commercial sectors, and 137 percentage points higher for the electric power sector.

the effects re-estimated, will alleviate some of this uncertainty by showing how those effects change as the assumed elasticities change.

To perform this sensitivity analysis, a set of high, medium, and low supply elasticity levels is selected. The medium level corresponds to the assumptions made for the previous two scenarios. A short-run elasticity of 0.12 is used for the high level, and a short-run elasticity of 0.06 is used for the low level. In each case, the long-run elasticity is assumed to be ten times larger than the short-run level. The demand shocks in this case are the same as in Scenario 1. Only the RFS requirements are imposed. This analysis focuses on the 2012-2030 present value of changes in total explicit expenditures relative to the baseline. In order to isolate the effects of the elasticities, the model is calibrated to the same baseline before imposing the shock.

Under the lowest elasticity assumption, the present value of the change in biomass expenditures is about $138 billion. As the assumed supply elasticity is increased, biomass supplies respond more to price signals. This results in smaller price effects relative to scenarios in which the supply elasticity is lower. The biomass expenditure effects and their present values relative to the baseline decrease slightly as the supply elasticity increases. In the highest elasticity case, the present value of the change in expenditures is $122 billion. This sensitivity analysis suggests that the results of this particular model are somewhat sensitive to the assumed supply elasticity.

5. Conclusion

A partial equilibrium, structural model of U.S. biomass supply and demand is developed and utilized in this study. The purpose is to examine the potential biomass price and quantity effects of the current cellulosic biofuel sub-mandate as defined in

EISA 2007 and the potential combination of the RFS and an RPS. First, the model was used to estimate a baseline projection of sector biomass demands, price, and biomass supply through the year 2030. Next, demand shocks representing the cellulosic sub-mandate and potential RPS were applied to the model and new projections were then estimated. The policy effects were estimated by comparing the results to the reference baseline. Finally, a supply elasticity sensitivity analysis was performed in which the assumed supply elasticity was varied over a range of plausible values, and the projections were compared to a common baseline.

In the first scenario, the binding cellulosic biofuel sub-mandate had fairly substantial biomass price and expenditure effects in the medium-term future. The effects were more moderate in the early periods of the projection when the mandate requirements are still low. As the mandated quantities increase, the competition between cellulosic ethanol producers and the other biomass demand sectors drives up biomass prices quickly. In the longer term, consumers adjust by shifting toward more competitive energy sources such as coal and natural gas. As a result, the effects revert to the more moderate levels. The results of the second scenario, which includes RPS requirements in addition to the RFS, follow the same logic. More competition between electricity providers and biofuel producers drives up biomass prices even further.

The sensitivity analysis indicates that the results are somewhat sensitive to the biomass supply elasticity. At higher elasticities biomass supply is more responsive, so the average biomass price and expenditure effects are slightly smaller. Doubling the supply elasticity assumption from the lowest to highest elasticity in this case results in a range of total expenditure present values ranging from $138 billion to $122 billion.

There are, of course, many limitations to this work. The most pressing concern is the use of limited historical biomass market data to try and project what will happen in the future. The domestic biomass market has undergone major changes in the recent past, and it is expected to undergo more changes in the future. Another issue relates to the final two years of available data, 2008 and 2009. Very high energy prices occurred in 2008, and those for biomass were no exception. However, the financial crisis and resulting recession caused a very rapid decline in both demand and prices in 2009. Simulations that use such volatile data as starting points can be somewhat unreliable. Among other factors, the speed at which the economy recovers will have a definite impact on the effects in the latter periods. Furthermore, the estimations in this model are not perfect, and more work needs to be performed to identify better supply elasticity estimates in particular.

However, there are few studies in the literature that analyze biomass supply and demand with a comprehensive structural model. Most studies in the past have looked only at particular demands or have tried to estimate biomass supply potentials for a given level of costs, and a few have gone so far as to examine how those supplies might be allocated to competing uses. This study aims to help bridge that gap in the literature. The result is a tool that can provide valuable, though imperfect, information to policymakers and other stakeholders in energy policy decisions.

Appendix

Table A.1 Variable names and descriptions

NAME	**DESCRIPTION**	**UNIT; SOURCE**
CRENRS	Expected net returns, corn	$/acre; FAPRI-MU Model
HAENRS	Expected net returns, hay	$/acre; FAPRI-MU Model
SBENRS	Expected net returns, soybeans	$/acre; FAPRI-MU Model
WHENRS	Expected net returns, wheat	$/acre; FAPRI-MU Model
DUM01	Dummy (1 if YEAR > 2000, 0 otherwise)	N/A; calculated
DUM09	Dummy (1 if YEAR = 2009, 0 otherwise)	N/A; calculated
COM_C	Commercial biomass demand, captive	Trillion btu; EIA historical data
COM_NC	Commercial biomass demand, non-captive	Trillion btu; EIA historical data
ELEC	Electric Power biomass demand	Trillion btu; EIA historical data
EXPORT	Exports biomass demand	Trillion btu; US Intl. Trade Commission
IND_C	Industrial biomass demand, captive	Trillion btu; EIA historical data
IND_NC	Industrial biomass demand, non-captive	Trillion btu; EIA historical data
RES_C	Residential biomass demand, captive	Trillion btu; EIA historical data
RES_NC	Residential biomass demand, non-captive	Trillion btu; EIA historical data
TRANS	Cell. Ethanol Production biomass demand	Trillion btu; EIA historical data
BMPRICE_C	Commercial biomass price	$/MMbtu; EIA historical data
BMPRICE_E	Electric Power biomass price	$/MMbtu; EIA historical data
BMPRICE_I	Industrial biomass price	$/MMbtu; EIA historical data
BMPRICE_R	Residential biomass price	$/MMbtu; EIA historical data
PROD	Biomass production	Trillion btu; EIA historical data
IMPORTS	Biomass imports	Trillion btu; US Intl. Trade Commission
COM_EXP	Commercial biomass expenditures	Million $; calculated
ELEC_EXP	Electric power biomass expenditures	Million $; calculated
IND_EXP	Industrial biomass expenditures	Million $; calculated
RES_EXP	Residential biomass expenditures	Million $; calculated
TOT_EXP	Total biomass expenditures	Million $; calculated
NGPRICE_I	Industrial natural gas price	$/MMbtu; EIA historical data
NGPRICE_R	Residential natural gas price	$/MMbtu; EIA historical data
PPI	Producer price index (1983 = Base)	Index; FAPRI-MU Model
CONSEXP	Real consumer expenditures	Million $; FAPRI-MU Model
ELPRICE_R	Residential electricity price	Cents per kilowatthour; EIA historical data
ELPRICE_C	Commercial electricity price	Cents per kilowatthour; EIA historical data
ELPRICE_I	Industrial electricity price	Cents per kilowatthour; EIA historical data
CLPRICE	Bituminous coal price	$/MMbtu; EIA historical data
YEAR	Year of observation	N/A; calculated

List of Equations

$$\begin{aligned}\text{PROD} = {} & \text{Intercept} \\ & + \beta 1 * (\text{BMPRICE\_I/PPI}) \\ & + \beta 2 * (\ (\text{CRENRS/PPI}) ** (-0.05) \\ & \qquad * (\text{HAENRS/PPI}) ** (-0.15) \\ & \qquad * (\text{SBENRS/PPI}) ** (-0.05) \\ & \qquad * (\text{WHENRS/PPI}) ** (-0.10)\ ) \\ & + \beta 3 * \text{DUM01} \\ & + \beta 4 * \text{DUM09} \\ & + \beta 5 * \text{lag(PROD)}\end{aligned} \tag{1}$$

$$\begin{aligned}\ln(\text{RES\_C}) = {} & \text{Intercept} \\ & + \beta 1 * \ln(\text{YEAR} - 1970) \\ & + \beta 2 * \text{DUM01}\end{aligned} \tag{2}$$

$$\begin{aligned}\text{RES\_NC} = {} & \text{Intercept} \\ & + \beta 1 * (\text{BMPRICE\_R/ELPRICE\_R}) \\ & + \beta 2 * (\text{BMPRICE\_R/NGPRICE\_R}) \\ & + \beta 3 * (\text{CONSEXP}) \\ & + \beta 4 * \text{DUM01} \\ & + \beta 5 * \text{lag(RES\_NC)} \\ & + \beta 6 * (\text{YEAR}-1970)\end{aligned} \tag{3}$$

$$\begin{aligned}\ln(\text{COM\_C}) = {} & \text{Intercept} \\ & + \beta 1 * \log(\text{YEAR} - 1970) \\ & + \beta 2 * \text{DUM01}\end{aligned} \tag{4}$$

$$\begin{aligned}\text{COM\_NC} = {} & \text{Intercept} \\ & + \beta 1 * (\text{BMPRICE\_C/ELPRICE\_C}) \\ & + \beta 2 * \text{lag(COM\_NC)} \\ & + \beta 3 * (\text{CONSEXP}) \\ & + \beta 4 * \text{DUM01}\end{aligned} \tag{5}$$

$$\begin{aligned}\ln(\text{IND\_C}) = {} & \text{Intercept} \\ & + \beta 1 * \ln(\text{YEAR} - 1970) \\ & + \beta 2 * \text{DUM01} \\ & + \beta 3 * \text{DUM09}\end{aligned} \tag{6}$$

$$\begin{aligned}\text{IND\_NC} = {} & \text{Intercept} \\ & + \beta 1 * (\text{BMPRICE\_I/CLPRICE}) \\ & + \beta 2 * (\text{BMPRICE\_I/NGPRICE\_I}) \\ & + \beta 3 * \text{lag(IND\_NC)} \\ & + \beta 4 * (\text{CONSEXP}) \\ & + \beta 5 * \text{DUM01} \\ & + \beta 6 * \text{DUM09}\end{aligned} \tag{7}$$

$$\begin{aligned}\text{ELEC} = {} & \text{Intercept} \\ & + \beta 1 * (\text{BMPRICE\_E/CLPRICE}) \\ & + \beta 2 * (\text{CONSEXP}) \\ & + \beta 3 * \text{lag(ELEC)} \\ & + \beta 4 * \text{DUM01}\end{aligned} \tag{8}$$

$$\text{Market Clearing ID} = \text{RES\_C} + \text{RES\_NC} \tag{9}$$

+ COM_C + COM_NC
+ IND_C + IND_NC
+ ELEC
+ TRANS
+ EXPORT
- PROD
- IMPORT

BMPRICE_R = Intercept (10)
+ β1 * BMPRICE_I
+ β2 * (YEAR - 1970)

BMPRICE_C = Intercept (11)
+ β1 *BMPRICE_I
+ β2 *(YEAR - 1970)

BMPRICE_E = Intercept (12)
+ β1 *BMPRICE_I
+ β2 *(YEAR - 1970)

Table A.2 Historical data summary

NAME	**1971-80 avg.**	**1981-90 avg.**	**1991-2000 avg.**	**2001-09 avg.**
COM_C	7.59	28.03	68.76	46.26
COM_NC	2.63	11.07	45.68	55.10
ELEC	3.56	62.79	426.17	402.25
EXPORT	.	0.00	1.10	2.48
IND_C	966.30	1303.87	555.76	370.40
IND_NC	278.33	496.06	1214.53	1165.90
RES_C	381.11	660.46	281.35	235.17
RES_NC	132.05	238.52	220.20	175.15
TRANS	0.00	0.00	0.00	0.00
BMPRICE_C	1.48	3.32	2.49	4.37
BMPRICE_E	1.04	0.87	0.67	2.14
BMPRICE_I	1.60	1.55	1.18	2.32
BMPRICE_R	1.48	3.43	3.20	6.75
PROD	1771.58	2800.79	2813.54	2452.70
COM_EXP	4.64	34.31	112.67	243.54
ELEC_EXP	3.91	30.23	288.63	875.07
IND_EXP	446.97	711.47	1437.85	2711.52
RES_EXP	223.93	819.77	704.10	1192.86
TOT_EXP	679.45	1595.77	2543.25	5023.00
IMPORT	.	0.70	3.89	7.48

Table A.3 Parameter estimates

EQUATION	**VARIABLE NAME**	**COEFFICIENT ESTIMATE**
PROD	Intercept	389.02
	(BMPRICE_I/PPI)	*280*
	EXPECTED REALNET RETURNS	-851.91
	DUM01	-165.79*
	DUM09	-138.58
	Lag(PROD)	*0.80*
RES_C	Intercept	5.93**
	(YEAR-1970)	0.03
	DUM01	-0.57**
RES_NC	Intercept	57.24
	(BMPRICE_R/ELPRICE_R)	*-30*
	(BMPRICE_R/NGPRICE_R)	*-25*
	CONSEXP	0.022
	(YEAR-1970)	-3.88
	DUM01	-3.76
	Lag(RES_NC)	0.78**
COM_C	Intercept	0.47
	(YEAR-1970)	1.07**
	DUM01	-0.42*
COM_NC	Intercept	-3.30
	(BMPRICE_C/ELPRICE_C)	-19.86
	Lag(COM_NC)	0.72**
	CONSEXP	0.0049*
	DUM01	-3.32
IND_C	Intercept	7.15**
	(YEAR-1970)	-0.15
	DUM01	-0.75**
	DUM09	0.36
IND_NC	Intercept	3.11
	(BMPRICE_I/CLPRICE)	*-247.26*
	(BMPRICE_I/NGPRICE_I)	*-100*
	Lag(IND_NC)	0.58**
	CONSEXP	0.16*
	DUM01	-190.25
	DUM09	-464.00**
ELEC	Intercept	-68.26
	(BMPRICE_E/CLPRICE)	-42.04
	CONSEXP	0.04
	Lag(ELEC)	0.82**
	DUM01	-51.62
BMPRICE_R	Intercept	-2.55**
	BMPRICE_I	2.29**
	(YEAR-1970)	0.12**

BMPRICE_C	Intercept	-0.26
	BMPRICE_I	1.18**
	(YEAR-1970)	0.06**
BMPRICE_E	Intercept	-0.95**
	BMPRICE_I	1.14**
	(YEAR-1970)	0.011**
*: Statistically siginificant at 0.05 level **: Statistically significant at 0.01 level Note: Italics indicate assumed values		

Table A.4 Elasticity estimates

NAME	**With Respect To**	**VALUE**	
		Short Run	Long Run
Commercial Biomass Demand	Commercial Biomass Price	-0.179	-0.646
	Commercial Electricity Price	0.179	0.646
	US Income	0.583	2.108
Electric Power Biomass Demand	Electric Power Biomass Price	-0.121	-0.681
	Electric Power Coal Price	0.121	0.681
	US Income	0.586	3.294
Industrial Biomass Demand	Industrial Biomass Price	-0.305[a]	-0.719
	Industrial Coal Price	0.275[a]	0.648
	Industrial Natural Gas Price	0.030[a]	0.070
	US Income	0.897	2.116
Residential Biomass Demand	Residential Biomass Price	-0.125[a]	-0.565
	Residential Electricity Price	0.040[a]	0.181
	Residential Natural Gas Price	0.085[a]	0.384
	US Income	0.787	-3.569
Biomass Supply	Industrial Biomass Price	0.081[a]	0.812[a]

[a]: Assumed values

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THE ROLE OF CAFE STANDARDS AND ALTERNATIVE-FUEL VEHICLE PRODUCTION INCENTIVES IN THE U.S. BIOFUELS MARKET

1. Introduction

The role of the U.S. government in supporting biofuels has been a source of heated debate in recent years. Taken together, the passage of both the Energy Policy Act (EPACT) of 2005 (PL 109-58) and the Energy Independence and Security Act (EISA) of 2007 (PL 110-140) marked a turning point in biofuels policy. The Renewable Fuel Standard (RFS) that these two acts created affects the biofuels industry by requiring fuel blenders to meet or exceed biofuel use mandates that are increasing each year to 2022. Other forms of direct government intervention in biofuels markets have included tax credits for both ethanol and biodiesel producers, tariffs on imported ethanol, and additional support for cellulosic ethanol producers. In light of these policies, an extensive volume of research developed to investigate their effects, and the general impacts of a larger biofuels market. Some authors focus on broad topics such as social welfare (de Gorter and Just 2009) while others focus more narrowly on individual market impacts (Du and Hayes 2009; Thompson, Whistance, and Meyer 2011; Whistance and Thompson 2010). One result from the market analysis literature is that the rising biofuel mandate must be reconciled with the limits of ethanol use in current motor fuel use. Expansion beyond the market for E10, fuel with 10% ethanol, requires more ethanol to be used in high-blend fuels, like E85, with up to 85% ethanol, that can only be used by flex fuel vehicles.

There are other government policies that affect the biofuel industry less directly. This study primarily focuses on the Corporate Average Fuel Economy (CAFE) standards and the alternative fuel vehicle (AFV) production incentives contained within the Alternative Motor Fuel Act (AMFA). In particular, we look at how changes in the fuel economy standards might shape future motor fuel demand, and thus biofuel demand, in the U.S. Furthermore, we investigate how changes in AFV incentives, in conjunction with the CAFE standards themselves, might also affect biofuel demand in the U.S. Finally, we trace out how these effects interact with biofuel use mandates of the RFS.

We develop and utilize a structural, partial-equilibrium model of the light-duty vehicle sector in the U.S. and link it to existing models of the petroleum/petroleum products market and the biofuels market. We use the full model to simulate a forward-looking baseline path for these markets assuming all current policies (i.e. RFS, CAFE, AMFA incentives) remain in place and are enforced. Comparing the baseline to counterfactual scenarios, in which the CAFE and AFV policies are modified, estimates the effects those policies can have over the baseline period.

This study is valuable because it sheds light on an often overlooked set of policies as they relate to the biofuel industry and biofuel policy. The CAFE standards are set to become much more stringent over the next decade and beyond, and the AMFA credits for flexible fuel vehicles (FFV) capable of using high-level blends of gasoline and ethanol such as E85 are to be phased out by 2020. This research provides information regarding these policy effects that is both timely and relevant to policymakers and other interested stakeholders in the transportation and biofuels industries.

2. Background

In this section, we provide a brief overview of the CAFE standards as well as the AMFA credits. Then, we highlight some of the previous studies that have focused on these policies, their effects in the transportation sector, and, in the case of a few select studies, the relationship between these policies and other biofuel-related policies.

The Energy Policy and Conservation Act (EPCA), passed in 1975 (PL 94-163), contained the original set of CAFE standards. In the wake of the first major oil price shock in the U.S., the standards were viewed as a stepping stone toward domestic energy security in addition to other environmental goals. The EPCA called for new, light-duty passenger vehicles to achieve an average fuel economy of 18 miles/gallon (mpg) by 1978. Beginning in 1982, light-duty cars and light-duty trucks were treated separately. Each type of vehicle had its own fuel economy targets to reach, with the targets for light-duty trucks less stringent. The required standards for model year 2011 vehicles were approximately 30 and 24 mpg for passenger cars and light-duty trucks, respectively (National Highway Transportation Safety Administration 2012c). Projected standards for model years 2016 and 2025 are 38 and 56 mpg for passenger cars and 29 and 40 mpg for light-duty trucks (National Highway Transportation Safety Administration 2010, 2012a). Manufacturers that fail to comply with the CAFE standards face a fine that is a function of both the number of vehicles sold and the margin by which the manufacturer fails to meet the standard. The original fine in EPCA was $50 per vehicle sold from that model year per mpg below the standard, but in 1997 that amount was raised to $55 (U.S. Government Accountability Office 2007).

The Alternative Motor Fuel Act (AMFA), passed in 1988, set the stage for many of the biofuel policies currently in place (PL 100-494). AMFA created incentives for automobile manufacturers to produce AFVs that would, in turn, lead to the widespread adoption of alternative fuels. The primary incentive allowed auto manufacturers to use an adjustment factor of 0.15 in determining their actual CAFE for the model year. For example, the fuel economy for an FFV using E85, MPG_{FFV} , would be calculated as:

$$MPG_{FFV} = 1/\left(\left(0.5/MPG_{gas}\right) + 0.5/(MPG_{E85}/0.15)\right) \tag{1}$$

where MPG_{gas} is the mileage if running on gasoline fuel (with no ethanol) and MPG_{E85} is the mileage if running on E85. The formula assumes that E85 and gasoline are each used half the time. The key factor is the division of E85 mileage by 0.15. The calculation assumes one gallon of E85 is equivalent to 0.15 gallons of gasoline, so essentially the ethanol used is not counted in the calculation. The adjustment factor effectively increases the fuel economy of the FFV while operating with the alternative fuel by a factor of 6.67. However, this adjustment is applied only to those model lines that have alternative fuel versions. The manufacturer's overall CAFE is a share-weighted harmonic average of all model lines, so the positive effect of the adjustment is muted somewhat. Manufacturers can claim a maximum credit resulting from this adjustment of 1.2 mpg to apply toward their overall CAFE for the model year.

Of these two policies, the CAFE standards seem to have garnered more attention in the academic literature. There are numerous studies that investigate the impact of CAFE standards on social welfare. At face value, the ambition of CAFE standards is to improve social welfare through reduced fuel consumption and greenhouse gas emissions. The actual welfare effects, however, are debated. Some studies have reached the conclusion that tighter CAFE standards result in reduced social welfare, mostly at the expense of consumers (Austin and Dinan 2005; Kleit 2004; Small 2012).

Such conclusions might stem from the unintended consequences of the CAFE standards that run counter to the original goals. The so-called "rebound effect" of CAFE standards is a prime example. The rebound effect is defined as the "fraction of fuel savings expected to result from an increase in fuel efficiency…that is offset by additional vehicle use" (NHTSA, 2010 p. 364). In other words, as CAFE standards reduce fuel consumption through better fuel economy they also reduce the cost of driving on a per-mile basis. That, in turn, increases the demand for vehicle travel which results in a smaller reduction in overall fuel consumption. Other externalities related to traffic safety, congestion costs, and air pollution might also arise from the rebound effect (Parry, Walls, and Winston 2007; Portney et al. 2003).

The rebound effect, as it relates directly to overall fuel consumption, is also relevant in a structural model such as the one developed in this study. There are several studies that have examined the effect more closely. In light of the definition above, the rebound effect is measured as the elasticity of vehicle miles traveled (Vmt) with respect to driving cost per mile multiplied by a factor of -1 (Small and Dender 2007). The rebound effect is, thus, expressed as the percent *increase* in Vmt for a given *decrease* in driving cost per mile. Most empirical studies have estimated rebound effects in the range of 10% to 30%. (Hymel, Small, and Dender 2010; National Highway Transportation Safety Administration 2010; Small and Dender 2007).

CAFE standards, the rebound effect, the flexibility provisions provided by AMFA, and biofuel policies such as the RFS are all interrelated. The interactions between them have received only minimal attention in the literature to this point. An important finding from this line of study is that the interactions among the policies might tend to reduce their overall effectiveness. The AMFA credits that can be applied toward meeting the CAFE standards have resulted in more AFVs being produced, but they can limit the effectiveness of CAFE standards by allowing auto manufacturers to produce vehicles that are more fuel *inefficient* than the standards would otherwise allow. (Collantes 2008; Liu and Helfand 2009).

As they relate to the RFS, tighter CAFE standards reduce overall fuel consumption and make it more difficult to meet the RFS requirements without an increase in the adoption of higher-level ethanol blends. At the same time, the AMFA credits are being phased out as part of EISA 2007 and with them go one incentive to produce FFVs capable of using such high-level blends. Thus, the problem of getting through the ethanol “blend wall”, the anticipated inelastic portion of the demand curve when E10 market is saturated and further expansion requires low enough prices to coax consumers to buy high-blend fuels, might only be exacerbated by tighter CAFE standards and reduced AMFA credits.

3. Methods

3.1. Conceptual framework

The model in this study consists of four related modules. Three of them form a structural, partial equilibrium model of the U.S. and international petroleum, petroleum products, and biofuels markets. They have been used in prior research to study the greenhouse gas consequences of U.S. biofuel policies (Thompson, Whistance, and Meyer 2011). The other module was developed as part of this analysis to enrich the petroleum modules and create an overall structural, partial equilibrium model of petroleum and biofuels markets to estimate the effects of transportation policies, such as CAFE standards and AMFA FFV production incentives. Similar approaches have been used to estimate the effects of U.S. biofuel and energy policies on domestic natural gas markets as well as domestic biomass markets (Whistance 2012; Whistance and Thompson 2010; Whistance, Thompson, and Meyer 2010).

The core of the CAFE module resembles the system of equations developed by Small and Van Dender (2007). It comprises three equations to estimate the average fuel economy of light-duty vehicles (MPGLDV), the miles traveled per licensed driver (VMTLDV), and the stock of light-duty vehicles per licensed driver (LDVTOT). The equations are represented as follows:

$$MPGLDV_t = f(Pgas_t, VMTLDV_t, Income_t, CAFEcom_t, Trend_t, MPGLDV_{t-1}) \quad (2)$$

$$LDVTOT_t = f(Pgas_t/MPGLDV_t, Pcar_t, Income_t, Trend_t, LDVTOT_{t-1}) \quad (3)$$

$$VMTLDV_t = f(Pgas_t/MPGLDV_t, LDVTOT_t, Income_t, Trend_t, VMTLDV_{t-1}) \quad (4)$$

where Pgas is the real price of gasoline, the ratio of Pgas to MPGLDV is the real cost of driving on a per mile basis, Pcar is the real price of a new car, Income is the average consumer expenditures per licensed driver, CAFEcom is a moving average of the current and 5 lagged CAFE standards, and Trend is a standard time trend. Dividing the result of equation 4 by the result of equation 2 provides an estimate of overall fuel use by light duty vehicles (FUELLDV), which is the primary link to the petroleum and petroleum product modules.

To make that connection, FUELLDV is disaggregated into the LDV demands for gasoline, diesel, and E85. This study assumes the amount of each type of LDV fuel demand is proportional to the estimated share of that type of vehicle in the overall stock of LDVs. An obvious criticism of this assumption is that it would break down when applied to FFVs. E85 is consumed at a much lower rate than the number of FFVs would indicate. This model tries to account for that issue by estimating the market penetration rate of E85, which is used to estimate actual E85 consumption. The remaining portion of fuel consumed by FFVs is then added to light-duty gasoline consumption.

The biofuels market is represented by an updated and much simplified version of the FAPRI-MU biofuels model (FAPRI-MU 2010). Here, the focus is on ethanol while biodiesel remains exogenous. The estimation of ethanol production differs from the FAPRI-MU version in that it does not rely on production capacity and capacity utilization. Rather, an ethanol supply curve is derived from the output of FAPRI-MU's stochastic baseline results (FAPRI-MU 2012). For each of the 500 stochastic model simulations over the ten-year baseline period, there are eleven observations of ethanol production, ethanol input prices, and ethanol output prices that can be used as data points. Ethanol production is estimated as a function of the wholesale ethanol price averaged over the current and previous three years, an index of natural gas prices, lagged production, and a time trend. This specification omits corn and distillers grains prices, the other two major input and output prices, but in a simulation scenario their effects are implicit.

There are three components of fuel ethanol consumption. Use of ethanol as a fuel additive is determined by the price of ethanol and the level of gasoline consumption by the transportation sector. The potential markets for both low-level and high-level blends are determined by the level of gasoline consumption and the flex fuel share of light-duty vehicles, respectively. In addition, a market penetration rate for each type of blend determines the actual level of use. The penetration rates depend on the relative prices of ethanol and gasoline.

In terms of both ethanol imports and exports, Brazil is a main trading partner for the U.S. The U.S. imports sugarcane-based ethanol from Brazil in order to help meet the RFS requirement for advanced biofuels. The U.S. also exports conventional ethanol to Brazil in order for Brazil to satisfy its own demand for ethanol. Although the Brazilian anhydrous-ethanol price is exogenous to this model, the relative prices of advanced and conventional ethanol to the Brazilian price determine U.S. ethanol imports and exports, respectively.

Renewable Identification Numbers (RINs) are tradable credits used by fuel blenders to show compliance with the RFS requirements. The FAPRI-MU biofuels model employs a set of equations to estimate RIN supply and demand. Those equations have been the basis for several previous studies that have examined the RIN markets more closely (Thompson, Meyer, and Westhoff 2009b, 2010, 2011). This model employs the same general structure of the RIN markets, but biodiesel and cellulosic RINs are held exogenous. The two elements of the mandate that are endogenous are compliance with both the overall mandate for all qualifying biofuels, including ethanol made from corn starch (conventional ethanol), and the sub-mandate for advanced biofuels that includes imported sugarcane ethanol that meets a higher greenhouse gas reduction target. The RFS regulations contain provisions, such as RIN deficits and rollover, which allow blenders some flexibility in meeting the requirements each year, but those provisions are not considered in this study. Rather, the RFS requirements are modeled as perfectly inelastic lower bounds on domestic biofuel use.

RIN prices are an indicator of the degree to which the RFS mandates are binding. If market conditions are such that the equilibrium demand for ethanol in absence of the mandate is less than the mandated volume, then the mandate is considered binding. Blenders must use more ethanol than they would choose otherwise. To obtain that quantity, fuel blenders must pay a higher price to ethanol producers, and to sell that quantity, blenders must charge a lower price to retail customers. The difference between the two prices is the “core” RIN value excluding speculation and transactions costs (Thompson, Meyer, and Westhoff 2010). If the opposite is true and equilibrium ethanol demand is higher than the RFS requirement, the mandate is considered non-binding and the core RIN value is zero.

The domestic and international petroleum products modules remain unchanged, for the most part, from the previous version. The basic structure of the model is summarized in the flowchart (figure 1). The domestic petroleum model encompasses four markets: crude oil, gasoline, distillate fuel, and residual oil. U.S. crude oil is supplied through domestic production as well as imports and refining is the primary demand, although some stocks are held for both market and strategic purposes. The composite U.S. refiner’s acquisition price of crude oil clears this market.

Supply and demand are modeled separately for each of the three refined products as well. Supply is determined mostly from overall petroleum refining and the refining yields for the three products. The primary product demands are disaggregated into transportation and residual (i.e. residential, commercial, industrial, etc.) categories. In

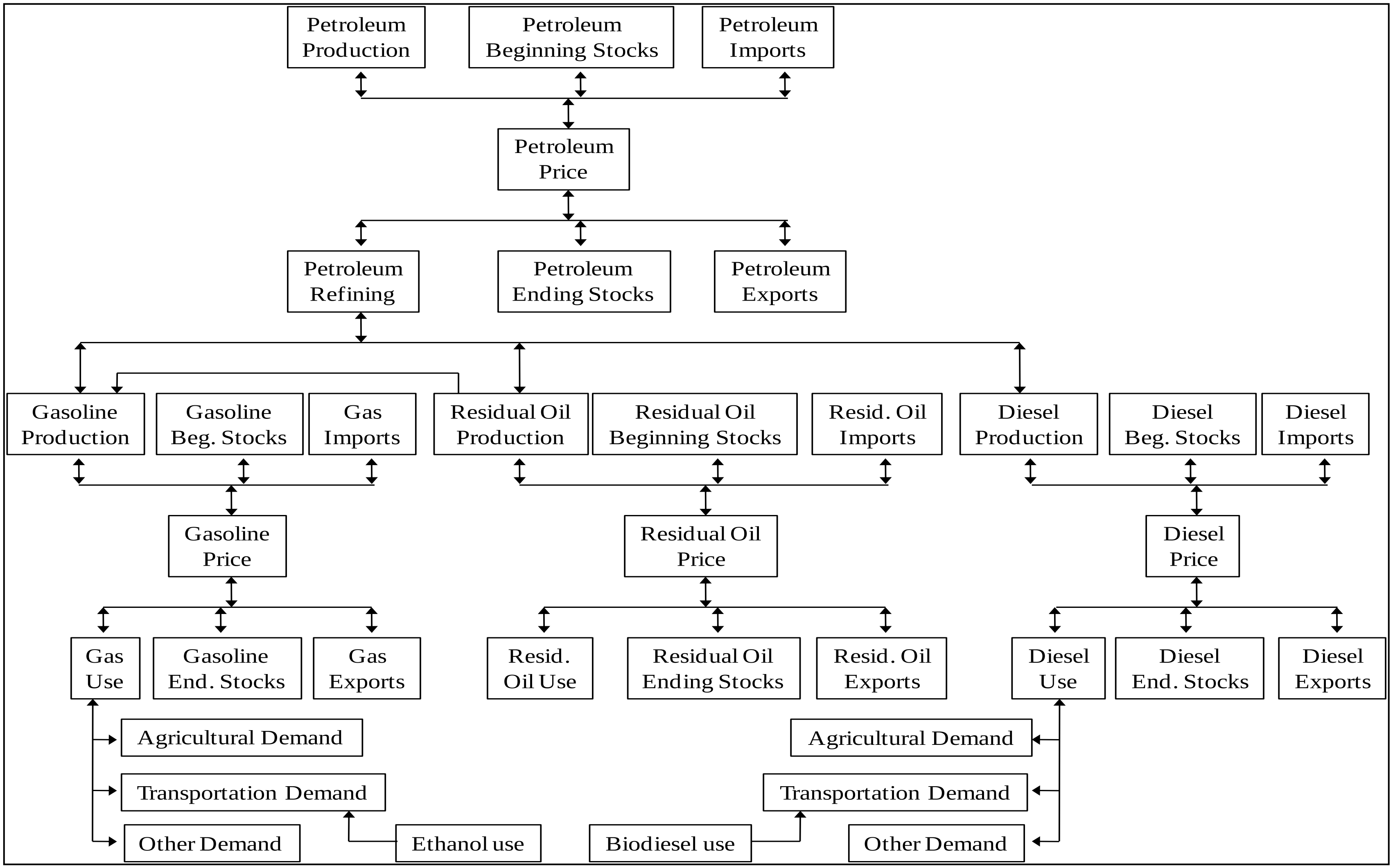

Figure 1. Flowchart depicting the domestic petroleum model structure
Source: Thompson et al. (2011)

addition, the demand for gasoline and distillate fuels is adjusted to include a separate category for agricultural purposes. Unlike Thompson et al. (2011), agricultural demand for petroleum products remains exogenous in this study. Another modification to this model relative to the previous version is the further disaggregation of the transportation demands for gasoline and distillate fuels into demand by LDVs, which is determined in the LDV module, and demand by other vehicles. Biofuel prices and quantities also play a role in petroleum product markets. Transportation demands for gasoline and distillate fuel include biofuel quantities on an energy equivalent basis, and their prices faced by consumers are share weighted averages of the biofuel and petroleum product prices, plus average federal and state level fuel taxes and the cost of mandate compliance (Thompson, Whistance, and Meyer 2011).The international petroleum module covers the same four markets and follows the same basic supply and demand structure. The domestic and international modules are connected through the trade equations for each product.

3.2. Data

Many of the historical data were obtained as part of the previous studies, and cover the period from 1970 to 2010. Sources for petroleum supply and use data include the Annual Energy Review published by the Energy Information Administration (EIA) and statistics published by the International Energy Agency (International Energy Agency 2012; U.S. Energy Information Administration 2012b). Data regarding LDVs for the same time period including fuel economy, vehicle miles traveled, and vehicle stock were obtained from the Highway Statistics series published by the Federal Highway Administration (U.S. Federal Highway Administration 2012).

The stock of LDVs per driver and the number of miles driven per driver show a steady, upward trend over the historical period, but miles traveled per driver increased at a faster rate. The average fuel economy of light-duty vehicles increased only slightly before the CAFE standards were enacted. After that, fuel economy rose steadily along with the CAFE requirements until the early 1990s. Along with the policy requirements, high oil prices and the high cost of driving, as a result, also contributed to the desire for greater fuel economy. The growth in average LDV fuel economy slowed in the late 1980's and early 1990's as the CAFE standards plateaued and cheaper oil made driving less costly. Fuel use increased in spite of higher fuel economy as drivers traveled more. The rebound effect from higher fuel economy may have played some role in increased travel, but low cost of driving for most of the period also played a role.

Automobile manufacturers in violation of CAFE standards must pay a penalty per vehicle sold per mpg they fall short of the standard. The penalty increased from $50 to $55 in 2001. The AMFA provisions allow automakers to reduce the potential fines they face by increasing their calculated CAFE up to 1.2 mpg through the production of FFVs. Thus, the 1.2 mpg credit has a value to auto manufacturers that can be expressed in terms of the penalty avoided per FFV sold. Various reports by the NHTSA and a report by the Departments of Transportation and Energy as well as the EPA provide the size of the credit, if any, claimed by automakers from 1993 to 2011 (National Highway Transportation Safety Administration 2001, 2002, 2012b; U.S. Department of Transportation, U.S. Department of Energy, and U.S. Environmental Protection Agency 2002). The gross monetary value of the credit per FFV sold is calculated each year from 1995 forward using vehicle sales data of the companies that claim the credit. In 2010, for example, the four automakers claiming at least some credit sold a combined 5 million vehicles in the U.S., of which 1.5 million were FFVs. The average credit claimed was approximately 1 mpg to be applied toward each company's calculated CAFE. The total potential fines that could have been collected had they fallen short of the requirement by the size of the credit claimed would have been:

$$\$55*(1 \text{ mpg credit})*(5 \text{ million vehicles sold}) = \$275 \text{ million} \tag{5}$$

and the value per FFV sold would have been :

$$\$275 \text{ million}/(1.5 \text{ million FFVs sold}) = \$183/\text{FFV sold} \tag{6}$$

This model uses the average gross value to try and capture the marginal effect of AMFA credits on FFV production. The gross value would be offset by the additional marginal cost of producing an FFV relative to a non-FFV, but those data were unavailable and could not be included in a calculation of the net value of the AMFA credit.

4. Results

This study investigates, in a forward looking manner, the potential market effects of CAFE standards and AMFA credits in two separate scenarios. Each scenario is compared to a baseline projection from the year 2011 to 2025. The baseline assumes current policies remain in place as they are written. The CAFE standards for the years 2017 to 2025, which were recently finalized, are considered current policy in the baseline. The AMFA credit is phased out by 2020 and the combined CAFE fuel economy requirement rises from 28 mpg to 50 mpg. The RFS is in effect although this model assumes the EPA exercises its authority to waive the cellulosic biofuel requirement each year. In the baseline, the overall and advanced mandates are binding in all years, as indicated by positive RIN prices. The baseline projection is calibrated to a side-case of the EIA's 2012

Table 1. Effects of holding combined CAFE standards constant at 26 miles per gallon, changes relative to the baseline

	2013	2016	2019	2022	2025	2012-2025 Average
Fuel economy of light duty vehicles, miles per gallon	-0.6	-2.2	-4.3	-6.7	-9.5	-4.3
Miles traveled by light duty vehicles, billion miles	-20	-89	-191	-305	-435	-190
Light duty vehicles, million vehicles	-0.4	-1.6	-3.5	-5.7	-8.1	-3.5
Gasoline share of light duty vehicles, percentage points	0.8	1.6	1.8	1.1	-0.4	1.2
Diesel share of light duty vehicles, percentage points	0.0	0.0	0.0	0.1	0.1	0.0
Flex-fuel share of light duty vehicles, percentage points	-0.8	-1.6	-1.8	-1.1	0.4	-1.2
Gasoline use by transportation sector, billion gallons*	2,834	9,546	17,104	24,711	33,102	16,141
Gasoline use by light duty vehicles, million gallons	2,976	9,731	17,421	25,452	34,058	16,514
Diesel use by transportation sector, million gallons	-29	-6.9	119	338	662	178
Diesel use by light duty vehicles, million gallons	23	150	397	744	1,218	446
Total ethanol disappearance, million gallons	105	936	1,952	2,994	4,069	1,878
E85 use, million gallons	-127	-124	-199	-567	-717	-261
Retail unleaded gasoline price, $/gallon	0.11	0.43	0.68	1.00	1.42	0.67
Retail diesel price, $/gallon	0.11	0.24	0.38	0.57	0.80	0.39
Implied retail ethanol price (conventional), $/gallon	0.80	0.98	1.23	1.28	1.34	1.14
Crude oil, refiners acquisition price, $/barrel	2.75	6.54	10.88	16.79	23.98	11.10
Conventional RIN price, $/RIN	-0.57	-0.32	-0.57	-0.61	-0.52	-0.48
Mandate compliance cost, billion dollars	-7.75	-5.64	-10.89	-11.81	-9.29	-8.53

*: For consistency, gasoline use by transportation sector matches the EIA definition which includes all fuel ethanol.

Annual Energy Outlook that also assumes the CAFE standards for 2017 to 2025 are in effect (U.S. Energy Information Administration 2012a).

In the first scenario, CAFE standards in the projection period are held constant at the 2010 level of 26 mpg. The AMFA credit is assumed to be phased out in this scenario. The estimated changes that occur relative to the baseline are summarized for the 15-year projection period (table 1). All else equal, this assumption reduces the incentive for automakers to pursue gains in fuel economy. In the absence of CAFE standards that grow over time, the growth in average fuel economy slows and more fuel is required by light-duty vehicles. The demand curves for gasoline, ethanol, and diesel shift out (i.e. to the right), and their equilibrium prices increase. Higher market prices induce greater production levels. An implication of higher gasoline and diesel production in the petroleum market is greater demand for crude oil and a higher refiner acquisition cost of oil.

The combination of lower average fuel economy and higher fuel prices increases the cost of driving on a per mile basis. As a result, there tend to be fewer cars per licensed driver and those drivers tend to travel fewer miles. The relative price changes, in conjunction with the lower fuel economy of FFVs relative to gasoline-powered vehicles, shift the mix of light-duty vehicles away from FFVs and toward gasoline-powered vehicles.

The interaction of CAFE standards with the RFS requirements occurs primarily through the shift in the blend-wall. Although the penetration rate of E85 falls, the penetration rate of low-level ethanol blends remains at nearly 100%. As fuel demand shifts out in the first scenario relative to the baseline, there is more room for E10 use to expand and help meet the rising RFS requirements. The expansion in the E10 market is enough to make the overall RFS mandate non-binding. Ethanol prices rise and, in response, ethanol production increases and ethanol exports decrease. Conventional RIN prices fall to zero as blenders have no trouble obtaining and submitting the requisite number of RINs to meet the total RFS mandate in each of the compliance years. The lower prices for advanced RINs show that the RFS requirement for advanced biofuels becomes less binding in this scenario. After 2015, the advanced RIN price falls to zero and indicates a non-binding advanced mandate. The cost of complying with the total mandate falls along with the falling RIN prices and, ignoring biodiesel and cellulosic compliance costs, is essentially zero when neither the advanced nor the overall mandate is binding.

In the second scenario, the CAFE standard rises as in the baseline, but the AMFA credit is no longer phased out as it is in the baseline. Beyond 2014, automakers are allowed to continue claiming a credit of up to 1.2 mpg to apply toward meeting the CAFE requirements. The extension of the AMFA credits effectively increases the potential fines automakers can avoid by producing and selling FFVs. The production of FFVs becomes more desirable and the FFV share of the total light-duty vehicle stock increases slightly at the expense of gasoline-powered vehicles (table 2). Because of the greater number of FFVs with the AMFA credit extension, the gasoline demand curve for light-duty vehicles is shifted back (i.e. to the left).

The expansion of FFVs increases the potential for E85 consumption and eases the blend-wall problem to a small extent, making the RFS requirement less binding. The small relative price movements of ethanol and gasoline imply the penetration rate of E85 remains virtually unchanged. E85 consumption increases a little. The third component of ethanol disappearance, use of ethanol as a voluntary fuel additive, declines enough to

Table 2. Effects of extending the AMFA credits, changes relative to the baseline

	2013	2016	2019	2022	2025	2015-2025 Average
Fuel economy of light duty vehicles, miles per gallon	0.0	0.0	0.0	0.0	0.0	0.0
Miles traveled by light duty vehicles, billion miles	0.0	0.0	0.1	0.0	-0.2	0.0
Light duty vehicles, million vehicles	0.0	0.0	0.0	0.0	0.0	0.0
Gasoline share of light duty vehicles, percentage points	0.0	-0.5	-2.2	-3.7	-3.8	-2.0
Diesel share of light duty vehicles, percentage points	0.0	0.0	0.0	0.0	0.0	0.0
Flex-fuel share of light duty vehicles, percentage points	0.0	0.5	2.2	3.7	3.8	2.0
Gasoline use by transportation sector, million gallons*	0.0	2.5	3.1	0.7	-8.1	0.4
Gasoline use by light duty vehicles, million gallons	0.0	-3.7	1.4	-1.8	-11.9	-8.3
Diesel use by transportation sector, million gallons	0.0	0.0	0.0	0.0	0.0	-0.1
Diesel use by light duty vehicles, million gallons	0.0	0.0	0.0	0.0	-0.2	-0.1
Total ethanol disappearance, million gallons	0.0	0.0	0.0	0.0	0.0	0.0
E85 use, million gallons	0.0	6.2	1.5	2.5	4.0	8.8
Retail unleaded gasoline price, $/gallon	0.00	-0.01	-0.00	-0.01	-0.01	-0.02
Retail diesel price, $/gallon	0.00	0.00	0.00	0.00	0.00	0.00
Implied retail ethanol price (conventional), $/gallon	0.00	0.07	0.02	0.04	0.03	0.11
Crude oil, refiners acquisition price, $/barrel	0.00	0.00	0.00	0.00	-0.01	0.00
Conventional RIN price, $/RIN	0.00	-0.08	-0.03	-0.03	-0.04	-0.13
Mandate compliance cost, billion dollars	0.0	-1.33	-0.48	-0.72	-0.68	-2.12

*: For consistency, gasoline use by transportation sector matches the EIA definition which includes all fuel ethanol.

offset most of the increases from E10 and E85. Total ethanol disappearance increases very slightly, and the lower prices for both conventional and advanced RINs indicate the mandate is less binding than in the baseline. As blenders face lower compliance costs, the savings are passed on to gasoline consumers in the form of slightly lower retail prices. The lower retail price boosts total motor gasoline demand by a fraction of a percent.

5. Sensitivity analysis

A key uncertainty in this study is the responsiveness of automakers to the AMFA credits. The credits should make the production of FFVs more desirable to automakers. Thus, the marginal effect of AMFA credits on FFV share is expected to be positive. The magnitude of that effect is less clear. While there are many studies that have investigated the relationship between vehicle choice at both the producer and consumer level, there are few empirical studies that have examined behavior in light of the AMFA credits, specifically. One such study estimated that AMFA credits would be responsible for one-half of the alternative-fueled vehicles sold in the following decade (Rubin and Leiby 2000). Given the extent to which the biofuel and auto industries have changed since that paper was published, it is unclear whether or not the same relationship would still hold. Moreover, this study focuses on the *share* of FFVs within the light-duty vehicle stock. The relationship found by Rubin and Leiby is somewhat less applicable to this representation as vehicle sales and scrappage are implicit.

As the model was being developed, the marginal effect of AMFA credits on FFV share was estimated to be negative. Although steps were taken to minimize omitted variable bias, data availability was limited. The small sample made it difficult to identify and correct for all the potential bias. The coefficient was restricted to a level of 0.002 for an elasticity of approximately 0.2.[7] In other words, a 10% increase in the potential penalty avoided by claiming the credit would increase the share of FFVs by 2.0%[8]. The rest of this section discusses how the results of an AMFA credit extension might differ if the FFV share with respect to potential penalty avoided is more or less responsive to the credit value.

The sensitivity analysis tested two alternative elasticity assumptions. The elasticity in the first test, relative to the baseline, was assumed to be lower by a factor of 10, so a 10% increase in the potential penalty avoided would increase FFV share by 0.2%. In the second test, the elasticity was assumed to be higher by a factor of 3.5 relative to the baseline, so a 10% increase in the potential penalty avoided would increase FFV share by 7%. In each case, the model was calibrated to a common baseline in which AMFA credits were phased out. Each model was then run with the AMFA credit extension in place. The results comparing the differences of each scenario relative to the common baseline are summarized for the 2015 to 2025 projection period (table 3).

The effects of extending the AMFA credits are muted in the low-elasticity scenario. Automakers respond only slightly to the increased incentive to produce FFVs. The response is strong enough to induce a very small increase in E85 consumption, which eases the blend-wall problem only slightly. On average the, the conventional RIN price falls by about $0.01 which equates to average yearly savings of approximately $169 million per year in mandate compliance costs.

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[7] The FFV share equation is estimated in log-level form with respect to the AMFA independent variable. The semi-elasticity is calculated as $\%\Delta y = 100*(\exp(0.002)-1)$ (Wooldridge 2006) .

[8] The shares are already measured in percentage terms, so a 10% increase in the avoided penalty would not increase the share by 2 percentage points (i.e. an increase from 10% to 12%). Rather, it would increase the share by 0.02*0.1 (i.e. 10% to 10.2%).

Table 3. Sensitivity of AMFA credit effects, 2015-2025 average changes relative to the baseline

	Low (ε=0.02)	Base (ε=0.2)	High (ε=0.7)
Gasoline share of light duty vehicles, percentage points	0.0	-2.0	-5.0
Flex-fuel share of light duty vehicles, percentage points	0.0	2.0	5.0
Gasoline use by transportation sector, million gallons	0.0	0.4	3.8
Gasoline use by light duty vehicles, million gallons	-0.8	-8.3	-21
Total ethanol disappearance, million gallons	0.0	0.0	2.2
E85 use, million gallons	0.8	8.8	25
Retail unleaded gasoline price, $/gallon	0.00	-0.02	-0.05
Implied retail ethanol price (conventional), $/gallon	0.01	0.11	0.28
Conventional RIN price, $/RIN	-0.01	-0.13	-0.33
Mandate compliance cost, billion dollars	-0.17	-2.12	-5.57

*: For consistency, gasoline use by transportation sector matches the EIA definition which includes all fuel ethanol.

If the elasticity is higher than in the base case, the effects of extending the AMFA credits become more pronounced. The share of FFVs increases by a larger amount, on average, in response to the AMFA incentives. The use of ethanol in the form of both low- and high-level blends increases enough to render the overall RFS requirement much less binding, with the conventional RIN price falling by an average of $0.33/RIN. Mandate compliance costs are substantially reduced during this period.

6. Conclusions

The findings suggest there are some notable relationships between transportation and biofuel policies. The CAFE standards, as they currently are written, will play a large role in determining the amount of fuel consumed by light-duty vehicles in the future. Vehicles with better fuel economy will tend to consume less fuel, both renewable and non-renewable, even after the rebound effect is taken into account. At the same time, the RFS requires increasing amounts of renewable fuels to be used. In the baseline projection, in which the CAFE standards and RFS mandates are in full effect, the requirements of both policies are met. The mandate compliance costs indicate, in part, the cost borne by consumers to achieve those results. Holding the CAFE standards constant at the 2010 level appears to relax the blend-wall constraint, looking forward, as fuel use expands relative to the baseline. The RFS requirements would be easier to achieve, in that case, as indicated by the reduced mandate compliance costs.

Alternative fueled vehicles, including flex-fuel vehicles capable of using E85, currently receive favorable treatment in the calculation of their fuel economy. Automakers that produce FFVs can take advantage of that favorable treatment by claiming AMFA credits to help meet the CAFE standards, subject to a 1.2 mpg limit that declines to zero by 2020 in the baseline. AMFA credits incentivize the production of FFVs, to some extent, by reducing the potential fines an auto manufacturer faces if it fails to meet the CAFE requirement. Under the assumed elasticity, an extension of the maximum AMFA credit limit of 1.2 mpg through the projection period makes it somewhat easier to meet the RFS requirements. However, the effects are quite small and the compliance costs are reduced only slightly when compared to the baseline. Higher and lower elasticity assumptions have the effect of magnifying and diminishing the effects of AMFA credit extension, respectively.

The results of this study are relevant in that they shed light on an often overlooked set of policy relationships. Although the results indicate the CAFE standards could have more of an impact on the degree to which the RFS requirements are binding than the

AMFA credits, there are uncertainties that still exist. The most prominent uncertainty relates to the response of automakers to the AMFA credit. The literature provides little indication of the appropriate magnitude of that elasticity, but the results of the sensitivity analysis show that the response matters. In addition, the model in this study takes a somewhat simplified view of biofuel and RIN markets. Biodiesel and cellulosic biofuels are not included in this study, and flexibility provisions in the RFS also are not considered. The resolution of these uncertainties remains an important extension along this line of research.

Appendix

Variable Definitions

AVDPEN	CAFE penalties avoided per FFV sold	dollars	Calculated
BDDDOM	Biodiesel consumption, MY	Million gallons	FAPRI-MU model, MY
BDDDOMCL	Biodiesel consumption, CY	Million gallons	FAPRI-MU model, CY calculated
BDDEXN	Biodiesel net exports, MY	Million gallons	FAPRI-MU model, MY
BDDEXNCL	Biodiesel net exports, CY	Million gallons	FAPRI-MU model, CY
BDDEXN_BASE	Base value of variable	See variable	See variable
BDEQV	Biodiesel equivalence factor		EISA 2007
BDPPLT	Biodiesel price, rack, CY	USD / gallon	FAPRI-MU model, rack, CY
BDPPLTM	Biodiesel price, rack, MY	USD / gallon	FAPRI-MU model, rack, MY
BDPREQ	Biodiesel retail price, MY	USD / gallon	FAPRI-MU model, MY
BDPREQCL	Biodiesel retail price, CY	USD / gallon	FAPRI-MU model, CY
BFPROD	Beef production	Million pounds	FAPRI-MU model, marketing year
BRSPRD	Barley production	Million bushels	FAPRI-MU model, marketing year
BDSPRDCL	Biodiesel production, CY	Million gallons	FAPRI-MU model, CY calculated
CARPI	New Car Price Index	1982-84=100	BLS
CKYPROD	Broiler production	Million pounds	FAPRI-MU model, marketing year
CRSPLT	Corn area planted	Thousand acres	FAPRI-MU model, marketing year
CRSPLT1	Corn area planted	Thousand acres	FAPRI-MU model, marketing year
CRSPRD	Corn production	Million bushels	FAPRI-MU model, marketing year
CTSPLT	Cotton area planted	Thousand acres	FAPRI-MU model, marketing year
CTSPLT1	Cotton area planted	Thousand acres	FAPRI-MU model, marketing year
CTSPRD	Cotton production	Million bales	FAPRI-MU model, marketing year
DIPRT	Retail #2 diesel price, CY	USD / gallon	FAPRI model, EIA
DRIVERS	Licensed drivers in the US	Thousands	Federal Highway Administration and Transportation Energy Data Book
DSLCONLDV	Diesel consumption light-duty vehicles	Million barrels	1994-forward AEOsupplemental data
DSLCONOTH	Diesel consumption, other vehicles	Million barrels	1994-forward AEOsupplemental data

DSLSHR	Diesel share of LDV	proportion	(EIA RTEC surveys) ; interpolated
DYMKSPRD	Milk production	Million pounds	FAPRI-MU model, marketing year
ENBDDDOM_RW	Rest of world biodiesel use	Millions of gallons	Calculated, OECD-FAO world less FAPRI-MU US, Brazil
ENCODDOM_RW	Rest of world petroleum use	Million barrels	Calculated from IEA world totals less EIA US data
ENCODEXP	Crude oil exports	Million barrels	Energy information Agency
ENCODNEX_RW	Rest of world net exports of petroleum	Million barrels	IEA
ENCODREF	Crude oil refining	Million barrels	Energy information Agency
ENCODSTK	Industry stocks (does not include SPR)	Million barrels	Energy information Agency
ENCODSTK_RW	Rest of world petroleum ending stocks	Million barrels	Calculated from IEA OECD totals less EIA US data
ENCODSTKR	Strategic Reserve	Million barrels	Energy information Agency
ENCOPFOB_WD	Petroleum price, Dubai Spot	USD per barrel	EIA, PET_PRI_RAC2_DCU_NUS_M
ENCORCAP	Crude oil refining capacity	Million barrels	Calculated
ENCORRET	Crude oil refining margin	USD / barrel	Calculated
ENCORRET_RW	Refining margin	USD per barrel	Calculated
ENCORUTL	Crude oil refining capacity utilization	Million barrels	Energy information Agency
ENCOSIMP	Crude oil imports	Million barrels	Energy information Agency
ENCOSPRD	Crude oil production	Million barrels	Energy information Agency
ENCOSPRD_NOPEC	Non-OPEC, non-US petroleum production	Million barrels	Calculated as IEA world less OPEC less EIA US data
ENCOSPRD_OPEC	OPEC petroleum production	Million barrels	IEA
ENCOSPRD_RW	Rest of world petroleum production	Million barrels	Calculated
ENDAPRDA	Aggregate diesel price with substitute	USD / gallon	Calculated
ENDFDAEN	Endogenous commodities	Million barrels	Calculated from Miranowski, J. 2005.
ENDFDAFV	Fruit/Veg/Other ag	Million barrels	Calculated from Miranowski, J. 2005.
ENDFDAGR	Total ag use of diesel, million barrels (assume 1/2 transport & 1/2 other)	Million barrels	Calculated from Miranowski, J. 2005.
ENDFDAGR_RW	Rest of world diesel use for agriculture	Million barrels	Calculated from IEA world totals less EIA US data
ENDFDAOC	Other crop	Million barrels	Calculated from Miranowski, J. 2005.
ENDFDAOL	Other Livestock	Million barrels	Calculated from Miranowski, J. 2005.
ENDFDDOM_RW	Rest of world diesel use	Million barrels	Calculated from IEA world totals less EIA US data
ENDFDELC	Diesel use in electricity	Million barrels	Energy information Agency
ENDFDEXP	Diesel exports	Million barrels	Energy information Agency
ENDFDNEX_RW	Rest of world net exports of	Million barrels	IEA

	diesel		
ENDFDOTH	Diesel use for other purposes	Million barrels	Energy information Agency
ENDFDSTK	Diesel ending stocks	Million barrels	Energy information Agency
ENDFDSTK_RW	Rest of world diesel ending stocks	Million barrels	Calculated from IEA OECD totals less EIA US data
ENDFDTRN	Diesel use in transportation	Million barrels	Energy information Agency
ENDFPFNL	No. 2 chosen	USD / gallon	Energy information Agency
ENDFPFOB_WD	Diesel price LA, No 2 Spot Price FOB	USD per gallon	EIA, PET_PRI_SPT_S1_M, update Ultra-Low Sulf. CARB
ENDFPWHL	No. 2 chosen	USD / gallon	Energy information Agency
ENDFSIMP	Diesel imports	Million barrels	Energy information Agency
ENDFSPRD	Diesel production	Million barrels	Energy information Agency
ENDFSPRD_RW	Rest of world diesel production	Million barrels	Calculated from IEA world totals less EIA US data
ENDFSYLD	Diesel yield from petroleum, adjusted for residual oil refining	Barrels of output / barrels of input	Calculated
ENDFSYLD_RW	Rest of world diesel yield	Barrels of output / barrels of input	Calculated
ENDFSYLD_US	US diesel yield	Barrels of output / barrels of input	Calculated
ENDPSPRD	Aggregate diesel production, excl substitute	Million barrels	Calculated
ENDPTXDF	Tax on petroleum element of fuels (federal with additional amount to proxy states' tax)	USD / gallon	1/1/2010 data from http://www.taxadmin.org/fta/rate/mf.pdf
ENETDDOM_RW	Rest of world ethanol use	Millions of gallons	Calculated, OECD-FAO world less FAPRI-MU US, Brazil
ENGAPRGA	Aggregate gasoline price with complements and substitutes	USD / gallon	Calculated
ENGBDREF	Other refining inputs: Motor Gasoline Blending Components	Million barrels	Energy information Agency
ENGPSPRD	Aggregate gasoline production from petro, excl complements and substitutes	Million barrels	Energy information Agency
ENGPTXGS	Tax on petroleum element of fuels (sum of federal and simple average of states in 2004)	USD / gallon	1/1/2010 data from http://www.taxadmin.org/fta/rate/mf.pdf
ENGSDAEN	Endogenous commodities	Million barrels	Calculated from Miranowski, J. 2005.
ENGSDAFV	Fruit/Veg/Other ag	Million barrels	Calculated from Miranowski, J. 2005.
ENGSDAGR	Total ag use of gasoline, million barrels (assume 90% transport, 10% other)	Million barrels	Calculated from Miranowski, J. 2005.
ENGSDAGR_RW	Rest of world gasoline use for agriculture	Million barrels	Calculated from IEA world totals less EIA US data
ENGSDAOC	Other crop	Million barrels	Calculated from Miranowski, J. 2005.
ENGSDAOL	Other Livestock	Million barrels	Calculated from Miranowski, J. 2005.

ENGSDDOM_RW	Rest of world gasoline use	Million barrels	Calculated from IEA world totals less EIA US data
ENGSDEXP	Gasoline exports	Million barrels	Energy information Agency
ENGSDNEX_RW	Rest of world net exports of gasoline	Million barrels	IEA
ENGSDOTH	Gasoline used for other purposes	Million barrels	Energy information Agency
ENGSDSTK	Gasoline ending stocks	Million barrels	Energy information Agency
ENGSDSTK_RW	Rest of world gasoline ending stocks	Million barrels	Calculated from IEA OECD totals less EIA US data
ENGSDTRN	Gasoline used for transportation	Million barrels	Energy information Agency
ENGSPFOB_WD	Gasoline price, ARA 10ppm Spot FOB	USD per gallon	EIA, PET_PRI_SPT_S1_M, history from ARA 50ppm
ENGSPGAS	Gasoline price, retail with tax (not compliance cost)	USD / gallon	EIA, nom. ret'l avg price, update all grades all formulations
ENGSSIMP	Gasoline imports	Million barrels	Energy information Agency
ENGSSPRD	Gasoline production	Million barrels	Energy information Agency
ENGSSPRD_RW	Rest of world gasoline production	Million barrels	Calculated from IEA world totals less EIA US data
ENGSSYLD	Gas yield from petroleum, adjusted for residual oil refining	Barrels of output / barrels of input	Calculated
ENGSSYLD_R	Gasoline yield from further refined residual oil	Barrels of output / barrels of input	Calculated
ENGSSYLD_RW	Rest of world gasoline yield	Barrels of output / barrels of input	Calculated
ENGSSYLD_US	US gasoline yield	Barrels of output / barrels of input	Calculated
ENNGDREF	Other refining inputs: Natural Gas Liquids	Million barrels	Energy information Agency
ENOTDREF	Other refining inputs: Other Hydrocarbons; Includes oxygenates	Million barrels	Energy information Agency
ENRODAGR_RW	Rest of world residual oil use for agriculture	Million barrels	Calculated from IEA world totals less EIA US data
ENRODDOM_RW	Rest of world residual oil use	Million barrels	Calculated from IEA world totals less EIA US data
ENRODELC	Residual oil used for electricity	Million barrels	Energy information Agency
ENRODEXP	Residual oil exports	Million barrels	Energy information Agency
ENRODNEX_RW	Rest of world net exports of resid. oil	Million barrels	IEA
ENRODOTH	Residual oil used for other purposes	Million barrels	Energy information Agency
ENRODREF	Other refining inputs: Unfinished Oils (net)	Million barrels	Energy information Agency
ENRODREF_G	Residual oil refined into gasoline	Million barrels	Calculated
ENRODSTK	Residual oil ending stocks	Million barrels	Energy information Agency
ENRODSTK_RW	Rest of world residual oil ending stocks	Million barrels	Calculated from IEA OECD totals less EIA US data
ENRODTRN	Residual oil used for transportation	Million barrels	Energy information Agency

ENROPFNL	Residual oil price, final user	USD / gallon	Energy information Agency
ENROPFOB_WD	Resid. oil price, ARA ≤ 1% Sulfur Spot FOB	USD per gallon	EIA, PET_PRI_SPT_S1_M,history update ECONSTAT
ENROPWHL	Residual oil price, wholesale	USD / gallon	Energy information Agency
ENROSIMP	Residual oil imports	Million barrels	Energy information Agency
ENROSPRD	Residual oil production	Million barrels	Energy information Agency
ENROSPRD_RW	Rest of world residual oil production	Million barrels	Calculated from IEA world totals less EIA US data
ENROSYLD	Residual oil yield, adjusted for residual oil refining	Barrels of output / barrels of input	Calculated
ENROSYLD_RW	Rest of world residual oil yield	Barrels of output / barrels of input	Calculated
ENROSYLD_US	US residual oil yield	Barrels of output / barrels of input	Calculated
ETD_BRA	Brazilian ethanol use	million gallons	FAPRI-MU model
ETADD	Rate of ethanol use as additive		FAPRI-MU model
ETDADCL	Ethanol additive use	Million gallons	FAPRI-MU model
ETDEXPCL	Ethanol exports	Million gallons	FAPRI-MU model
ETDISCL	Ethanol use in calendar year	Million gallons	FAPRI-MU model
ETDISSA	Ethanol use in marketing year	Million gallons	FAPRI-MU model
ETDTESCL	Ethanol ending stocks	Million gallons	FAPRI-MU model
ETE10PEN	Penetration of E10	proportion	FAPRI-MU model
ETE85PEN	Ethanol E85 penetration rate	proportion	FAPRI-MU model
ETIBCAP	Max potential blend	proportion	FAPRI-MU model
ETM_BRA	Brazilian ethanol imports	million gallons	FAPRI-MU model
ETN_ROW	Non-US, non-Brazil net ethanol imports	million gallons	FAPRI-MU model
ETNCADV			
ETPADCL	Implied advanced ethanol retail price	$/gallon	FAPRI-MU model
ETPBZACL	Ethanol price, Brazil CY	$/gallon	FAPRI-MU model
ETPFBCL	Ethanol Rack Price, NE FOB	$/gallon	FAPRI-MU model
ETPRTCL	Ethanol retail price, calendar year	USD / gallon	FAPRI-MU model, calendar year
ETPRTSA	Ethanol retail price, marketing year	USD / gallon	FAPRI-MU model, marketing year
ETS_BRA	Brazilian ethanol production	million gallons	FAPRI-MU model
ETSIMNCL	Ethyl alcohol net imports, cal. yr.	Million gallons	FAPRI-MU model, CY

ETSIMPCL	Ethanol imports	Million gallons	FAPRI-MU model, CY
ETSPCECL	Cellulosic ethanol production	Million gallons	FAPRI-MU model, CY
ETSPNCCL	Non-corn ethanol production	Million gallons	FAPRI-MU model, CY
ETSPOACL	Other advanced ethanol production	Million gallons	FAPRI-MU model, CY
ETSPRDCL	Ethanol prod., cal. yr.	Million gallons	FAPRI-MU model, CY
ETSSUGCL	Sugar ethanol production	Million gallons	FAPRI-MU model, CY
ETTAXEX	Ethanol tax credit	$/gallon	FAPRI-MU model
ETX_BRA	Brazilian ethanol exports	million gallons	FAPRI-MU model
FFVCONACT	Ethanol E85 use, CY	Million barrels	Calculated
FFVCONPOT	Potential E-85 market	Million barrels	Calculated
FFVSHR	FFV share of LDV	Proportion	EIA
FUELLDV	Fuel consumption, total	Trillion btu	Calculated
GASCONLDV	Gasoline consumption by light-duty vehicles	Million barrels	1994-forward AEOsupplemental data
GASCONOTH	Gasoline consumption by other vehicles	Million barrels	1994-forward AEOsupplemental data
GASHRTRN	Gasoline heat rate	Million btu / barrel	EIA
GASSHR	Gas share of LDV	proportion	EIA RTEC surveys
GDP_RW	Rest of world real GDP	Trillions of USD	ERS
HASPRD	Hay production	Million tons	FAPRI-MU model, marketing year
LDVTOT	Total light duty vehicle stock	million vehicles	Federal Highway Administration; EIA
MPGDSL	Fuel Economy - Diesel	Miles per gallon	(EIA RTEC surveys)
MPGFFV	Fuel Economy - FFV	Miles per gallon	Calculated
MPGGAS	Fuel Economy - Gasoline	Miles per gallon	(EIA RTEC surveys)
MPGLDV	Fuel economy – All LDVs	Miles per gallon	calculated
MTDISCL	MTBE use, calendar year	Million gallons	Calculated, calendar year
MTDISSA	MTBE disapp., MY	Million gallons	FAPRI-MU model, MY
OTHSHR	Other share of LDVs	Proportion	calculated
OTSPRD	Oat production	Million bushels	FAPRI-MU model, marketing year

PCIUW	Consumer Price Index	Index	FAPRI-MU model
PKPROD	Pork production	Million pounds	FAPRI-MU model, marketing year
PNSPRD	Peanut production	Million pounds	FAPRI-MU model, marketing year
POILRAP	Refiners' crude oil acquisition price	USD / barrel	FAPRI-MU model; projections from EIA's AEO
POP_RW	Rest of world population	Millions of people	ERS
POPTOTW	US population	Millions of people	FAPRI-MU model
PPI	Producer price index	Index	FAPRI-MU model
PPINGAS	PPI, natural gas		
PRCCAR	Price of new car	Dollars	Transportation Energy Data Book
RCODDSL	Real Cost of driving, diesel	$/mile	calculated
RCODFFV	Real Cost of driving, FFV	$/mile	calculated
RCODGAS	Real Cost of driving, gas	$/mile	calculated
RCSPRD	Rice production	Million hundredweights	FAPRI-MU model, marketing year
RFAD	Advanced mandate	Million gallons	EISA 2007
RFADC	Mandate cost, advanced	Million dollars	FAPRI-MU model
RFADCPG	Advanced RIN price	$/RIN	FAPRI-MU model
RFBIOFC	Mandate cost, marketing year, Biodiesel	USD millions	FAPRI-MU model, marketing year
RFCE	Cellulosic mandate	Million gallons	EISA 2007
RFCN	Conventional mandate	Million gallons	EISA 2007
RFCNC	Mandate cost, conventional	Million dollars	FAPRI-MU model
RFCNCPG	Conventional RIN price	$/RIN	FAPRI-MU model
RFTO	Overall mandate	million gallons	EISA 2007
RSSPRD	Rapeseed production	Million bushels	FAPRI-MU model, marketing year
SBSPLT	Soybean area planted	Thousand acres	FAPRI-MU model, marketing year
SBSPLT1	Soybean area planted	Thousand acres	FAPRI-MU model, marketing year
SBSPRD	Soybean production	Million bushels	FAPRI-MU model, marketing year
SFSPRD	Sunflower production	Million pounds	FAPRI-MU model, marketing year
SGSPRD	Sorghum production	Million bushels	FAPRI-MU model, marketing year

TKPROD	Turkey production	Million pounds	FAPRI-MU model, marketing year
UGPFBCL	gasoline price, wholesale FOB Omaha	$/gal	FAPRI-MU model
UGPRTCL	Unleaded gas price	USD / gallon	FAPRI model, EIA
VMTLDV	Light duty vehicle miles traveled	Billion miles	Federal Highway Administration; EIA
WHSPLT	Wheat area planted	Thousand acres	FAPRI-MU model, marketing year
WHSPLT1	Wheat area planted	Thousand acres	FAPRI-MU model, marketing year
WHSPRD	Wheat production	Million bushels	FAPRI-MU model, marketing year
ZCE92W	Consumer expenditure	Real USD	FAPRI-MU model
zENCOSBAL_RR	Statistical discrepancy	Million barrels	Calculated
zENCOSBAL_RW_RR	Rest of world petroleum balance error	Million barrels	Calculated
zENDFSBAL_RR	Statistical discrepancy (calculated)	Million barrels	Calculated
zENDFSBAL_RW_RR	Rest of world diesel balance error	Million barrels	Calculated
zENGSSBAL_RR	Statistical discrepancy (calculated)	Million barrels	Calculated
zENGSSBAL_RW_RR	Rest of world gasoline balance error	Million barrels	Calculated
zENROSBAL_RR	Statistical discrepancy (calculated)	Million barrels	Calculated
zENROSBAL_RW_RR	Rest of world resid. oil balance error	Million barrels	Calculated
zETSBAL_RR	EtoH discrepancy	Million gallons	Calculated

Model Specification

Light-duty vehicle and biofuels markets

RCODGAS = (ENGAPRGA*100/PCIUW)/MPGGAS + zRCODGAS_RR;

RCODDSL = ((ENDFPFNL+ENDPTXDF)*100/PCIUW)/MPGDSL + zRCODDSL_RR;

RCODFFV = (0.8*(ETPRTCL*100/PCIUW)+ 0.2*(ENGAPRGA*100/PCIUW))/MPGFFV + zRCODFFV_RR;

(LOG(DSLSHR_F)) = -0.19314
+ 0.016558*LOG(RCODGAS*100)
+ (-0.01127)*LOG(RCODDSL*100)
+ 0.955068*LAG(LOG(DSLSHR_F))
+ zDSLSHR_F_RR;

(LOG(FFVSHR_F)) = -2.32087
+ 1.445591*LOG(RCODGAS*100)
+ (-0.99101)*LOG(RCODFFV*100)

```
                         + 0.002*(AVDPEN/PPI)
                         + 0.629633*LAG(LOG(FFVSHR/(1-FFVSHR)))
                         + zFFVSHR_F_RR;

DSLSHR = MAX(0, MIN(DSLSHR_F,0.9));
FFVSHR = MAX(0, MIN(FFSSHR_F, 0.9));

GASSHR = 1 - FFVSHR - DSLSHR - OTHSHR + zGASSHR_RR;

LOG(MPGLDV) = 1.64649
                         + 0.063098*LOG(ENGAPRGA*100/PCIUW)
                         + 0.381025*LOG(VMTLDV)
                         + (-0.42015)*LOG(ZCE92W*1E6/DRIVERS)
                         + 0.344126*LOG((CAFECOM
                                         + LAG(CAFECOM)
                                         + LAG2(CAFECOM)
                                         + LAG3(CAFECOM)
                                         + LAG4(CAFECOM)
                                         + LAG5(CAFECOM))/6)
                         + 0.527351*LOG(LAG(MPGLDV))
                         + 0.00126*(ZTIME-1983)
                         + zMPGLDV_RR;

LOG(LDVTOT*1000/DRIVERS)  = -2.11481
                                         + (-0.01513)*LOG((ENGAPRGA*100/PCIUW)/MPGLDV)
                                         + (-0.08)*LOG(PRCCAR*100/CARPI)
                                         + 0.2856*LOG(ZCE92W*1E6/DRIVERS)
                                         + 0.713337*LOG(LAG(LDVTOT*1000/DRIVERS))
                                         + (-0.00308)*(ZTIME-1978)
                                         + zLDVTOT_RR;

LOG(VMTLDV*1E6/DRIVERS) = 0.179488
                                         + (-0.06899)*LOG((ENGAPRGA*100/PCIUW)/MPGLDV)
                                         + 0.137615*LOG(LDVTOT)
                                         + 0.194204*LOG(ZCE92W*1E6/DRIVERS)
                                         + 0.677605*LOG(LAG(VMTLDV*1E6/DRIVERS))
                                         + (-0.00334)*(ZTIME-1978)
                                         + zVMTLDV_RR;

FUELLDV = (VMTLDV*1E9/MPGLDV)*(5253000)/42/1E12 + zFUELLDV_RR;

GASCONLDV = ((GASSHR+(1-ETE85PEN)*FFVSHR)*FUELLDV)/(GASHRTRN*1E6)*1000000
                 + zGASCONLDV_RR;

DSLCONLDV = (DSLSHR*FUELLDV)/5825000*1000000 + zDSLCONLDV_RR;

FFVCONPOT = (FFVSHR*FUELLDV)/3985000*1000000 + zFFVCONPOT_RR;

LOG(ETE85PEN/(1-ETE85PEN))= 0.6 + (-2)*(ETPRTCL/UGPRTCL)
                                         + 25*MAX(0,0.67-(ETPRTCL/UGPRTCL))
                                         + zETE85PEN_RR;

LOG(ETE10PEN/(1-ETE10PEN))= 2.8 + (-1)*(ETPRTCL/UGPRTCL) + zETE10PEN_RR;

FFVCONACT = ETE85PEN*FFVCONPOT + zFFVCONACT_RR;
```

```
LOG(ETSPRDCL) = 2.42525
                        + 0.125*LOG(ETPFBCL
                                + LAG(ETPFBCL)
                                + LAG2(ETPFBCL)
                                + LAG3(ETPFBCL)/4)
                        + (-0.02674)*LOG(PPINGAS)
                        + 0.75121*LAG(LOG(ETSPRDCL))
                        + 0.01022*(ZTIME-2010)
                        + zETSPRDCL_RR;

ETSIMPCL = -501.271
                        + 777.8148*(ETPADCL/ETPBZACL)
                        + 75.79728*(ZTIME-2010)
                        + zETSIMPCL_RR;

ETSIMPCLfake = -501.271
                        + 777.8148*(ETPADCLfake/ETPBZACL)
                        + 75.79728*(ZTIME-2010)
                        + zETSIMPCL_RR;

ETDEXPCL = 369.3242
                        + (-101.875)*(ETPFBCL/ETPBZACL)
                        + 33.30779*(ZTIME-2010)
                        + zETDEXPCL_RR;

ETDADCL = 100 + (-100)*(ETPRTCL/PPI)
                        + 1*((ENGSDTRN*42)*(ETADD)*(1-
                (FFVCONACT*42)/(ENGSDTRN*42)/0.74))
                        + (-0.9)*MTDISCL
                        + zETDADCL_RR;

ETDISCL = (ETE10PEN*((ENGSDTRN*42)*(ETIBCAP-ETADD)*(1-
(FFVCONACT*42)/(ENGSDTRN*42)/0.74))
                        + ETDADCL
                        + (FFVCONACT*42) )
                        + zETDISCL_RR;

ETSBAL = ETSPRDCL + ETSIMPCL + LAG(ETDTESCL - ETDTESCL - ETDEXPCL - ETDISCL +
zETSBAL_RR;

ETPFBCL = ETPRTCL
                        -(UGPRTCL - (ENGSPGAS-ENGPTXGS))
                        +(ETTAXEX)
                        + RFCNCPG
                        + zETPFBCL_RR;

ETPADCL = ETPRTCL
                        -(UGPRTCL - (ENGSPGAS-ENGPTXGS))
                        + (ETTAXEX)
                        + RFADCPG
                        + zETPADCL_RR;

ETPADCLfake = ETPRTCL
                        -(UGPRTCL - (ENGSPGAS-ENGPTXGS))
                        + (ETTAXEX)
                        + RFADCPGfake
```

```
                        + zETPADCL_RR;

TRINPROD = (ETSPRDCL-ETSPCECL)
                        + lag(ETDTESCL)
                        - ETDTESCL
                        + (ETSIMPCL - ETDEXPCL)
                        + BDEQV*(BDSPRDCL-BDDEXNCL)
                        + zTRINPROD_RR ;

RFCNCPG = (RFCNCPG**2 + (TRINPROD/1000-(RFTO-RFCE)/1000)**2 +0.00001 )**(1/2)
                        - (RFCNCPG + (TRINPROD/1000-(RFTO-RFCE)/1000))
                        + zRFCNCPG_RR ;

RFCNC = RFCNCPG*((ETSPRDCL - ETSPNCCL*ETNCADV - ETSPCECL - ETSSUGCL)
                        +LAG(ETDTESCL)
                        - ETDTESCL
                        - ETDEXPCL) ;

ARINPROD = ETSPNCCL*ETNCADV
                        + ETSIMPCL
                        + ETSSUGCL
                        + ETSPOACL
                        + BDEQV*(BDSPRDCL-BDDEXNCL)
                        + zARINPROD_RR ;

ARINPRODfake = ETSPNCCL*ETNCADV
                        + ETSIMPCLfake
                        + ETSSUGCL
                        + ETSPOACL
                        + BDEQV*(BDSPRDCL-BDDEXNCL)
                        + zARINPROD_RR ;

RFADCPG = MAX(0 , RFCNCPG , RFADCPGfake ) - RFADCPG + zRFADCPG_RR;

RFADCPGfake = (RFADCPGfake**2 + (ARINPRODfake/1000-(RFAD-RFCE)/1000)**2 +0.00001
)**(1/2)
                        - (RFADCPGfake + (ARINPRODfake/1000-(RFAD-RFCE)/1000));

RFADC = RFADCPG*(ETSPNCCL*ETNCADV + ETSIMPCL + ETSSUGCL) ;

RFETC = RFCNC + RFADC;
```

U.S. Petroleum and petroleum products

```
ENCOSPRD = exp (0.075804

                        + 0.245173 * log( ( 4*lag1(POILRAP/PPI)
                                                        +3*lag2(POILRAP/PPI)
                                                        +2*lag3(POILRAP/PPI)
                                                        +lag4(POILRAP/PPI) )/10  )
                        + 0.8 * log(lag1(ENCOSPRD))
                        + 0.002629 * (ztime - 2010)
                        + zENCOSPRD_RR  )

        %AR( ENCOSPRD , 1, M=CLS1);
```

```
ENCORUTL = 0.90395
                        + 0.006829*(ENCORRET/PPI)
                + zENCORUTL_RR
        %AR( ENCORUTL , 1, M=CLS1);

ENCODSTK = exp (1.293463
                        + -0.5 * log(max(0.0001,POILRAP /PPI))
                        + zENCODSTK_RR )


ENGSDSTK = exp (-6.65991
                        + -0.5* log(max(0.0001,(ENGSPGAS-ENGPTXGS)/PPI))
                        + 1.0* log(ENGSSPRD + ENGSSIMP)
                        + zENGSDSTK_RR  )

ENDFDSTK = exp (1.130589
                        + -0.5* log(max(0.0001,ENDFPWHL/PPI))
                        + zENDFDSTK_RR )

ENRODSTK = exp (4.016922
                        + -0.5 * log(max(0.0001,ENROPWHL/PPI))
                        + 0.11558* (ztime - 2010)
                        + zENRODSTK_RR  )

GASCONOTH = (-1.03346
                        + 0.735864* (lag((GASCONOTH)/POPTOTW))
                        + -0.01* (ENGAPRGA*100/PCIUW)
                        + -0.01466*(ztime-2010)
                        + 0.051012* (ZCE92W/POPTOTW)
                        + zGASCONOTH_RR  )*POPTOTW
        %AR( GASCONOTH , 1, M=CLS1);

ENRODELC =  exp(0.779199
                        + 0.881546* lag(log(ENRODELC))
                        + -0.02408* log(max(0.001,ENROPFNL)*100/PCIUW)
                        + -0.08691* log(ztime-1970)
                        + zENRODELC_RR  )
        %AR( ENRODELC , 1, M=CLS1);

ENDFPFNL = -0.43025
                + 1.043019* ENDFPWHL
                + ENDPTXDF
                + zENDFPFNL_RR
        %AR( ENDFPFNL , 1, M=CLS1);

ENRODREF_G = exp (1.095275
                        + 0.2*log((max(0.00001,ENGSPGAS-ENGPTXGS)*ENGSSYLD_R
                        /ENROPWHL))
                        + 0.8* log( lag1(ENRODREF_G) )
                        + zENRODREF_G_RR )

(ENCOSIMP-ENCODEXP) = 925.0944
                                + 182.8618* ((POILRAP-ENCOPFOB_WD)/PPI)
                                + 23.03515*(ztime-2010)
                                + 6.335826*(ztime-2010)*((POILRAP-ENCOPFOB_WD)/PPI)
                                + 0.769721* lag1((ENCOSIMP-ENCODEXP) )
```

```
                              + zENCOSIMP_RR

ENCOSBAL = ENCOSPRD
                  + ENCOSIMP
                  + lag(ENCODSTK)
                  - ENCODREF
                  - ENCODEXP
                  - ENCODSTK
                  + zENCOSBAL_RR;

ENCORRET =   ( ENGSSYLD_US * (ENGSPGAS-ENGPTXGS)
                           + ENDFSYLD_US * ENDFPWHL
                           + ENROSYLD_US * ENROPWHL ) * 42
                           - POILRAP
                           + zENCORRET_RR ;

(ENCORCAP-lag1(ENCORCAP)) = 67.0786
                                             + 21.72842* lag1(ENCORRET/PPI)
                                             + zENCORCAP_RR

ENCODREF = ENCORUTL*ENCORCAP + zENCODREF_RR;

ENDFSYLD_H = 0.129303
                           + 0.033919*log(ztime-1975)
                           + zENDFSYLD_H_RR

ENGSSYLD_H = 0.164342
                           + 0.018499*log(ztime-1975)
                           + zENGSSYLD_H_RR

ENROSYLD_H = 0.537197
                           + -0.10368*log(ztime-1975)
                           + zENROSYLD_H_RR

ENDFSYLD_US = MAX(0.002,MIN(0.9,ENDFSYLD_H)) - ENDFSYLD_US ;

ENGSSYLD_US = MAX(0.002,MIN(0.9,ENGSSYLD_H)) - ENGSSYLD_US ;

ENROSYLD_US = MAX(0.002,MIN(0.9,ENROSYLD_H)) - ENROSYLD_US ;

ENGPSPRD =  ENGSSYLD_US * (ENCODREF)
                           +ENNGDREF
                           +ENGBDREF
                           - ENGPSPRD
                           + zENGPSPRD_RR
                           +ENRODREF_G*ENGSSYLD_R;

ENGSSPRD = ENGPSPRD
                           + (ETDISCL *0.667)/42
                           + (MTDISCL * ((112000 -114100*0.9)/0.1)/114100 )/42
                           - ENGSSPRD
                           + zENGSSPRD_RR;

log(ENGSSIMP) = 6.961422
                           + 12.92959* ((ENGSPGAS - ENGPTXGS - ENGSPFOB_WD)/PPI)
                           + -1.71949* log(ztime-1970)
```

```
                        + zENGSSIMP_RR

log(ENGSDEXP) = -4.85755
                        + -12.9296* ((ENGSPGAS - ENGPTXGS - ENGSPFOB_WD)/PPI)
                        + 3.644096* log(ztime-1970)
                        + zENGSDEXP_RR

ENGSDTRN = GASCONLDV + GASCONOTH + FFVCONACT + zENGSDTRN_RR;

ENGSSBAL = ENGSSPRD
                        + ENGSSIMP
                        + lag(ENGSDSTK)
                        - ENGSDTRN
                        - ENGSDOTH
                        - ENGSDEXP
                        - ENGSDAGR
                        - ENGSDSTK
                        + zENGSSBAL_RR;

ENGAPRGA = (IF          ztime<1998 THEN UGPRTCL + zENGAPRGA_RR
                        ELSE    +(UGPRTCL)     *( (1-ETDISCL*0.667/(ENGSSPRD*42))
                                                        +lag1(1-
                                                ETDISCL*0.667/(ENGSSPRD*42))
                                                        +lag2(1-
                                                ETDISCL*0.667/(ENGSSPRD*42)) ) /3
                                +(ETPRTCL/0.667)*((ETDISCL*0.667/(ENGSSPRD*42))
                                                        +lag1(ETDISCL*0.667/(ENGSSPRD*42))
                                                        +lag2(ETDISCL*0.667/(ENGSSPRD*42))
                                                )/3)
                    + zENGAPRGA_RR ;

UGPRTCL = -0.07336
                        + 1.008387* ENGSPGAS
                        + (RFETC)/(ENGSDTRN*42 - (ETDISCL *0.667)
                        + (MTDISCL * ((112000 -114100*0.9)/0.1)/114100) )
                        + zUGPRTCL_RR ;


ENDFSPRD = ENDFSYLD_US * (ENCODREF +ENRODREF) + zENDFSPRD_RR;

log(ENDFSIMP) = 2.243291
                        + 8.058797* ((ENDFPWHL-ENDFPFOB_WD)/PPI)
                        + 0.695516* log(ztime-1970)
                        + zENDFSIMP_RR

log(ENDFDEXP) = 4.137835
                        + -8.0588* ((ENDFPWHL-ENDFPFOB_WD)/PPI)
                        + zENDFDEXP_RR

(DSLCONOTH + (BDDDOM*0.25+lag(BDDDOM)*0.75) *(118296/129500)/42)
                = 77.03739
                        + 0.61608* lag(DSLCONOTH
                                                +
                                                (BDDDOM*0.25+lag(BDDDOM)*0.75)*(118296/1
                                                29500)/42)
                        + -17.7612* ENDAPRDA/PPI
```

```
                        + 0.047237* ZCE92W
                        + zDSLCONOTH_RR

ENDFDTRN = DSLCONLDV + DSLCONOTH + zENDFDTRN_RR;

ENDAPRDA = (IF ztime < 2006 THEN DIPRT
                ELSE (DIPRT)*( (1-(BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25+lag(BDDDOM)*0.75)*(118296/129500)))
                                +lag1(1-(BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25+lag(BDDDOM)*0.75)*(118296/129500)))
                                +lag2(1-(BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25+lag(BDDDOM)*0.75)*(118296/129500))) )/3
                        +BDPREQCL/(118296/129500)*(((BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25+lag(BDDDOM)*0.75)*(118296/129500)))
                                +lag1(  (BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)))
                                +lag2(  (BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500)/((ENDFDTRN)*42
                                        +(BDDDOM*0.25
                                        +lag(BDDDOM)*0.75)*(118296/129500))) )/3)
                        + zENDAPRDA_RR;


DIPRT = 0.094231
                        + 1.091119* ENDFPWHL
                        + ENDPTXDF
                        + (RFBDC)/((ENDFDTRN)*42)
                        + zDIPRT_RR ;

ENDFDOTH = 126.3116
                        + 0.772575* lag(ENDFDOTH)
                        + -23.7604* ENDFPFNL*100/PCIUW
                        + -0.00275* ZCE92W
                        + zENDFDOTH_RR

ENDFSBAL = ENDFSPRD
                        + ENDFSIMP
                        + lag(ENDFDSTK)
                        - ENDFDTRN
                        - ENDFDELC
```

```
                        - ENDFDOTH
                        - ENDFDEXP
                        - ENDFDAGR
                        - ENDFDSTK
                        + zENDFSBAL_RR;

ENROSPRD = ENROSYLD_RW * (ENCODREF ) - ENRODREF_G + zENROSPRD_RR;

ENROSIMP- ENRODEXP) = 311.5465
                                + 380.553* ((ENROPWHL-ENROPFOB_WD)/PPI)
                                + 215.9193* lag1((ENROPWHL-ENROPFOB_WD)/PPI)
                                + -79.534* log(ztime-1970)
                                + zENROSIMP_RR

ENRODTRN/POPTOTW = -0.09073
                                + 0.689993* lag(ENRODTRN/POPTOTW)
                                + -0.02782* ENROPFNL*100/PCIUW
                                + 0.03056 * (ZCE92W/POPTOTW)
                                + -0.0121 * (ztime-1970)
                                + zENRODTRN_RR

ENROSBAL = ENROSPRD
                        + ENROSIMP
                        + lag(ENRODSTK)
                        - ENRODTRN
                        - ENRODELC
                        - ENRODOTH
                        - ENRODEXP
                        - ENRODSTK
                        + zENROSBAL_RR;

ENROPFNL = 0.033107
                        + 1.013518* ENROPWHL
                        + zENROPFNL_RR

ENDFDAGR = ENDFDAEN + ENDFDAOC + ENDFDAOL + ENDFDAFV + zENDFDAGR_RR ;

log(ENDFDAEN/(+ 0.00128493066366085 * CRSPRD
                        + 0.00203057664971979 * WHSPRD
                        + 0.00137008458055313 * SBSPRD
                        + 0.00603023008653676 * RCSPRD
                        + 0.160734875238472 * CTSPRD
                        + 0.000537714323955417 * BFPROD
                        + 9.12108193315099E-05 * PKPROD
                        + 3.20342088877249E-05 * (CKYPROD+TKPROD)
                        + 4.46929551151695E-05 * DYMKSPRD))
        = 0.58392
                + -0.18952*log(ztime-1970)
                + -0.00145* log(max(0.001,ENDAPRDA/PPI))
                + zENDFDAEN_RR

ENGSDAGR = ENGSDAEN + ENGSDAOC + ENGSDAOL + ENGSDAFV + zENGSDAGR_RR ;

log(ENGSDAEN / (+ 0.000247039797618068 * CRSPRD
                        + 0.000591914545884515 * WHSPRD
                        + 0.000309586100112243 * SBSPRD
```

```
                    + 0.000909063935944724 * RCSPRD
                    + 0.0358132985377046 * CTSPRD
                    + 0.000276280573669583 * BFPROD
                    + 0.000035297995591232 * PKPROD
                    + 2.05051820398957E-05 * (CKYPROD+TKPROD)
                    + 1.04922987303059E-05 * DYMKSPRD))
       = 3.303469
              + -0.96772*log(ztime-1970)
              + zENGSDAEN_RR
```

International petroleum and petroleum products

```
ENCOSPRD_NOPEC = exp(  4.503544
                           + 0.1*  log((ENCOPFOB_WD/PPI)
                                                                 +
                                                          1*lag1(ENCOPFOB_WD/PPI)
                                                                 + 1*
                                                                 lag2(ENCOPFOB_WD/P
                                                                 PI)
                                                                 +
                                                                 2*lag3(ENCOPFOB_WD/
                                                                 PPI)
                                                                 +lag4(ENCOPFOB_WD/
                                                                 PPI))
                           + -0.0048*  (ztime-2009)
                           + 0.483331*  log(lag1(ENCOSPRD_NOPEC))
                           + -0.01374*  log(lag2(ENCOSPRD_NOPEC))
                           + zENCOSPRD_NOPEC_RR  )
       %AR( ENCOSPRD_NOPEC , 1, M=CLS1);

ENCOSPRD_OPEC =      17176.01
                     + 19.30558*  (ENCOPFOB_WD/PPI)
                     + 5.295123*  (( lag1(ENCOPFOB_WD/PPI)
                                                          + 1*lag2(ENCOPFOB_WD/PPI)
                                                          +2*lag3(ENCOPFOB_WD/PPI)
                                                          +lag4(ENCOPFOB_WD/PPI)))
                     + -23.3095*  (ztime-2009)
                     + -0.42875*  (ENCOSPRD_NOPEC+ENCOSPRD)
                     + zENCOSPRD_OPEC_RR
       %AR( ENCOSPRD_OPEC , 2, M=CLS2);

ENCODSTK_RW = 2241.35
                     + -13.3269 * (ENCOPFOB_WD/PPI)
                     + zENCODSTK_RW_RR
       %AR( ENCODSTK_RW , 1, M=CLS1);

ENGSDSTK_RW = exp(-6.12843
                           + -1.06545* log((ENGSPFOB_WD/PPI))
                           + zENGSDSTK_RW_RR)*(max(0.1,ENGSSPRD_RW))
       %AR( ENGSDSTK_RW , 1, M=CLS1);

ENDFDSTK_RW = exp(-6.21626
                           + -1.5* log((ENDFPFOB_WD/PPI))
                           + zENDFDSTK_RW_RR)*(max(0.1,ENDFSPRD_RW))
       %AR( ENDFDSTK_RW , 1, M=CLS1);
```

```
ENRODSTK_RW = exp(-4.37056
                                 + -0.75* log((ENROPFOB_WD/PPI))
                                 + zENRODSTK_RW_RR)*(max(0.1,ENROSPRD_RW))
        %AR( ENRODSTK_RW , 1, M=CLS1);

ENCODDOM_RW = 2594.083
                         + 250*(ENCORRET_RW/PPI)
                         + 0.9*(lag1(ENCODDOM_RW))
                         + zENCODDOM_RW_RR

ENGSDDOM_RW =  302.7598
                         + -1147.54* ( ENGSPFOB_WD*100/PCIUW
                                                          +lag1(ENGSPFOB_WD*100/PCIUW)
                                                          +lag2(ENGSPFOB_WD*100/PCIUW) )
                         + 803.8278* ( ENDFPFOB_WD*100/PCIUW
                                                          +lag1(ENDFPFOB_WD*100/PCIUW)
                                                          +lag2(ENDFPFOB_WD*100/PCIUW) )
                         + 0.129342* ((GDP_RW) - zENGSDDOM_RW_Y1 * lag1((GDP_RW)) )
                         + -40.9231* ((ztime-2009)-zENGSDDOM_RW_Y1*lag1((ztime-2009)) )
                         + zENGSDDOM_RW_RR
                - ( IF ztime<2005 THEN 0 ELSE  ENETDDOM_RW *0.667/42 ) ;

ENDFDDOM_RW =   686.6769
                         + 1268.89* ( ENGSPFOB_WD*100/PCIUW
                                                          +lag1(ENGSPFOB_WD*100/PCIUW)
                                                          +lag2(ENGSPFOB_WD*100/PCIUW) )
                         + -1270.69* ( ENDFPFOB_WD*100/PCIUW
                                                          +lag1(ENDFPFOB_WD*100/PCIUW)
                                                          +lag2(ENDFPFOB_WD*100/PCIUW) )
                         + 0.103393* lag1((ENDFDDOM_RW))
                         + 0.187503* ((GDP_RW) - zENDFDDOM_RW_Y1 * lag1((GDP_RW)) )
                         + 23.56318* ((ztime-2009)-zENGSDDOM_RW_Y1*lag1((ztime-2009)) )
                         + zENDFDDOM_RW_RR
                - ( IF ztime<2005 THEN 0 ELSE    ENBDDDOM_RW * (118296/129500) / 42 ) ;

ENRODDOM_RW =   855.2915
                         + -2493.33* ( ENROPFOB_WD*100/PCIUW)
                         + 0.10625* ((GDP_RW)  - zENRODDOM_RW_Y1 * lag1((GDP_RW)) )
                         + -64.1799* ((ztime-2009)-zENGSDDOM_RW_Y1*lag1((ztime-2009)) )
                         + zENRODDOM_RW_RR

ENCORRET_RW = ( ENGSSYLD_RW * ENGSPFOB_WD
                         + ENDFSYLD_RW * ENDFPFOB_WD
                         + ENROSYLD_RW * ENROPFOB_WD ) * 42
                         - ENCOPFOB_WD
                         + zENCORRET_RW_RR;

ENCOSPRD_RW = ENCOSPRD_OPEC + ENCOSPRD_NOPEC + zENCOSPRD_RW_RR  ;

ENGSSYLD_RW = 0.174883
                         + 0.01636*log(ztime-1978)
                         + zENGSSYLD_RW_RR

ENDFSYLD_RW = 0.234346
                         + 0.029057*log(ztime-1978)
                         + zENDFSYLD_RW_RR
```

```
ENROSYLD_RW = 0.02018
                        + -0.06169*log(ztime-1978)
                        + zENROSYLD_RW_RR

ENGSSPRD_RW = (ENCODDOM_RW*ENGSSYLD_RW) + zENGSSPRD_RW_RR ;

ENDFSPRD_RW = (ENCODDOM_RW*ENDFSYLD_RW) + zENDFSPRD_RW_RR ;

ENROSPRD_RW = (ENCODDOM_RW*ENROSYLD_RW) + zENROSPRD_RW_RR ;

ENCODNEX_RW = (ENCOSIMP - ENCODEXP) + zENCODNEX_RW_RR ;

ENGSDNEX_RW = (ENGSSIMP - ENGSDEXP) + zENGSDNEX_RW_RR ;

ENDFDNEX_RW = (ENDFSIMP - ENDFDEXP) + zENDFDNEX_RW_RR ;

ENRODNEX_RW = (ENROSIMP - ENRODEXP) + zENRODNEX_RW_RR ;

ENCOSBAL_RW = ENCOSPRD_RW
                        - ENCODNEX_RW
                        - ENCODDOM_RW
                        + lag1(ENCODSTK_RW)
                        - ENCODSTK_RW
                        + zENCOSBAL_RW_RR ;

ENGSSBAL_RW = ENGSSPRD_RW
                        - ENGSDNEX_RW
                        - ENGSDDOM_RW
                        - ENGSDAGR_RW
                        + lag1(ENGSDSTK_RW)
                        - ENGSDSTK_RW
                        + zENGSSBAL_RW_RR ;

ENDFSBAL_RW = ENDFSPRD_RW
                        - ENDFDNEX_RW
                        - ENDFDDOM_RW
                        - ENDFDAGR_RW
                        + lag1(ENDFDSTK_RW)
                        - ENDFDSTK_RW
                        + zENDFSBAL_RW_RR ;

ENROSBAL_RW = ENROSPRD_RW
                        - ENRODNEX_RW
                        - ENRODDOM_RW
                        - ENRODAGR_RW
                        + lag1(ENRODSTK_RW)
                        - ENRODSTK_RW
                        + zENROSBAL_RW_RR ;

ENETDDOM_RW = IF ztime<2005 THEN 0 ELSE ENETDDOM_RW_BASE ;
ENBDDDOM_RW = IF ztime<2005 THEN 0

                        ELSE ENBDDDOM_RW_BASE + zENBDDDOM_RW_US *(BDDEXN-
                BDDEXN_BASE)        ;
```

Elasticities

Elasticity valued for 2007-10 average values				
Variable	**Definition**	**Elasticity**		**Term (e.g. with respect to)**
		Short-run	Long-run	
ENCOSPRD	US petroleum production	0.25	1.23	Real petroleum price
ENCOSIMP-ENCODEXP	US petroleum net imports	-0.03	-0.13	US price less world price, real
		0.00	0.00	US price less world price, real, times trend
ENCODSTK	US petroleum ending stocks	-0.50		Real petroleum price
ΔENCORCAP	Change in US refining capacity	0.03		Real refining margin
ENCORUTL	US refining capacity utilization	0.06		Real refining margin
ENGSSIMP	US gasoline imports	4.24		US price less world price, real
ENGSDEXP	US gasoline exports	-4.24		US price less world price, real
GASCONOTH	US gasoline use, non-LDV	-0.02	-0.07	Real price
		1.69	6.39	Real income
ENGSDSTK	US gasoline ending stocks	-0.50		Real price
		1.00		Supply
ENDFSIMP	US diesel imports	-0.07		US price less world price, real
ENDFDEXP	US diesel exports	0.07		US price less world price, real
DSLCONDOTH	US diesel use, non-LDV	-0.03	-0.08	Real price
		0.34	0.89	Real income
ENDFDAEN	US diesel use, agriculture	0.00		Real price
ENDFDOTH	US diesel use, other	-0.07	-0.29	Real price
		-0.05	-0.21	Real income
ENDFDSTK	US diesel ending stocks	-0.50		Real price
ENRODREF_G	US residual oil, further refining	0.20	1.00	Gasoline to resid. oil price ratio
ENROSIMP-ENRODEXP	US residual oil net imports	7.63		US price less world price, real
ENRODTRN	US resid. oil use, transportation	-0.04	-0.13	Real price
		1.49	4.80	Real income
ENRODELC	US resid. oil use, electricity	-0.02		Real price
ENRODSTK	US residual oil ending	-0.50		Real price

	stocks			
ENCOSPRD_NOPEC	Non-OPEC ROW petroleum production	0.02	0.03	Real petroleum price
ENCOSPRD_OPEC	OPEC petroleum production	0.02		Real petroleum price
				Non-OPEC petroleum production
ENCODDOM_RW	ROW petroleum use	-0.09	-0.88	Real refining margin
ENCODSTK_RW	ROW petroleum ending stocks	-0.25		Real price
ENGSDDOM_RW	ROW gasoline use	-0.69		Real gasoline price
		0.58		Real diesel price
		1.07		Real income
ENDFDDOM_RW	ROW diesel use	0.49		Real gasoline price
		-0.58		Real diesel price
		0.99		Real income
ENRODDOM_RW	ROW residual oil use	-0.53		Real price
		1.16		Real income
ENGSDSTK_RW	ROW gasoline ending stocks	-1.07		Real price
				Supply
ENDFDSTK_RW	ROW diesel ending stocks	-1.50		Real price
				Supply
ENRODSTK_RW	ROW residual oil ending stocks	-0.75		Real price
				Supply
DSLSHR	Diesel share of LDVs	-0.01	-0.25	Real cost of driving, diesel
FFVSHR	Flex-fuel share of LDVs	-0.99	-2.68	Real cost of driving, E85
		1.45	3.90	Real cost of driving, gasoline
		0.00	0.01	Avoided penalty per FFV sold
MPGLDV	Fuel economy of LDVs	0.06	0.13	Real cost of gasoline
		0.38	0.81	Miles traveled
		-0.42	-0.89	Real income
		0.34	0.73	CafE standards
LDVTOT	LDV stock	-0.02	-0.05	Real cost of driving
		-0.08	-0.28	Real price of new car
		0.29	1.00	Real income
VMTLDV	Miles traveled	-0.07	-0.21	Real cost of driving
		0.19	0.60	Real income
ETSIMPCL	Ethanol imports	2.44		Real ethanol price, advanced
ETDEXPCL	Ethanol exports	-0.73		Real ethanol price, conventional

Elasticity valued for 2011-25 average values			
Variable	**Definition**	**Elasticity**	**Term (e.g. with respect to)**

		Short-run	Long-run	
ENCOSPRD	US petroleum production	0.25	1.23	Real petroleum price
ENCOSIMP-ENCODEXP	US petroleum net imports	-0.07	-0.31	US price less world price, real
		-0.02	-0.10	US price less world price, real, times trend
ENCODSTK	US petroleum ending stocks	-0.50		Real petroleum price
ΔENCORCAP	Change in US refining capacity	0.05		Real refining margin
ENCORUTL	US refining capacity utilization	0.11		Real refining margin
ENGSSIMP	US gasoline imports	5.41		US price less world price, real
ENGSDEXP	US gasoline exports	-5.41		US price less world price, real
GASCONOTH	US gasoline use, non-LDV	-0.02	-0.06	Real price
		1.54	5.82	Real income
ENGSDSTK	US gasoline ending stocks	-0.50		Real price
		1.00		Supply
ENDFSIMP	US diesel imports	-2.72		US price less world price, real
ENDFDEXP	US diesel exports	2.72		US price less world price, real
DSLCONDOTH	US diesel use, non-LDV	-0.03	-0.08	Real price
		0.38	0.98	Real income
ENDFDAEN	US diesel use, agriculture	0.00		Real price
ENDFDOTH	US diesel use, other	-0.09	-0.38	Real price
		-0.06	-0.28	Real income
ENDFDSTK	US diesel ending stocks	-0.50		Real price
ENRODREF_G	US residual oil, further refining	0.20	1.00	Gasoline to resid. oil price ratio
ENROSIMP-ENRODEXP	US residual oil net imports	0.83		US price less world price, real
ENRODTRN	US resid. oil use, transportation	-0.07	-0.24	Real price
		1.82	5.87	Real income
ENRODELC	US resid. oil use, electricity	-0.02		Real price
ENRODSTK	US residual oil ending stocks	-0.50		Real price
ENCOSPRD_NOPEC	Non-OPEC ROW petroleum production	0.02	0.03	Real petroleum price
ENCOSPRD_OPEC	OPEC petroleum production	0.03		Real petroleum price
				Non-OPEC petroleum production
ENCODDOM_RW	ROW petroleum use	-0.12	-1.25	Real refining margin
ENCODSTK_RW	ROW petroleum ending stocks	-0.36		Real price
ENGSDDOM_RW	ROW gasoline use	-0.67		Real gasoline price

		0.61		Real diesel price
		1.14		Real income
ENDFDDOM_RW	ROW diesel use	0.56		Real gasoline price
		-0.73		Real diesel price
		1.25		Real income
ENRODDOM_RW	ROW residual oil use	-0.83		Real price
		1.51		Real income
ENGSDSTK_RW	ROW gasoline ending stocks	-1.07		Real price
				Supply
ENDFDSTK_RW	ROW diesel ending stocks	-1.50		Real price
				Supply
ENRODSTK_RW	ROW residual oil ending stocks	-0.75		Real price
				Supply
DSLSHR	Diesel share of LDVs	-0.01	-0.25	Real cost of driving, diesel
FFVSHR	Flex-fuel share of LDVs	-0.99	-2.68	Real cost of driving, E85
		1.45	3.90	Real cost of driving, gasoline
		0.00	0.01	Avoided penalty per FFV sold
MPGLDV	Fuel economy of LDVs	0.06	0.13	Real cost of gasoline
		0.38	0.81	Miles traveled
		-0.42	-0.89	Real income
		0.34	0.73	CafE standards
LDVTOT	LDV stock	-0.02	-0.05	Real cost of driving
		-0.08	-0.28	Real price of new car
		0.29	1.00	Real income
VMTLDV	Miles traveled	-0.07	-0.21	Real cost of driving
		0.19	0.60	Real income
ETSIMPCL	Ethanol imports	0.61		Real ethanol price, advanced
ETDEXPCL	Ethanol exports	-0.12		Real ethanol price, conventional

Table A.1. Summary of baseline results

	2013	2016	2019	2022	2025	2012-2025 Average
Fuel economy of light duty vehicles, miles per gallon	21	22	23	25	27	23
Miles traveled by light duty vehicles, billion miles	2666	2736	2836	2963	3121	2843
Light duty vehicles, million vehicles	223	228	234	240	248	233
Gasoline share of light duty vehicles, percent	91	89	85	82	79	86
Diesel share of light duty vehicles, percent	1	2	2	3	3	2
Flex-fuel share of light duty vehicles, percent	6	7	9	11	13	9

Gasoline use by transportation sector, million gallons*	133,908	135,127	131,370	127,583	122,854	130,792
Gasoline use by light duty vehicles, million gallons	126,824	123,333	118,262	112,261	105,805	118,116
Diesel use by transportation sector, million gallons	42,385	46,002	46,699	47,733	48,533	46,039
Diesel use by light duty vehicles, million gallons	980	1,824	2,530	3,066	3,489	3,289
Total ethanol disappearance, million gallons	14,411	16,163	17,656	19,952	19,421	17,275
E85 use, million gallons	327	319	415	1,405	1,492	657
Retail unleaded gasoline price, $/gallon	3.70	3.60	3.38	3.45	3.72	3.50
Retail diesel price, $/gallon	4.04	3.80	3.60	3.64	3.72	3.80
Implied retail ethanol price (conventional), $/gallon	2.80	2.44	2.24	2.26	2.37	2.40
Crude oil, refiners acquisition price, $/barrel	115	123	135	145	155	133
Conventional RIN price, $/RIN	0.57	0.32	0.57	0.61	0.52	0.48
Mandate compliance cost, billion dollars	7.94	5.64	10.89	11.81	9.29	8.56

*: For consistency, gasoline use by transportation sector matches the EIA definition which includes all fuel ethanol.

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A CRITICAL ASSESSMENT OF RIN PRICE BEHAVIOR AND THE IMPLICATIONS FOR ETHANOL AND GASOLINE PRICE RELATIONSHIPS

1. Introduction

In recent years, the U.S. government has supported biofuel production through various means including tax credits, production subsidies, import tariffs, and mandates. At present, many of those interventions have expired or are set to expire at the end of 2012 under the current policy regime. The Renewable Fuel Standard (RFS) that sets out minimum biofuel use mandates remains in effect under current legislation. A critical element of implementing the RFS is the compliance system involving tradable credits known as Renewable Identification Numbers (RINs). A RIN is generated whenever a biofuel that complies with the RFS is produced. Fuel blenders submit RINs at the end of each calendar year to prove that they comply with the RFS. Consequently, RINs are key indicators of how the mandates affect markets, but they have not been subject to careful assessment. As the RIN markets continue to evolve and more data become available, we are in a better position to see how those markets interact with each other and with broader agriculture and energy markets. The goal of this study is to assess critically RIN price behavior and the prior assumptions that have been made in regards to that behavior.

2. RFS and RIN overview

The RFS, as laid out in the Energy Independence and Security Act (EISA) of 2007 (PL 110-140) is a complicated policy with a hierarchy of renewable fuel requirements[9].

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[9] The RFS was devised first in the Energy Policy Act of 2005. The EISA of 2007 expanded and updated those provisions. The hierarchies described in this study reflect what is expected under the rules of EISA. It

At the broadest level, the RFS requires at least a certain amount of renewable fuels achieving a 20% reduction in greenhouse gas (GHG) emissions. Beneath the umbrella of the total renewable fuel requirement is a sub-mandate that requires a minimum level of so-called “advanced” biofuels that achieve a 50% reduction in GHG emissions. In a similar fashion, there are two sub-mandates to the advanced requirement. One is for cellulosic biofuels that achieve at least a 60% reduction in GHG emissions and another is for biomass-based diesel. The amounts required by the sub-mandates do not necessarily sum to the amounts required by the broader mandates. This creates two gaps within the RFS, commonly referred to as the “conventional” gap and the “other-advanced” gap (Thompson, Meyer, and Westhoff 2011). The conventional gap is the difference between the advanced requirement and the overall requirement and can be met through the use of conventional (i.e. corn-starch based) ethanol. The other-advanced gap is the difference between the sum of the cellulosic and biodiesel[10] requirements and the advanced requirement. This gap can be met through the use of sugarcane ethanol, which typically is imported from Brazil, or other advanced biofuels.

RINs are the instrument through which the Environmental Protection Agency (EPA) tracks RFS compliance. The RIN itself is a 38-digit code that identifies, among other things, the type of renewable fuel it to which it applies, the renewable fuel producer, and when the fuel was produced (McPhail, Westcott, and Lutman 2011). RINs are generated and assigned to renewable fuel as it is produced. The RINs remain with the assigned batch of fuel until an obligated party (i.e. fuel blender) incorporates it into the motor fuel

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is unclear how certain price relationships might have evolved in the transition from one set of rules to the next.

[10] A gallon of biodiesel is given a 1.5 gallon equivalence value relative to ethanol. Here, and throughout, biodiesel volumes are adjusted accordingly when comparing volumes across the mandate hierarchy.

pool. As soon as blenders make use of the renewable fuel, the RINs may be separated and the blender retains title to those detached RINs.

Obligated parties under the RFS show compliance by submitting to the EPA an amount of RINs that is equivalent to their renewable volume obligation (RVO). RINs are tradable, so some obligated parties might use extra biofuels beyond their RVO and sell RINs to other obligated parties who do not blend as much biofuel as required to meet their own RVO. The RFS also includes some flexibilities regarding compliance. For example, an obligated party can carry a deficit if it is unable to meet its RVO in a particular year. The only stipulation is that the blender cannot carry a deficit for two consecutive years. In other words, a blender who chooses to carry a deficit forward must meet its full RVO plus the deficit the following year. Furthermore, if a blender has excess RINs on hand, the blender may keep some to assist in meeting its RVO for the next year. In the latter case, obligated parties are subject to a “rollover” cap equal to 20% of the next year’s RVO (U.S. Environmental Protection Agency 2010).

3. Theories and realities of the RIN market

Applying economic theory to the case of the RFS and RINs leads to certain implications. In this section, some of the consequences of the RFS hierarchical requirements and the implementing mechanisms for relative RIN prices are listed. Then, actual RIN price data are used to investigate whether these theoretical implications hold. The application is informed by a description of current market events that might help to explain certain deviations or surprises.

Because RINs are used by obligated parties to demonstrate compliance, their market value is closely related to the degree to which the RFS requirements are binding

(Thompson, Meyer, and Westhoff 2009b). If the conditions in a biofuel market are such that the equilibrium quantity of biofuel use, in absence of the mandate, would be greater than the amount required by the RFS, the RFS is *not binding*. If, however, the equilibrium quantity would be less than the RFS requirement, then the RFS is *binding* (see figure 1). In the presence of a binding mandate, there is a gap between the price ethanol producers are willing to accept from fuel blenders and the price ethanol consumers are willing to pay to the fuel blenders. In other words, a binding mandate creates a price wedge that is equal to the “core” RIN value (Thompson, Meyer, and Westhoff 2010). The core RIN value does not include speculative value or transactions costs that may play some role in RIN pricing.

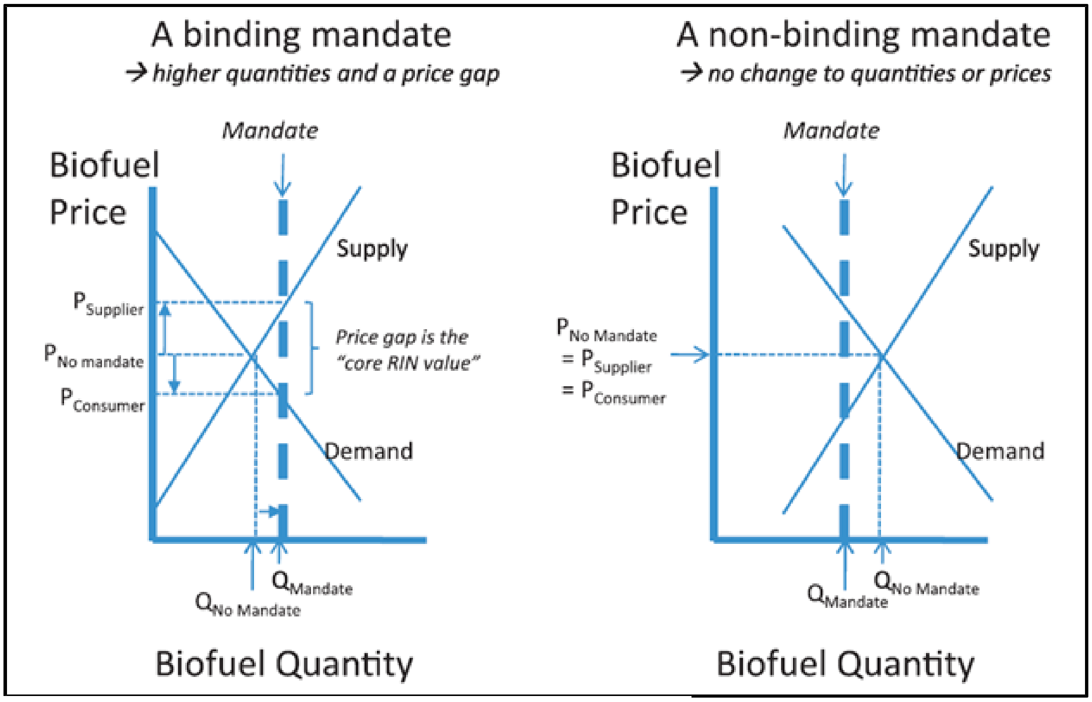

Figure 1. Source – Thompson, Meyer Westhoff (2009)

To illustrate how the degree to which the RFS requirements are binding can affect RIN prices, consider an example from the conventional ethanol market. Market conditions such as low oil prices or low corn yields make conventional ethanol less competitive with petroleum-based fuels and increase the difficulty in meeting the overall RFS requirement. In those situations the mandate might become binding, if it was not already so, or it might become *more* binding. Either by shifting demand or supply back (left), those shocks would create a larger wedge in the figure and represent the potential for higher RIN prices.

The mandate hierarchy, in turn, creates a hierarchy within RINs and RIN prices. Each mandate is a *minimum* use requirement. The implication is that fuels used in excess of a given sub-mandate can fill the gap between itself and the broader mandates, but not vice-versa. As an example, suppose market conditions are such that the requirement for biodiesel is no longer binding by itself. The amount of biodiesel used beyond the RFS biodiesel requirement can then be used to meet part of the other-advanced gap and reduce the need for sugarcane ethanol imports from Brazil. In the extreme case, assuming there are no capacity constraints or other hindrances, biodiesel use in excess of the advanced requirement less the cellulosic sub-mandate could, in theory, go on to help fill the conventional gap. In that case, there would be less need for conventional ethanol to meet the overall RFS requirement.

This hierarchy applies to RIN prices, as well. Because excess RINs from narrow RVOs can be "demoted", or used to satisfy the broader RVOs, the price for broader RINs acts as a price floor for narrower RINs. The type-price hierarchy is summarized by the following equation:

$$PrRIN_{Conventional} \leq PrRIN_{Advanced} \leq Min(PrRIN_{Biodiesel}, PrRIN_{Cellulosic}) \quad (1)$$

To see why the type-price hierarchy must hold, imagine the price for an advanced RIN was less than the price for a conventional RIN. Blenders know the advanced RIN can also be used to satisfy the overall requirement, so they would shift demand away from buying conventional RINs and toward advanced RINs. In theory, arbitrage would ensure the price of the narrow RIN could not persist below the price of the broader RIN (Thompson, Meyer, and Westhoff 2010).

There is also another hierarchy in RIN prices from the perspective of RIN vintage. In any given compliance period, there can be up to three vintages of RINs traded physically. This is allowed by a combination of the rollover provisions and EPA reporting requirements. RINs have, at most, a two-year lifespan according to the RFS regulations. RINs generated in the current year can be used at the end of the year in which they are generated to help meet the RFS, be rolled over to apply against the RFS in the following year (within the 20% limit), or else expire if unused. However, annual compliance reports for a compliance year are due by the end of February the following calendar year, so it is possible for rolled-over RINs to be traded briefly in the year following their official expiration date.

Broadly speaking, the vintage-price hierarchy is related to RIN expiration. RINs generated in the current year have the longest lifespans and can be used to meet the RFS requirements this year or, potentially, next year. RINs generated the previous year can be used only to meet the requirement in the current year or they expire. Much like RINs associated with broader mandates relative to RINs of narrow sub-mandates, older RINs have a limited potential for use relative to newer RINs, so their prices should act as a price floor for RINs with longer lifespans. The following equation expresses the vintage-price hierarchy:

$$PrRIN_{t-1} \leq PrRIN_t \tag{2}$$

As an example of this hierarchy, consider the early months in a year when compliance reports are being filed. The hierarchy should hold at that time because, if current vintage RINs are selling for less than the previous vintage, then obligated parties could claim a deficit for the previous year and immediately offset it through purchases of the cheaper RINs. Arbitrage forces would bring the vintage prices together, in theory.

To determine if the hierarchies of RIN prices implied from theory hold in practice, this study examines daily RIN price data from Oil Price Information Service (OPIS) going back to January 2009. The data cover both fuel-type and vintage and are provided in units of $/RIN, rather than $/gallon. This distinction is important as some biofuels are assigned more than one RIN per gallon of fuel produced. For example, a gallon of biodiesel obtains 1.5 RINs, so if a biodiesel RIN is worth $1/RIN the value attached to a gallon of biodiesel would be $1.5. Plots of the daily RIN prices are provided in the appendix.

The hierarchy of the RFS mandates was evident in the prices of RINs in each year with only a few isolated exceptions. Specifically, the conventional RIN price is lowest and the advanced RIN price is less than the biodiesel RIN price[11]. The first exception occurred in late 2010. For most of 2009 and 2010, the 2009-vintage biodiesel and conventional RINs had similar price movements (figure A.1). Their values converged toward zero and the price movements became more synchronous in late 2010 as their expiration date approached. However, between October 2010 and March 2011, at which

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[11] The EPA has used its authority to waive cellulosic requirement each year since 2010. As part of the waiver, the EPA offers cellulosic credits to blenders at a price per RIN (after adjusting for inflation) equal to either $0.25 or $3.00 less the wholesale price of gasoline, whichever is higher. If a blender chooses to use one of these credits, it must also submit an advanced RIN to demonstrate compliance. Thus, the hierarchy still will hold in the event of a cellulosic waiver. Because the price of cellulosic RINs has largely been determined by the waiver events, this study does not include them in the analysis.

point the 2009-vintage could no longer be traded, there were several occasions in that period when biodiesel RINs were cheaper than conventional RINs. The differences, when they occurred, were usually \$0.0025/RIN or less and lasted from 1 to 4 days. Another instance in which this price hierarchy contradicted our expectations took place in early 2011 (figure A.3). For the first three trading days that year, 2011-vintage biodiesel RINs were cheaper than advanced RINs of the same vintage. The factors that contribute to such price anomalies, albeit only briefly observed, are unclear.

The vintage-price relationship has been violated several times in the case of biodiesel (figure A.6). Biodiesel RIN prices have, in a few instances, run counter to the theoretical expectations based on vintage. The first instance occurred in early 2011, when the price of the 2010-vintage RINs was higher than the 2011-vintage for 13 days, and by an average of \$0.039/RIN, or 5.1%. This exception is striking particularly because of the timing. During that period in early 2011, obligated parties would have been filing annual 2010 compliance reports with the EPA, which means they would be making decisions regarding RIN deficits or RIN carryover.

In this case, there are three potential confounding factors related to biodiesel policy. The blender’s decision to claim a deficit is influenced, in part, by its expectation of the degree to which the current and future mandates will be binding because of the prohibition against carrying deficits in consecutive years. Moreover, the deficit must be made up in the following year, so a deficit in 2010 would increase a blender’s RVO in 2011. The expiration of the biodiesel tax credit at the end of 2009 led to sharply lower biodiesel production in 2010 and a more binding 2010 mandate. Although the tax credit was reinstated in late 2010, a somewhat bleaker outlook for biodiesel combined with a growing mandate may have increased the expectation that the 2011 requirement would be even more binding. Furthermore, the RFS regulations limited the size of the deficit an obligated party could claim on the 2010 biodiesel mandate to 57% of the 2010 biodiesel RVO (U.S. Environmental Protection Agency 2010). This could have created a situation in which blenders with excess 2010 RINs wanted to carryover as many as they could to aid in meeting the 2011 mandate. At the same time, blenders trying to find RINs were willing to pay a somewhat higher price for RINs to meet their 2010 RVO if they expected to pay even higher RIN prices in late 2011 in the event that they declared a 2010 deficit.

A similar exception to the vintage-price hierarchy, in which 2010-vintage RINs were more expensive than the 2011-vintage RINs, occurred for 69 of the 74 final trading days allowed for 2010-vintage RINs. This occurrence included a 49 consecutive day stretch lasting from late November 2011 through early February 2012. The price difference averaged $0.049/RIN, or 3.8%. This occurrence is surprising because 2010-vintage RINs were quickly approaching the end of their valid lifespans, so their value should have been diminishing, relative to the 2011-vintage. In this case, there were other external factors that, again, may have influenced the behavior of obligated parties. In November 2011, the EPA began issuing Notices of Violation to parties that used allegedly fraudulent RINs to satisfy their RVOs. Those announcements might have shaken blender confidence in 2011-vintage RINs, thus leading blenders to turn to the available, and potentially more credible, 2010-vintage RINs as a way to meet their 2011 RVO (within the rollover limit). OPIS also issued several reports of RINs from small biodiesel producers selling for discounted rates as obligated parties considered such RINs to be riskier (Oil Price Information Service 2012)

Earlier this year, the vintage-price hierarchy was violated again in the biodiesel RIN market as 2011-vintage RINs sold for a premium compared to the 2012-vintage for 15 of 17 trading days spanning May 16 to June 8. Over that period the average difference between the two vintages was $0.04/RIN, or 2.8%. There are several possible reasons these violations could have occurred. Although fraudulent RINs might still have been a concern, biodiesel producers and fuel blenders were facing other market uncertainties as well. For example, the tax credit given to biodiesel producers was allowed to expire at the end of 2011. This had a negative impact on producers' operating margins and might have increased the degree to which blenders expected the 2012 mandate to be binding. In addition, there was uncertainty surrounding the degree to which the 2013 mandate would be binding. At the time these violations were occurring, the EPA had not yet finalized the 2013 RFS requirement for biodiesel. The EPA ruled in September that the 2013 biodiesel mandate would be set at 1.28 billion gallons, up from 1.0 billion gallons in 2012.

There were two periods of persistent violations of the vintage-price hierarchy occurring in the advanced RIN market earlier this year (figure A.7). The first lasted for 21 trading days from late January and through the middle of February. The 2011-vintage RINs exceeded the 2012-vintage by an average of $0.02/RIN, or 2.3%. The second occurrence lasted for 13 trading days in July and early August. The average price difference over that period was $0.01/RIN, or 2.5%. Potential reasons for these violations remain unclear, but in a personal communication, an official from OPIS suggested potential liquidity issues as a source of volatility in advanced RIN markets. That volatility might influence behavior in ways that are unexpected.

The behavior of conventional RIN prices provides a stark contrast to that of advanced and biodiesel RIN prices. Conventional RIN prices have followed the expected vintage-price hierarchy completely (figure A.5). There is not a single violation of this expected relationship in price data going back to January 2009.The reason might be that the conventional ethanol RIN market does not face as many of the same uncertainties as those for advanced and biodiesel RINs. For example, there has been no indication of fraudulent RIN activity in the conventional market. There also is less uncertainty regarding the level of the overall mandate, although blenders must still consider the degree to which the requirement is expected to be binding. The conventional RIN market also is more established than the advanced RIN market, so it might be the case that the conventional RIN market is more liquid.

4. Extensions to domestic biofuels markets

This section primarily focuses on the relationships between gasoline and biofuel prices at the wholesale and retail levels. Previous studies have highlighted the role of the RFS requirements, tax credits, and other biofuel market interventions in those relationships (de Gorter and Just 2009; de Gorter, Drabik, and Just 2011; Du and Hayes 2009; Thompson, Whistance, and Meyer 2011). The prices for advanced and conventional RINs provide clues to the type of relationships we expect between gasoline and ethanol prices.

At the wholesale (i.e. blender) level, ethanol and gasoline are inputs to a final motor fuel product, and they can be viewed as either complements or substitutes (de Gorter and Just 2009; Luchansky and Monks 2009; Szklo, Schaeffer, and Delgado 2007; Thompson, Meyer, and Westhoff 2009a; Tyner, Taheripour, and Perkis 2010). The relationship seems to depend on the relative prices of the inputs and whether or not the RFS requirement is binding. When the gasoline blendstock is more expensive than ethanol at the wholesale level, blenders might view ethanol as a gasoline substitute and the prices might have a strong positive correlation. When ethanol is more expensive than the gasoline blendstock, blenders might view the two products as complements and the prices might have a weak or, perhaps, negative correlation. As a complement, ethanol would be used in fixed proportion to gasoline, subject to either the RFS mandate if it is binding or other oxygenate requirements if the RFS is not binding.

Figure 2 illustrates the relationship between gasoline and conventional ethanol prices at the wholesale level. The upper chart plots the weekly spot prices for reformulated blendstock for oxygenate blending (RBOB) and ethanol, with RIN attached, from January 2008 through September 2012. The lower chart plots weekly conventional RIN prices (left vertical axis) and cumulative weekly overall RIN generation (right vertical axis). The shaded columns represent the overall RFS requirement for that year (right vertical axis).

A theoretical implication of a binding RFS mandate is that it reduces any type of gasoline-ethanol price relationship at the wholesale level. In the presence of a binding mandate, ethanol supply and demand are unable to adjust fully to the equilibrium level that would occur otherwise. The wholesale price must remain at a level high enough to induce the necessary level of production, and the retail price of ethanol in blended fuels must be low enough to induce that same level of consumption (see figure 1). An ethanol demand shift, such as one caused by a shift in gasoline prices, will affect the retail ethanol price and the RIN price but the wholesale ethanol price will remain unaffected if a binding mandate disallows quantity changes. Thus, the relationship between wholesale gasoline and ethanol prices is reduced, at least, if the potential for the rollover and deficit provisions to put some flexibility into the mandate is taken into account.

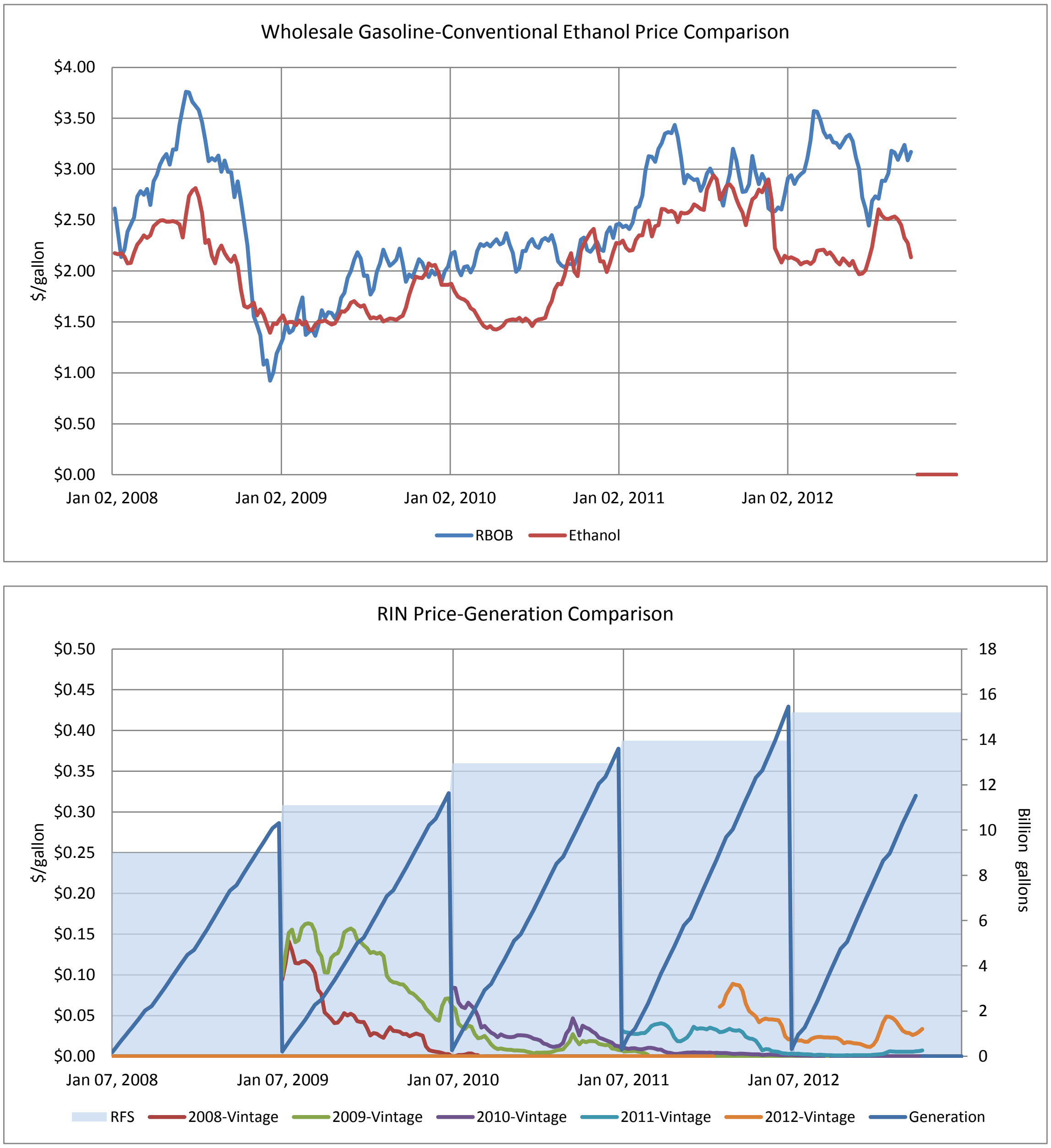
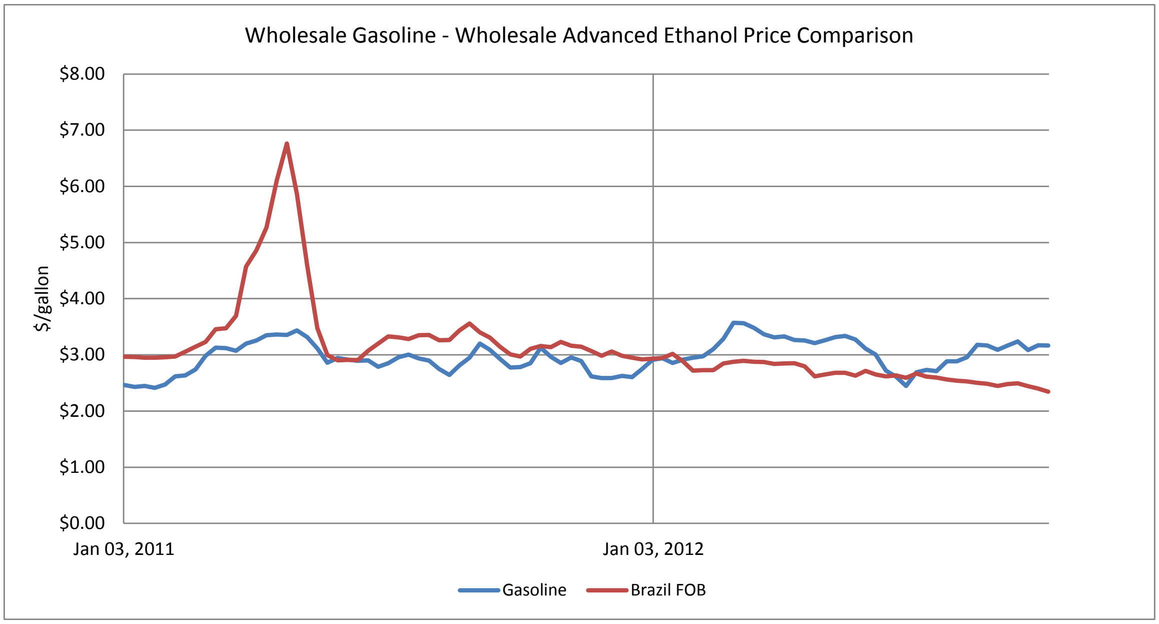


Figure 2. Source(s) – Oil Price and Information Service, Energy Information Administration, Agriculture Marketing Service, EISA 2007, and Environmental Protection Agency

gasoline and ethanol prices move in a nearly lockstep manner throughout most of 2008. This is consistent with a view of these two fuels as substitutes. Toward the end of 2008, however, as the RBOB price continued its downward trend, the ethanol price fell only until it reached a level of $1.50/gallon. The ethanol price fluctuated around that level for the next several months, even after RBOB prices recovered. The mandate was binding around that time, as suggested by conventional RIN values that began 2009 in the $0.10 to $0.15 range. In 2009 and 2010, the gasoline-ethanol price relationship seems to break down toward the end of each year as ethanol prices spike higher and RBOB prices dip lower. There are several possible factors that might contribute to this behavior. For example, as the annual compliance period draws to a close, blenders might be under more pressure to obtain the necessary quantity of RINs to demonstrate compliance. Blenders' expectations of the degree to which the following year's mandate will be binding might also be starting to take shape at that time of year. At the same time, the summer driving season is ending and gasoline prices normally fall. Corn supplies remained tight throughout 2011, but a surge in petroleum prices meant the mandate was less binding and the relationship between RBOB and ethanol prices seemed to hold. As opposed to the two prior years, late-2011 was marked by a sharp decline in ethanol prices as corn prices dropped. In 2012, a major drought adversely affected the corn crop and both corn and ethanol prices increased in response. Conventional RIN prices also increased sharply, which reflected blenders' concerns that the RFS mandate would be more difficult to achieve.



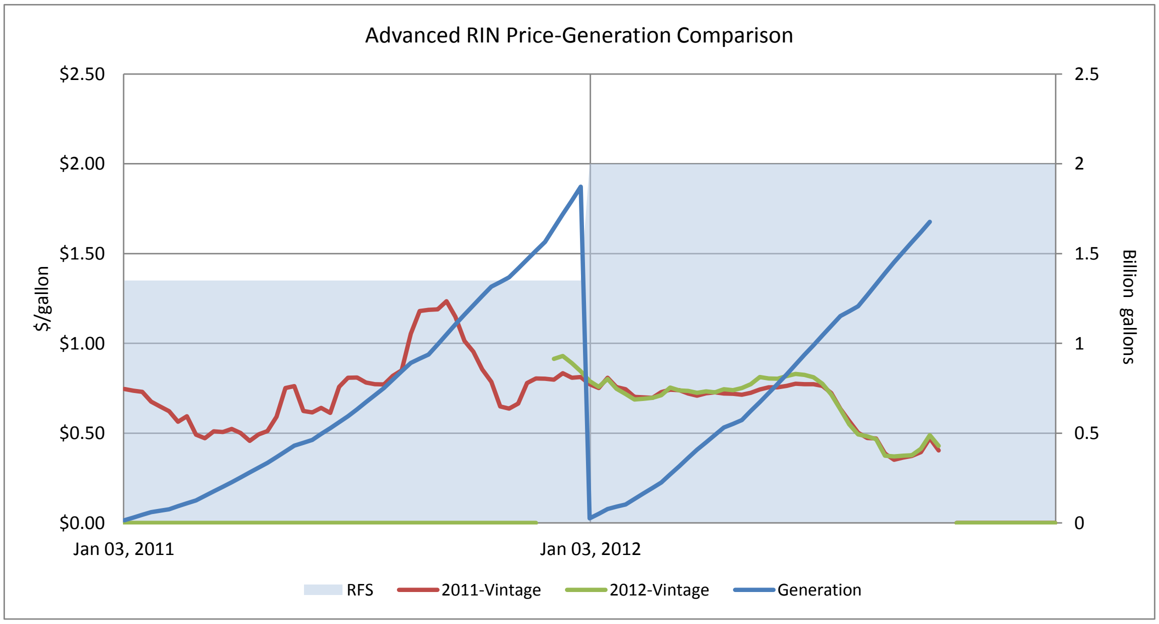


Figure 3. Source(s) – Oil Price and Information Service, Energy Information Administration, UNICA, EISA 2007, and Environmental Protection Agency

Advanced RIN prices have been well above zero since the beginning of 2011, so the advanced mandate appears to have been binding since then. The comparison of the wholesale advanced ethanol price, calculated as the Brazilian anhydrous ethanol price plus transportation costs, and the wholesale gasoline price show that their relationship is similar but it may not be as strong as the relationship between wholesale conventional ethanol and gasoline prices (figure 3). The lack of a clear relationship between the two prices also seems to fit the price behavior that might be expected in the presence of a binding mandate.

In the previous section, the core RIN value was defined as the difference between the price blenders must pay to purchase ethanol for blending (i.e. wholesale) and the price they can charge fuel retailers (i.e. resale) excluding speculative value and transactions costs. These basic relationships can be defined as follows:

$$PrRIN_{Adv} = (PrEth_{Brz} + Cost_{Tran}) - TaxCred - PrEth_{Res} \tag{3}$$

$$PrRIN_{Con} = PrEth_{Whl} - TaxCred - PrEth_{Res} \tag{4}$$

$$PrEth_{Res} = PrEth_{Ret} - (PrGas_{Ret} - PrGas_{Whl}) \tag{5}$$

The first equation is based on the fact that, at present, the advanced gap is met primarily through the use of sugarcane ethanol imported from Brazil. Blenders in the U.S. that wish to blend sugarcane ethanol must pay the Brazilian anhydrous ethanol price, $\mathrm{PrEth}_{\mathrm{Brz}}$, and the transportation cost for delivery, $\mathrm{Cost}_{\mathrm{Tran}}$, including the 2.5% ad valorem tariff and the \$0.54/gallon specific tariff[12]. In the second equation, $\mathrm{PrEth}_{\mathrm{Whl}}$ is the price blenders pay to conventional ethanol producers for delivery. In either case, the resale price is the same; from the terminal, blenders charge $\mathrm{PrEth}_{\mathrm{Res}}$ to fuel marketers/distributors for resale in blended fuels at retail outlets further down the supply chain. Equations 3 and 4 are also adjusted, historically, for the ethanol producer tax credit, TaxCred, that expired at the end of 2011. $\mathrm{PrEth}_{\mathrm{Res}}$ is the retail price of ethanol, $\mathrm{PrEth}_{\mathrm{Ret}}$, less any markups at the retail level. The markups are assumed to be the same as those between retail and wholesale gasoline prices, $\mathrm{PrGas}_{\mathrm{Ret}}$ and $\mathrm{PrGas}_{\mathrm{Whl}}$.

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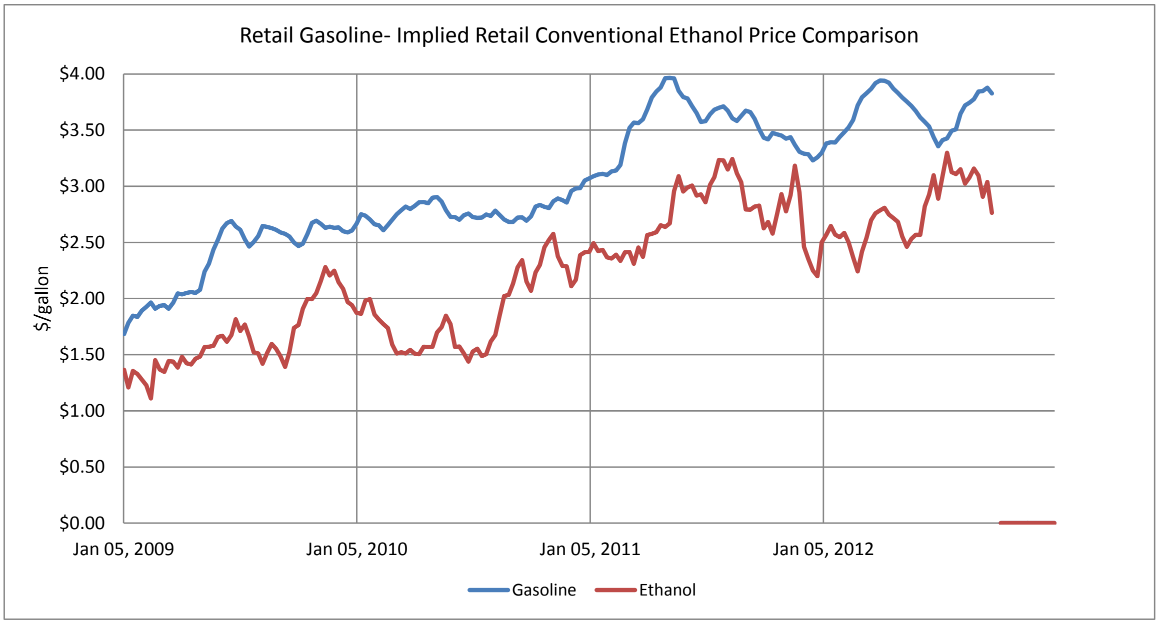
[12] The \$0.54/gallon specific tariff expired at the end of 2011.

There are no retail ethanol price data because ethanol is sold to consumers only in blended fuels. The *implied* retail prices for each type of ethanol can be determined by combining either equation 3 or equation 4 with equation 5, rearranging, and solving for $\text{PrEth}_{\text{Ret}}$. The relationship between retail gasoline and retail ethanol prices should be less affected by whether or not the mandate is binding. An ethanol demand shift at the wholesale level will have an effect on $\text{PrEth}_{\text{Res}}$, which will translate into some effect on $\text{PrEth}_{\text{Ret}}$. This effect would occur regardless of whether or not the mandate is binding. The relationships between the retail gasoline and implied conventional and advanced ethanol prices are shown in figures 4 and 5, respectively. In each case, there appears to be a fairly strong relationship between the two price series, even when the mandate is binding.

The examples of observational evidence presented in the preceding section are simple illustrations of the gasoline-ethanol price relationships that were described, but more formal techniques also exist to test for such relationships. Simple correlation measures would also give an idea of the price relationships, but they could be misleading if, for example, an unobserved factor affected both price variables in a systematic manner. Cointegration tests have evolved as a means for analyzing the relationships between two or more variables in a way that, potentially, avoids the pitfalls of spurious correlation.

The first stage of a cointegration test looks for a unit-root in each of the variables of interest. Variables that exhibit a unit-root process are considered non-stationary. Non-stationary variables generally take the form of:

$$z_t = z_{t-1} + \epsilon_t \tag{4}$$



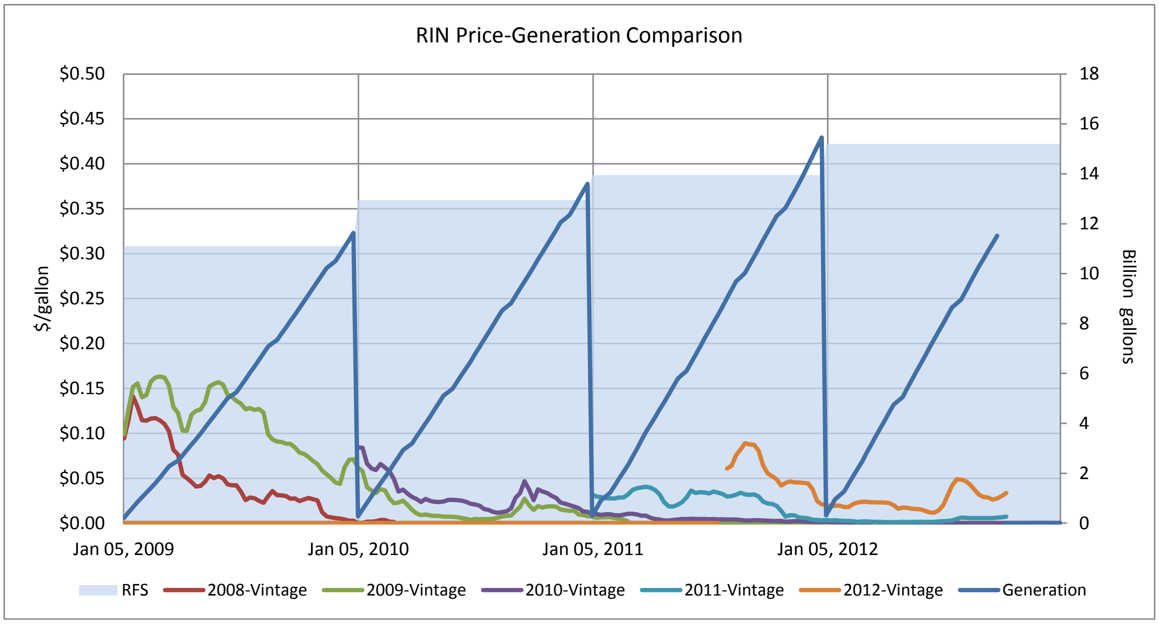


Figure 4. Source(s) – Oil Price and Information Service, Energy Information Administration, Agriculture Marketing Service, EISA 2007, and Environmental Protection Agency

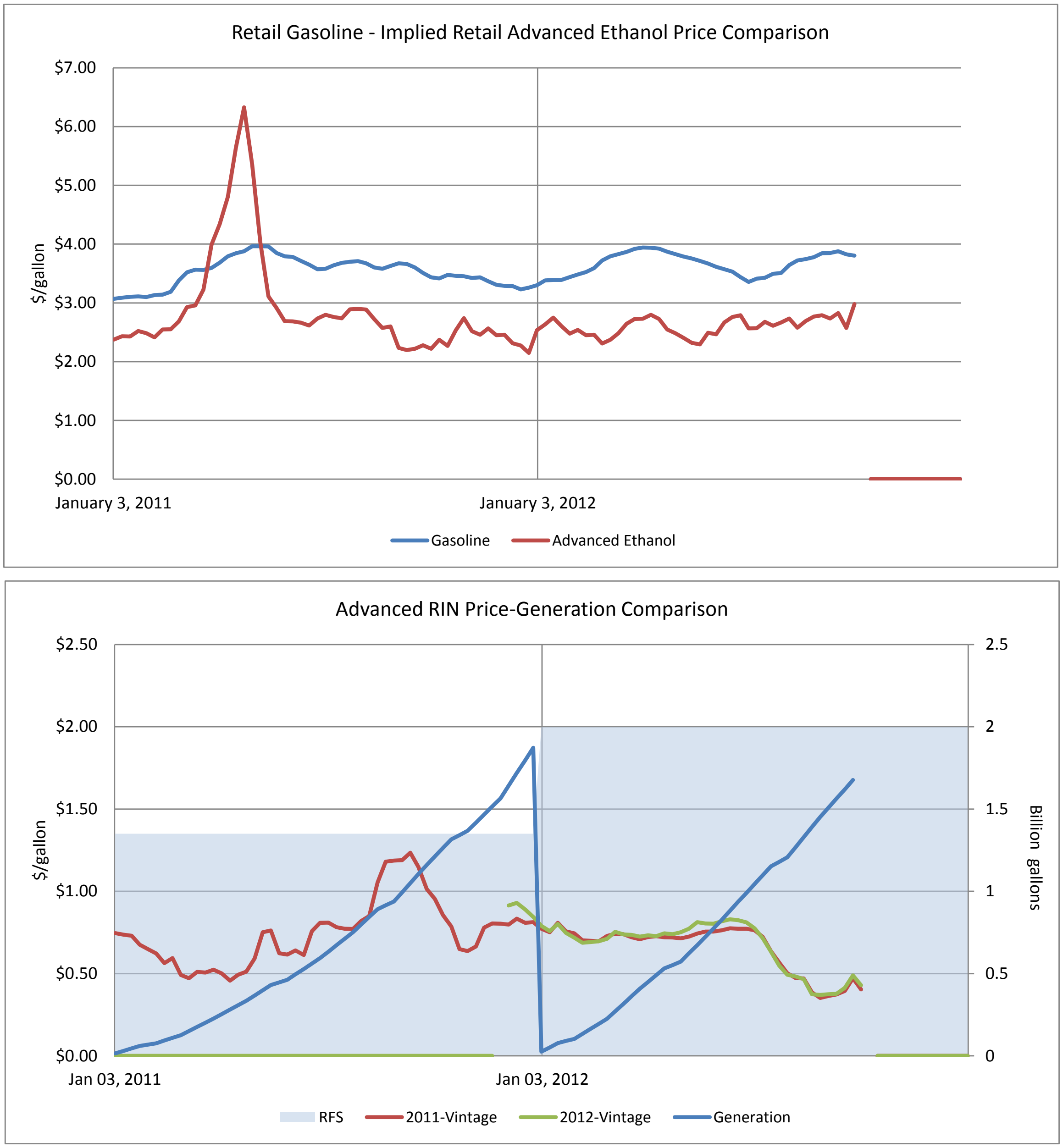


Figure 5. Source(s) – Oil Price and Information Service, Energy Information Administration, UNICA, EISA 2007, and Environmental Protection Agency

although constant terms and trends can also be included (Greene 2008). Regressions that include non-stationary variables can suffer from spurious correlation. Relationships appear to exist between variables that are, in fact, unrelated. The gasoline and ethanol price variables were examined for unit-roots by using the Augmented Dickey-Fuller (ADF) test. The lag-structure for each ADF test was chosen according to the minimum value of the Schwarz Information Criterion (SIC). The ADF tests the hypothesis that a given variable exhibits a unit-root process (i.e. it is non-stationary) against the alternative hypothesis that it is stationary. If the ADF test-statistic is larger than a given critical value, the hypothesis of non-stationarity can be rejected in favor of stationarity.

Variables are said to be cointegrated if their degrees of non-stationarity are equal and there exists a linear combination of the two variables such that their residuals are stationary (Greene 2008). If that is the case, their estimated relationship is not considered spurious. The simplest technique for detecting cointegration among two variables consists of running a regression of one variable on the other and testing the residuals for stationarity using the ADF test as before. That is the approach taken in this study.

In the context of this study, the results of a cointegration test, in addition to RIN price data, can give an indication of whether or not the relationship between wholesale gasoline and ethanol prices changes when the mandate is binding relative to when it is not binding. If the two variables appear to be cointegrated, there is evidence of a clear, non-spurious relationship between them, although it is not proven. A relationship such as that might be expected to hold when the RFS requirements are non-binding and the wholesale ethanol price can move more freely in the presence of a retail ethanol demand shock. If the variables do not appear to be cointegrated, there is less evidence of a clear relationship, which might be expected when the mandates are binding and retail ethanol demand shocks caused by gasoline price changes have no effect on wholesale ethanol prices.

Previous research has employed cointegration, as well as other time series techniques, to investigate the relationship between agricultural, biofuel and other energy commodities (Du and McPhail 2012; McPhail 2011; Serra et al. 2010; Zhang et al. 2009, 2010). The studies try to account for structural change within the markets either in broad terms, such as pre-ethanol boom and ethanol boom (Zhang et al. 2009) or using supply and demand shocks (McPhail 2011). The previous studies generally agree that the links between these commodity markets have varied as the structure of the markets changed. In those prior studies, structural changes were determined using statistical methods in the absence of RIN market information.

This study extends that line of research by conducting cointegration tests over regimes that, at the wholesale level, are defined according to RIN price levels. Regimes were identified as periods of time in which the weekly average RIN price exceeded the value of transactions costs (i.e. the RFS requirement is, or is expected to be, binding) and those periods in which RIN prices were less than transactions costs (i.e. the RFS requirement is, or is expected to be, non-binding). Transactions costs were assumed to be $0.01 per RIN. There were two regimes identified in the analysis of wholesale gasoline and wholesale conventional ethanol prices. The two-week periods prior to the changes in regime were assumed to be transition periods, and they were excluded from the testing procedure.

Two regimes were identified for the wholesale conventional ethanol-gasoline price comparison. The first regime consisted of 144 observations that extended from January 5, 2009 to October 24, 2011. The data generating process (DGP) appears to be a random walk with an upward trend. There was one four-week period from late-July into August 2010 in which the average conventional RIN price fell to just less than $0.01/RIN, indicating a potential regime change. However, the rather transient nature of that period suggests that a full regime change was unlikely. Those four observations were included as part of the first regime. The SIC favored a two-period autoregressive lag structure, so that was the structure used in the ADF test. The ADF test, itself, could not reject the unit-root hypothesis at the 5% confidence level for either the wholesale gasoline price or the wholesale conventional ethanol price (table A.1). Although this result is not conclusive evidence that the variables are non-stationary, it does allow for the second stage of the cointegration test.

In the second stage, the residuals were determined from a regression with the following form:

$$PrGas_{Whl} = \alpha + \beta PrEth_{Whl} + \epsilon \tag{5}$$

where the wholesale gasoline and ethanol prices were the dependent and independent variables, respectively. A graph of the residuals also indicates random walk behavior with a slight upward trend. The ADF test of the residuals, again, could not reject the unit-root hypothesis of at the 5% confidence level. The evidence suggests the two price variables are not cointegrated over this time period. Given the average RIN price for that regime was $0.04/RIN, the mandate could be considered binding for the regime as a whole. The results of the cointegration test over this time period lend support to the idea that the relationship between wholesale gasoline and ethanol prices might be weak in the presence of a binding mandate. In light of these results, the nature of the relationship during that regime between gasoline and ethanol at the wholesale level appears to be complementary.

The second regime consisted of 34 observations that extended from October 24, 2011 forward to June 11, 2012. For the first 16 observations of 2012 the RIN price was above the assumed level of transactions costs by an average of $0.0017/RIN. For this analysis all of those observations remained a part of the second regime. The DGP for both price series appears to be a random walk with a slight drift. The SIC preferred a two-period lag structure for the gasoline price and a one-period lag structure for the ethanol price. The ADF test could not reject the hypothesis of non-stationarity in either price series at the 5% confidence level.

The residuals were obtained from an estimation of equation 5 over the time period covering the second regime. A graph of the residuals indicates random walk behavior with a zero-mean. The ADF test of these residuals rejected the unit-root hypothesis of at the 5% confidence level. In this case, the evidence suggests wholesale gasoline and ethanol prices are cointegrated during the second regime. During this regime, the average RIN price was $0.009/RIN, so the mandate could be considered non-binding. The results of the cointegration test for this period lend support to the idea that there is a clearer relationship between wholesale gasoline and ethanol prices when the mandate is non-binding. These results also suggest the two products are substitutes over this period.

Only one regime is apparent in the wholesale advanced ethanol-gasoline price comparison as advanced RIN prices remain above $0.35/RIN for the entire period. The regime consists of 91 observations extending from the beginning of 2011. The DGP for both series appears to be a random walk around a non-zero constant. Two-period lag structures were favored for the ADF tests. The ADF tests for the two price series rejected the null hypothesis of non-stationarity at the 5% level, indicating that each series exhibits stationary behavior. Although the two variables appear to be stationary, the cointegration test proceeds as before. The ADF test of the residuals could not reject the non-stationarity hypothesis at the 5% confidence level, but it could reject it at the 10% level. In this case, there is weak evidence the binding mandate could reduce the links between these two prices.

The implied retail ethanol-gasoline price relationships for both advanced and conventional ethanol were tested over one regime. In the case of conventional ethanol, the ADF test could not reject the non-stationarity hypothesis for implied retail ethanol prices and gasoline prices. Similar to the test at the wholesale level, the ADF test indicates the gasoline and advanced ethanol prices are stationary over the period. The results of the ADF tests for the residuals were mixed. The results of the conventional ethanol-gasoline comparison strongly rejected the hypothesis of non-stationarity, indicating the implied retail price of conventional ethanol and the retail price of gasoline share some cointegrating relationship over the period. However, the results of the implied retail advanced ethanol-gasoline comparison could not reject the unit-root hypothesis, suggesting the two prices do not share a cointegrating relationship over the period.

5. Concluding remarks

Previous studies have hinted at the expected relationships between ethanol, gasoline, and RINs in the context of the RFS. The purpose of this study was to go a step further and use the available RIN price data to assess those expectations critically. Observational evidence of the conventional, biodiesel, and advanced RIN markets provides mixed evidence for the expected type-price and vintage-price hierarchies for RINs. Violations of those hierarchies occur, although violations of the type-price hierarchy appear to be smaller in magnitude, less frequent, and less persistent than violations of the vintage-price hierarchy. Confounding factors such as RIN-fraud worries and policy uncertainty might contribute to vintage-price violations to some extent, but it is unclear how large a role they play.

Ethanol and gasoline price relationships were tested both observationally and empirically. At the wholesale level, gasoline and ethanol prices were expected to have a stronger relationship in the presence of a non-binding RFS requirement (potentially indicating a substitute-like relationship) and a weaker relationship when the requirement is binding (potentially indicating complement-like relationship). Observational evidence and basic cointegration tests seem to support that argument. Gasoline and implied ethanol prices at the retail level were expected to have a fairly strong relationship regardless of whether or not the mandate is binding. In this case, the results are mixed. Observational evidence lends support to the idea, but cointegration tests indicated otherwise for the relationship between retail gasoline and advanced ethanol.

There still exist many uncertainties and areas for improvement. It is difficult to draw any strong conclusions regarding the causes of RIN hierarchy violations. Caution must also be used when interpreting the results of the cointegration tests. The second regime for the wholesale conventional ethanol-gasoline relationship was a small sample and included several observations that slightly exceeded the \$0.01/RIN trigger. Furthermore, the regime trigger itself was chosen arbitrarily and may not fully account for the RIN rollover and deficit flexibility provisions in the RFS. A different trigger would imply a different regime composition, and in such a case the results might differ. Although this study sheds more light on the relationships between ethanol, gasoline, and RINs, there still is much to be learned.

Appendix

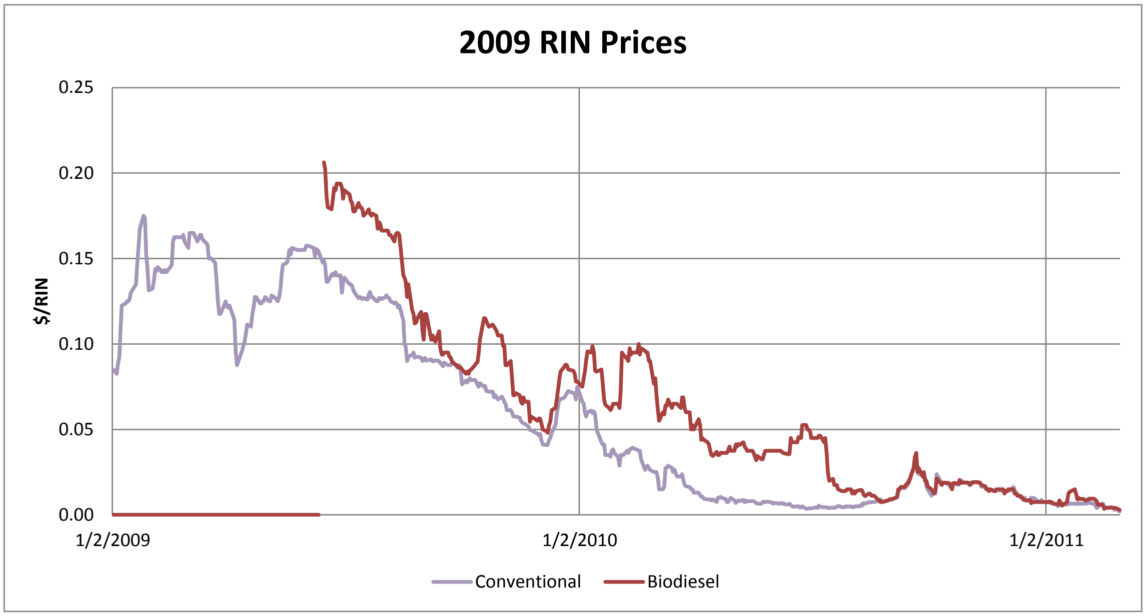


Figure A.1. Source – Oil Price Information Service

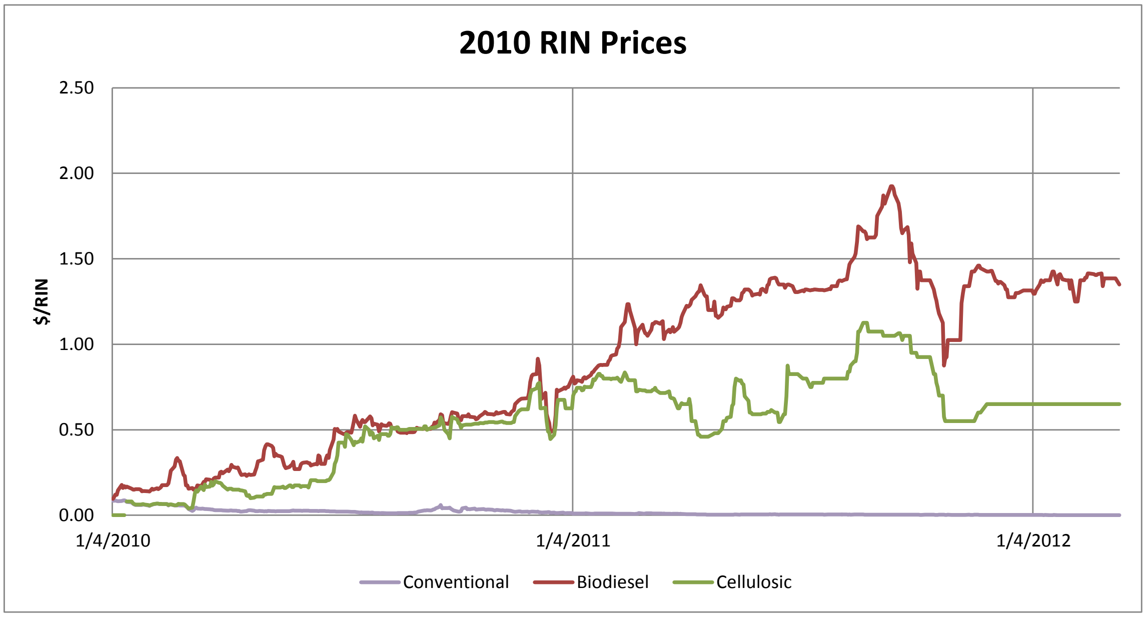


Figure A.2. Source – Oil Price Information Service

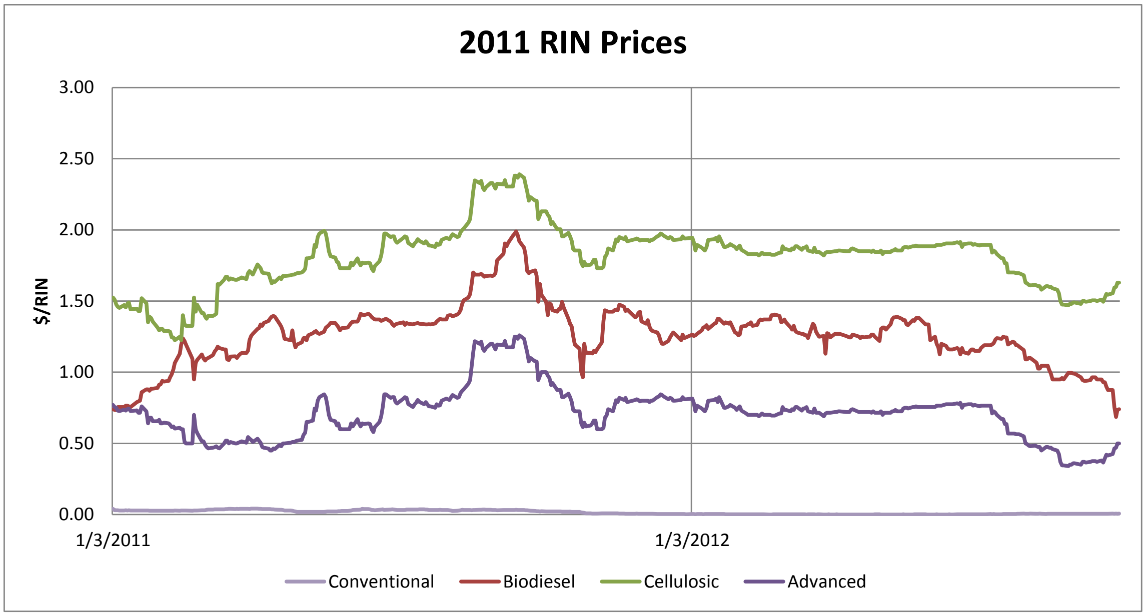


Figure A.3. Source – Oil Price Information Service
Note: Cellulosic calculated as the value of waiver credit offered by EPA plus the advanced RIN price.

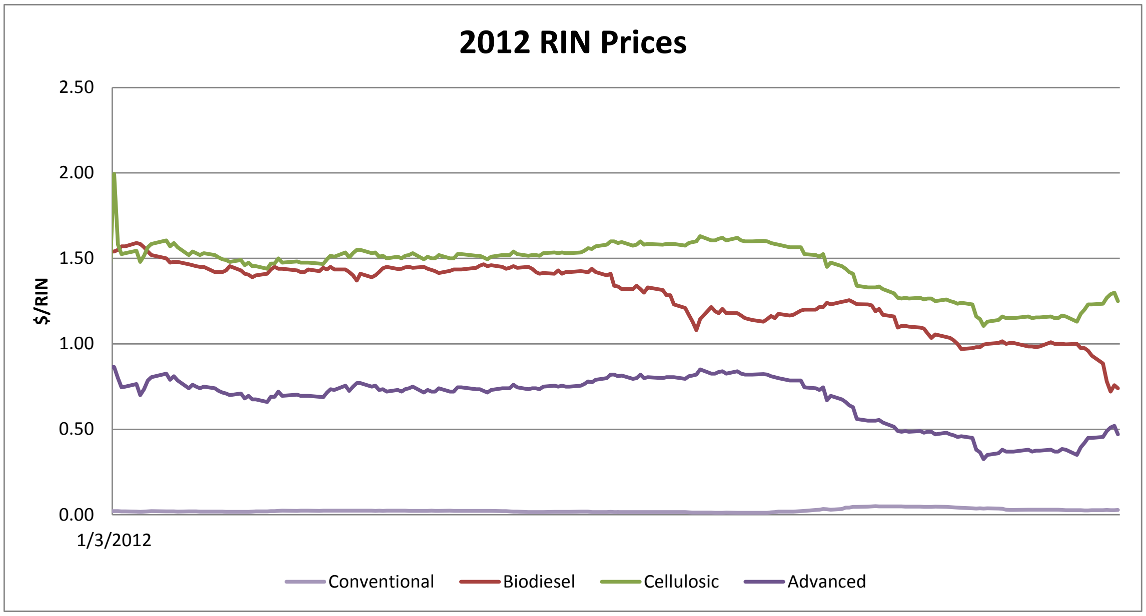


Figure A.4. Source – Oil Price Information Service
Note: Cellulosic calculated as the value of waiver credit offered by EPA plus the advanced RIN price.

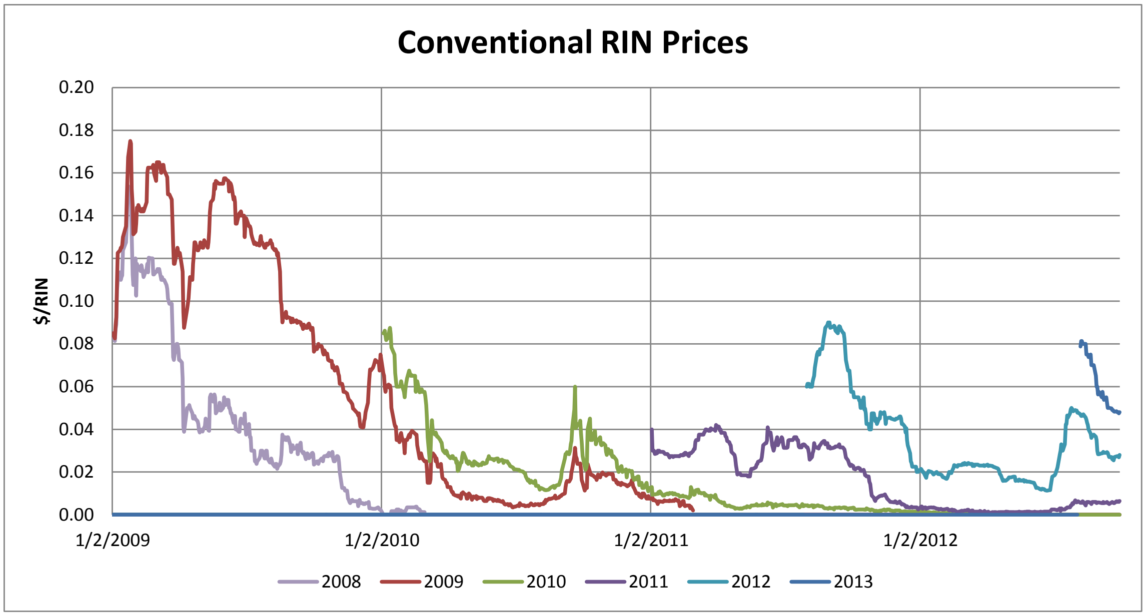


Figure A.5. Source – Oil Price Information Service

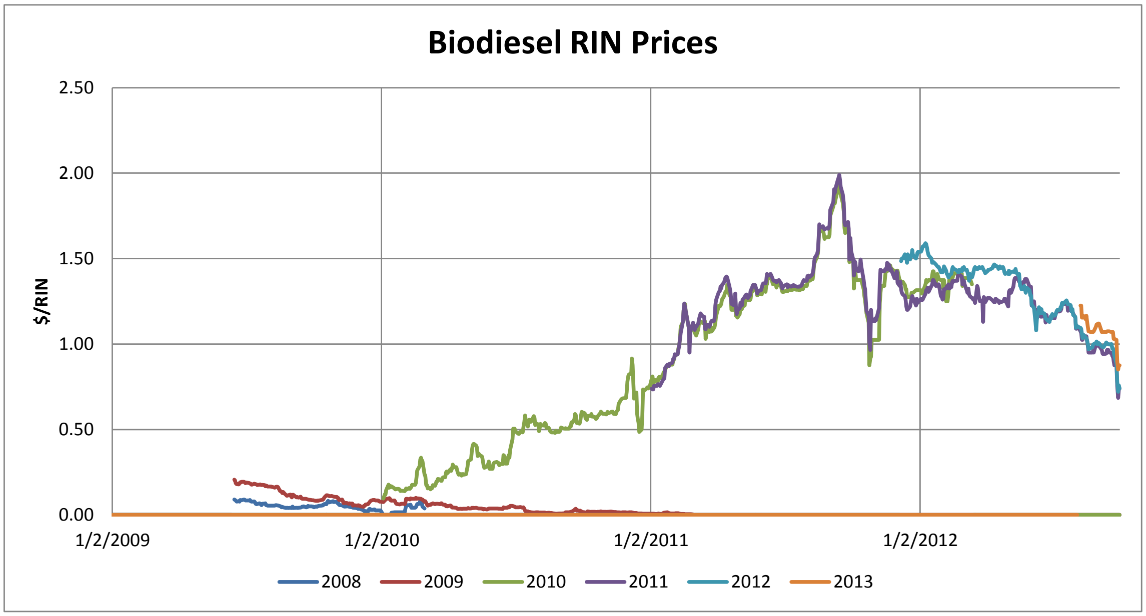


Figure A.6. Source – Oil Price Information Service

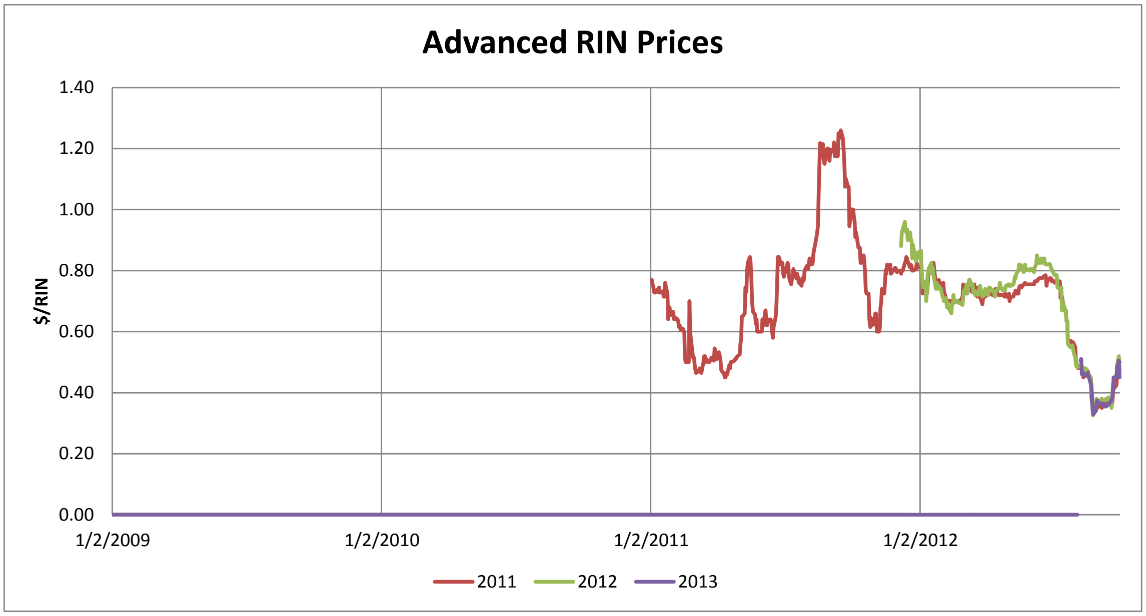


Figure A.7. Source – Oil Price Information Service

Table A.1. Summary of cointegration tests

Wholesale Conventional Ethanol-Gasoline		ADF	P-value
Regime 1	Gas price	-18.7114	0.0791
	Ethanol price	-8.8215	0.5088
	Residual	-16.5187	0.1252
Regime 2	Gas price	-0.2346	0.6234
	Ethanol price	-0.4703	0.5703
	Residual	-16.9670	0.0116
Wholesale advanced ethanol-gasoline			
	Gas price	-19.8546	0.0085
	Ethanol price	-15.6634	0.0275
	Residual	-20.0513	0.0531
Implied retail conventional ethanol-gasoline			
	Gas price	-14.8656	0.1787
	Ethanol price	-19.8043	0.0654
	Residual	-23.0471	0.0046
Implied retail advanced ethanol-gasoline			
	Gas price	-14.8707	0.0341
	Ethanol price	-21.857	0.0048
	Residual	-13.8948	0.2007

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