

Stacking low carbon policies on the renewable fuels standard: Economic and greenhouse gas implications

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HIGHLIGHTS

- ▶ The addition of a LCFS to the RFS increases the share of second generation biofuels.
- ▶ The addition of a carbon price to these policies encourages fuel conservation.
- ▶ These combined policies significantly increase the reduction in GHG emissions.
- ▶ They also achieve greater energy security and economic benefits than the RFS alone.

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ABSTRACT

This paper examines the economic and GHG implications of stacking a low carbon fuel standard (LCFS) with and without a carbon price policy on the Renewable Fuel Standard (RFS). We compare the performance of various policy combinations for food and fuel prices, fuel mix and fuel consumption. We also analyze the economic costs and benefits of alternative policy combinations and their distributional effects for consumers and producers in the transportation and agricultural sector in the US. Using a dynamic, multi-market, partial equilibrium model of the transportation and agricultural sectors, we find that combining the RFS with an LCFS policy leads to a reduction in first generation biofuels and an increase in second generation biofuels compared to the RFS alone. This policy combination also achieves greater reduction in GHG emissions even after considering offsetting market mediated effects. Imposition of a carbon price with the RFS and LCFS policy primarily induces fuel conservation and achieves larger GHG emissions reduction compared to the other policy scenarios. All these policy combinations lead to higher net economic benefits for the transportation and agricultural sectors relative to the no policy baseline because they improve the terms of trade for US.

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1. Introduction

Biofuel production is being promoted to achieve multiple objectives including enhanced energy security, reduced dependence on oil and mitigation of greenhouse gas (GHG) emissions from the transportation sector. At the same time, concerns about the competition for land posed by food crop based biofuels and its implications for food prices are leading to emphasis on the next generation of biofuels from cellulosic biomass. While conventional biofuels have been produced in the US using one dominant

feedstock (corn), advanced biofuels and particularly cellulosic biofuels can potentially be produced using a variety of feedstocks, including crop and forest residues and energy crops. These biofuels typically have lower life-cycle GHG intensity compared to corn ethanol and would divert less land from food production per unit fuel produced since they could be produced either from crop by-products or from energy crops that can potentially be grown productively on low quality land that is marginal for food crop production.

A key policy mechanism to induce the production of biofuels is the Renewable Fuels Standard (RFS) which sets volumetric targets for different categories of biofuels, based on the type of feedstock used and their GHG intensity relative to fossil fuels.² The targets

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² The RFS establishes three categories of renewable fuels each with a separate volumetric mandate and a specific lifecycle GHG emission threshold. The

for different categories are nested within the overall target, such that the target for cellulosic biofuels is set as a lower bound while the target for conventional biofuels (principally corn ethanol) is set as an upper bound. While this allows for the possibility that cellulosic biofuels could displace conventional biofuels it would occur only if their costs of production decreased sufficiently to allow them to be competitive with conventional biofuels. Moreover, the thresholds for GHG intensity establish minimum requirements for biofuels and do not create incentives to consume even lower carbon biofuels if they are more expensive. The RFS also grandfathered certain corn ethanol production plants from the GHG requirements, thus providing no incentive for reducing the carbon intensity from fuel produced by these plants (CARB, 2009).

This has led to interest in supplementing the RFS with other low carbon policies such as a Low Carbon Fuel Standard (LCFS) that would shift the mix of biofuels towards those with lower carbon intensity. A national LCFS does not currently exist, but a state-wide LCFS has been established in California that calls for a 10% reduction in the carbon intensity (CI) of transport fuels sold in the state by 2020 (CARB, 2009). British Columbia in Canada has a similar LCFS policy. Various Northeast, Mid-Atlantic and Mid-west states and the states of Washington and Oregon have been investigating the design of an LCFS for their regions. Policies similar to the LCFS are being implemented under the European Union's (EU) Fuel Quality Directive. While the LCFS would lower the GHG intensity of transportation fuel, its effect on fuel consumption and total GHG emissions is ambiguous (Holland et al., 2009). In contrast, a carbon price policy would add to the cost of consuming both biofuels and fossil fuels based on their carbon intensity and could contribute not only to GHG mitigation but also to lowering overall fuel consumption. However, previous studies show that a very high carbon price would be needed to incentivize cellulosic biofuel production (Chen et al., 2012a). A mix of policies may therefore be needed to achieve the multiple goals of reducing GHG emissions and dependence on fossil fuels while increasing energy security.

The purpose of this paper is to examine the economic and GHG implications of stacking a low carbon fuel standard (LCFS) with and without a carbon price policy on the RFS. We compare the performance of various policy combinations for food and fuel prices, vehicle kilometers traveled (VKT), fuel mix and fuel consumption. We also analyze the economic costs and benefits of alternative policy combinations and their distributional effects for consumers and producers in the transportation and agricultural sector in the US.

These combined policies are likely to differ from the RFS alone in the mix of biofuels that is consumed while continuing to at least meet the RFS. To the extent that a change in the policy mix changes the mix of biofuels consumed it will have implications for land required for biofuels and for food crop prices. Furthermore, these policies will differ implicitly or explicitly in their impact on the relative prices of alternative fuels and, therefore, in the extent to which fossil fuels are displaced by biofuels.

In examining the effect of these policies on GHG emissions, we consider both domestic emissions and GHG emissions in the rest of the world (ROW) due to market-mediated effects. Specifically, an increase in food prices could lead to indirect land use changes

(ILUCs) that would release the carbon stored in natural vegetation and forests as new land is brought into crop production (Searchinger et al., 2008). Biofuel production will also displace demand for fossil fuels and lower the price of fossil fuels in the world market and cause demand to rebound back to some extent. The price induced increase in fossil fuel consumption (and VKT) is referred to as the "rebound effect" which will offset a part of the initial reduction in demand (Chen and Khanna, 2012). The magnitude of this rebound effect will influence the extent to which the RFS and the LCFS will contribute to achieving the goal of energy security and GHG emission mitigation. We do not estimate the ILUC-effect of biofuel production in the ROW; instead we use the ILUC effect estimated by other studies to examine the order of magnitude of the direct and indirect effects of the policies considered on global GHG emissions.

We undertake this analysis by using an integrated model of the fuel and agricultural sectors, Biofuel and Environmental Policy Analysis Model (BEPAM), which incorporates the interconnections between transportation sector policies and land use due to their influence on the demand for biofuels. The model endogenously determines the effects of alternative policy combinations for the mix of fuels produced, for the cost of fuel and agricultural commodities and for VKT in 2035. It considers biofuels that can be produced from several feedstocks and can be blended with gasoline or diesel as well as sugarcane ethanol that can be imported from Brazil.

The economic and environmental implications of the RFS have been studied extensively (Beach and McCarl, 2010; Chen et al., 2012a; Hertel et al., 2010; Searchinger et al., 2008). Beach and McCarl (2010) use the Forest and Agricultural Sector Optimization Model (FASOM) while Chen et al. (2012a) employ an earlier version of the BEPAM model to analyze the implications of the RFS for land use, crop price and GHG emissions. Hertel et al. (2010) and Searchinger et al. (2008) apply the Global Trade Analysis Project (GTAP) and Food and Agricultural Policy Research Institute (FAPRI) models, respectively, to investigate the direct and indirect land use changes induced by the mandate for corn ethanol. There are only a few studies analyzing the performance of a LCFS and comparing it to other policies. Holland et al. (2009) show that in a closed economy the LCFS always imposes an economic cost and that a carbon tax would be the least cost approach to reducing GHG emissions. However, their analysis does not consider an open economy with trade in food and fuel or the impacts of the LCFS on agricultural consumers and producers. In an open economy, these policies will affect the terms of trade for the US to varying extents; they will lower the world price of (fuel) imports while raising the world price of crops exported by the US. This improvement in terms of trade could offset some or all of the efficiency cost of a fuel standard; thus the net economic costs/benefits of these policies need to be empirically examined. Using the GTAP model, CARB (2009) provides an assessment of the economic and GHG effects of a 10% LCFS in California.

The rest of the paper is organized as follows. Section 2 describes the policies analyzed. In Section 3 we describe the numerical model, BEPAM. The data and assumptions are described in Section 4 and the simulation results under various policy scenarios are discussed in Section 5. Sensitivity analysis and conclusions are provided in Sections 6 and 7, respectively.

2. Policy scenarios

2.1. Low carbon fuel standard

We consider an LCFS that restricts the ratio of GHG emissions from all fuels blended/consumed in that year to the total energy

(footnote continued)

categories are renewable fuel, advanced biofuel, and cellulosic biofuel. Advanced biofuels are those obtained from feedstocks other than corn starch with a lifecycle GHG emission displacement of 50% compared to conventional gasoline in 2005. Cellulosic biofuels are those derived from 'renewable biomass' and achieving a lifecycle GHG emission displacement of 60% compared to conventional gasoline in 2005.

produced by all those fuels in that year to be below a specified GHG intensity level for that year. We assume that the LCFS is targeted to achieve a reduction in the combined CI of gasoline and diesel blends by allowing carbon credit trading between these two types of fuel blends. We set annual rates of reduction in CI to linearly achieve a 15% reduction in average fuel CI between 2015 and 2030. We discuss the implications of alternative targets for the LCFS, but do not present those results for brevity. We consider the LCFS to be binding at the aggregate level of the transportation sector instead of the firm and thereby implicitly allow for the possibility of trade among fuel providers. Some firms might over-achieve the LCFS while others may under-achieve it, and the industry as a whole meets the LCFS cost-effectively.

2.2. Renewable fuel standard

Unlike the LCFS, which sets annual targets for the average CI of the transportation fuel, the RFS established by the Energy Independence and Security Act sets annual mandates for the quantities of different categories of biofuels to be blended with gasoline or diesel. The volumes of second generation biofuels as mandated by EISA are considered unlikely to be achieved by 2022, but to be exceeded by 2035, according to the AEO (EIA, 2010a). We, therefore, use the AEO projections for the annual volumes of first generation biofuels and second generation biofuels (cellulosic ethanol and BTL) to set the achievable biofuel quantities for the period 2007–2035. The target ranges from 28 B ethanol equivalent liters (eel) in 2007 to 179 B ethanol equivalent liters in 2035. We assume that commercial production of cellulosic biofuels will be feasible in 2015. The nested nature of the mandates for the different types of biofuels implies an upper limit of 57 B l of annual production for corn ethanol after 2015, and upper limit of 76 B l for corn ethanol and advanced biofuels. Cellulosic biofuels are required to meet the rest of the mandated volume and can exceed that level if they are competitive with other biofuels.

2.3. Carbon tax

Climate change legislation is yet to be enacted in the US. The proposed American Clean Energy and Security (ACES) Act in June 2009 would have established a cap-and-trade program for GHG emissions. We use the carbon prices expected to prevail with the implementation of the ACES Act in the base case analyzed by the EIA (2010a); these prices range from \$20 per metric ton in 2010 to \$65 per metric ton in 2030 and onwards. Our analysis here does not consider any government subsidies on biofuels.

3. Biofuel and environmental policy analysis model (BEPAM)

BEPAM is a multi-market, dynamic, price-endogenous, non-linear mathematical programming model that simulates the US agricultural and fuel sectors and formation of market equilibrium in the commodity and fuel markets including trade with the ROW.³ The model solves for quantities and prices in the various fuel and agricultural sector markets by maximizing consumers' and producers' surpluses in those markets subject to various material balances, technological and policy constraints over the time horizon of 2007–2035. The policy constraints take the form of an annual quantity mandate and an annual constraint on average CI of fuel to meet the LCFS for each of gasoline and diesel

blends. A detailed description of the model equations can be found in Chen et al. (2012a,b).

3.1. Transportation sector

The transportation sector is represented by downward sloping demand curves for vehicle kilometers traveled (VKT) with three types of vehicles that use gasoline or its substitutes as fuel; conventional vehicles (CVs), flex fuel vehicles (FFVs) and gasoline-hybrid vehicles (HVs). It also includes a downward sloping demand curve for VKT by all on-road transport vehicles, heavy duty trucks and light duty vehicles that use diesel and diesel substitutes as fuel (DVs). A demand curve for VKT using electric vehicles (EVs) is also included but the amount of VKT with them is fixed exogenously. The demand for VKT by each of the other four types of vehicles endogenously generate demands for liquid fossil fuels and biofuels given the energy content of alternative fuels, the fuel economy of each type of vehicle and limits on the extent to which the two can be blended in particular types of vehicles. We assume biofuels are perfect substitutes for liquid fossil fuels, subject to their energy content, and that the consumer price of biofuels for consumers will be equal to the energy equivalent price of the fossil fuel they replace. The model endogenously determines these prices and the cost of VKT and quantity of VKT consumed with each type of vehicle.

We include upward sloping supply curves for domestic gasoline production and for gasoline supply from the ROW. The excess supply of gasoline to the US at various prices is determined by specifying a demand curve for it by the ROW. In the case of diesel we assume that it is produced domestically only and include an upward sloping supply curve to represent its marginal costs of production and price responsiveness.

The biofuel sector includes several first and second generation biofuels; the former include domestically produced corn ethanol and soy diesel as well as imported sugarcane ethanol. Second generation biofuels are produced from cellulosic biomass that can be obtained from crop or forest residues and from dedicated energy crops, miscanthus and switchgrass. Biomass from these feedstocks can be converted to either lignocellulosic ethanol (LE) that can be blended with gasoline or to produce BTL using the Fischer–Tropsch process that can be blended with diesel. The latter is a drop in fuel that can be blended with diesel. LE has the same energy content as corn ethanol and is subject to blend limits with gasoline in conventional vehicles. The cost of processing biofuels is assumed to decline over time as their cumulative production increases.

3.2. Agricultural sector

The agricultural sector considers the 295 Crop Reporting Districts (CRDs) in 41 states as the spatially heterogeneous decision units and includes 15 major row crops, 8 livestock activities, and various types of biomass feedstocks for biofuels mentioned above. Crops can be produced using alternative tillage and rotation practices. The model incorporates spatial heterogeneity in crop and livestock production activity, where crop production costs, yields and land availability are specified differently for each region and each crop. Equilibrium prices in markets for crop and livestock commodities are determined by specifying domestic and export demand/import supply functions for individual commodities, including crop and livestock products. Demand for feed is met by feed crops and byproducts of crop processing, such as soy meal and DDGS (a byproduct of corn ethanol production) based on dry matter, nutrient content and cost.

The model includes several types of land, that is, regular cropland, idle land, cropland pasture, pasture land, and forestland

³ Details of the model are available from the authors on request.

pasture, for each CRD. Cropland availability in each CRD is assumed to change in response to crop prices, using estimated price elasticities of crop-specific and total acreage. Idle land and cropland pasture are assumed to be available to be converted to conventional crop or energy crop production. Other land, including pasture land and forestland pasture are fixed at 2007 levels while land enrolled in the Conservation Reserve Program is fixed at levels authorized by the Farm Bill of 2008.

4. Data and assumptions

4.1. Transportation sector

Demands for VKT with CVs, FFVs, HVs and DVs are obtained from EIA (2010a) for the period 2007–2035. VKTs with EVs are those kilometers traveled by electric cars and light trucks using electricity as the only source of energy and are obtained from the VISION model (EIA, 2010a; Yang, 2011). Gasoline, diesel, ethanol and biodiesel consumed by on-road vehicles in 2007 are obtained from Davis et al. (2010). Retail fuel prices, markups, taxes and subsidies are obtained from EIA (2010a) and demand elasticity for VKT is from Parry and Small (2005). We assume that the demand curves for VKT with all types of vehicles are linear with a price elasticity of -0.2 at the level of kilometers consumed in 2007.

Fuel economy in terms of kilometers per liter of fuel for each vehicle type is also derived from EIA (2010a). Fuel demands by vehicles are constrained by biofuel blend limits that are technologically determined and specific to fuel and vehicle types, in addition to a minimum ethanol blend for all gasoline to meet the oxygenate additive requirement. The short-run supply curves of gasoline in the US and demand and supply curves for gasoline for the ROW are assumed to be linear and calibrated for 2007 using data on fuel consumption and production in the US and for the ROW (EIA, 2010b; Greene and Tishchishyna, 2000). We assume similar price responsiveness for the domestic supply curve of diesel. The exports of gasoline from the ROW to the US and its price responsiveness are determined by specifying demand and supply functions for gasoline for the ROW.

4.2. Agricultural sector

The feedstock costs of biofuels are estimated at the CRD level and consist of two components: a cost of producing the feedstock which includes costs of inputs and field operations, and a cost of land (Chen et al., 2011). The costs of converting feedstock to biofuel are estimated using an experience curve approach. An experience curve approach is used to define the relationship between the processing costs of these biofuels and their cumulative production (de Witt et al., 2010). The initial individual biofuel conversion costs and experience indexes are obtained from various sources (as described in Chen et al., 2012b). The conversion efficiencies (yield of biofuel per metric ton of feedstock) are exogenously fixed and based on the estimates in GREET 1.8c for corn ethanol and Wallace et al. (2005) for cellulosic ethanol. We use US ethanol retail prices and imports from Brazil and Caribbean countries in 2007 as well as an assumed elasticity of the excess supply of ethanol import to calibrate the sugarcane ethanol import supply curve for the US.

Biodiesel pathways include soybean oil biodiesel, DDGS corn oil biodiesel, and renewable diesel from waste grease, and various cellulosic biomass feedstocks. Feedstock costs for soybean oil diesel are assumed to be the endogenously determined market price for soybean oil. The conversion rate and cost from vegetable oil (including corn oil from DDGS) or waste grease to biodiesel is obtained from FASOM (Beach and McCarl, 2010). The conversion

coefficient of DDGS to corn oil and the cost of extracting oil from DDGS are based on a report by Business Wire (2006).

We estimate the rotation, tillage and irrigation specific costs of production in 2007 prices for 15 row crops and three perennial grasses at county level and aggregate them to the CRD level for computational ease. Data on crop and livestock production, prices, consumption, exports and imports as well as land availability and the conversion rates from primary commodities to secondary (or processed) commodities are obtained primarily from USDA/NASS (2009). Elasticity and demand/supply shift parameters for agricultural commodities are assembled from a number of sources described in Chen et al. (2011). The conversion costs from primary to secondary commodities as well as nutrition requirements and costs of production for each livestock category are obtained from Adams et al. (2005). Nutrient contents of livestock feeds are obtained from NRC (1998) and Akayezu et al. (1998) while DDGS prices are estimated based on Ellinger (2008). The responsiveness of total cropland to crop prices and corn and soybeans acres to their own and cross-prices is obtained from Huang and Khanna (2010). The sensitivity of model results to changes in these elasticity of demand for agricultural commodities and in the rate of growth of crop productivity has been analyzed in Chen et al. (2011, 2012b).

Yields of conventional crops on marginal lands are assumed to be 66% of those on average cropland (Hertel et al., 2010). Yields of bioenergy crops are assumed to be the same on marginal land as on regular cropland and there is a conversion cost for the use of idle land/cropland pasture for bioenergy crop production. We impose a limit of 25% on the amount of land in a CRD that can be converted to perennial grasses due to concerns about the impact of monocultures of perennial grasses on biodiversity or sub-surface water flows. In the absence of long term observed yields for miscanthus and limited data for switchgrass, we use a crop productivity model MISCANMOD to simulate their potential yields. The methods for estimating the delivered costs of miscanthus and switchgrass are described in Jain et al. (2010). Costs of producing row crops and alfalfa are obtained from the crop budgets compiled for each state by state extension services. Application rates for fertilizer are assumed to remain constant over time regardless of yield increases. Corn stover and wheat straw yields and costs of collection are estimated based on grain-to-residue ratios and residue collection rates under different tillage in the literature (Sheehan et al., 2003; Wortmann et al., 2008).

4.3. Lifecycle analysis

We use lifecycle analysis to estimate the GHG emissions during the process of crop production, transportation and conversion to liquid fuel as well as the soil carbon sequestered during the process of producing the feedstocks to determine the CI of each biofuel pathway. To implement the LCFS, the CI of each fuel needs to be specified ex ante. We assume a national average value for the CI of first generation biofuels since we cannot distinguish corn produced for food from that produced for fuel. For second generation biofuels, CIs are estimated for each feedstock that differ across CRDs due to differences in crop yields, production practices, and input application rates. Life cycle GHG emissions for conventional gasoline in 2005 are based on Rubin (2010). We estimate the lifecycle GHG emissions most of the biofuel pathways included in the analysis using data on feedstock production and biofuel conversion, distribution and consumption. We assume soil carbon under energy crops and conservation till will increase at a rate as suggested in Anderson Teixeira et al. (2009) and Adler et al. (2007).

The collection of crop residues such as corn stover and wheat straw may lead to a loss of soil carbon (Anderson Teixeira et al., 2009). Given the complexity of the issue involved and the difficulty in quantifying this soil carbon loss (EPA, 2010), we

assume that at a collection rate of 50% under conservation till and 30% under conventional till there is no soil carbon loss resulting from crop residue collection.

The national average life-cycle CIs and costs of biofuels are summarized in Table 1. Assumptions underlying the estimation of the costs of biofuel production are described in Chen et al. (2012b). Table 1 shows that second generation biofuels have significantly lower CI than fossil fuels and compared to first generation biofuels; second generation biofuels from energy crops could in fact be sinks for carbon rather than sources due to their large potential to sequester carbon in the soil. In addition, some second generation biofuels, such as those using miscanthus as the feedstock, have significantly lower land requirements in terms of liters of biofuel per hectare. It can be seen, however, that the costs of second generation biofuels are much higher than first generation biofuels and BTL diesel is more expensive than LE though the carbon intensity of these two types of second generation biofuels are similar in magnitude.

5. Results

We analyze the effects of the RFS as projected in EIA (2010a) by itself (RFS), the RFS with LCFS (RFS+LCFS), and the RFS with LCFS and carbon price (RFS+LCFS+CO₂ Price) policy over the 2007–2035 period. We compare these to a no policy, business-as-usual (BAU), scenario. We summarize the effects of alternative policies for the fuel sector in 2035 in Table 2.

5.1. Effects of alternative policies on fuel mix

The various policies considered here lead to a significant increase in ethanol and biodiesel production compared to the BAU scenario. Biofuel mixes also vary significantly across policy scenarios, with the RFS producing the largest volume of the first generation biofuels (corn ethanol and sugarcane ethanol) and the RFS+LCFS+CO₂ price producing the smallest. The RFS encourages low cost first generation ethanol production, particularly corn ethanol, (61 B l of corn and sugarcane ethanol), since it creates incentives to produce the least cost mix of biofuels to meet the mandate. Under the RFS, a particular biofuel pathway only has to meet a certain threshold of reduction in GHG intensity to be qualified to meet the mandate. By treating all second generation biofuels (LE and BTL) the same, the RFS does not give incentives to use feedstocks that can lead to even lower GHG intensity than the threshold. There is 85 B l of LE and 33 B ethanol equivalent liters of biodiesel and BTL (the biodiesel component is negligible) in 2035. Moreover, the RFS will lower the demand for fossil fuels displaced by biofuels and their price in the domestic and world market. It also provides an implicit subsidy to biofuel consumers and lowers the price of fuel for consumers, lowering the cost of VKT and increasing demand for driving. The RFS, therefore, leads to a higher level of VKT 2.2% and increases total energy equivalent fuel consumption by 1.9% compared to the BAU.

On the other hand, the LCFS is technology neutral and creates incentives for fuel suppliers to determine how to cost-effectively meet the CI standard by choosing an appropriate mix of transportation fuels; by substituting low carbon fuels for fossil fuels

Table 1
Biofuel CIs and costs of production.

Fuel	CI (g CO ₂ e/MJ)	Cost in 2007 prices (cents/MJ)	Feedstock yield (mg/ha)	Biofuel yield (l/ha)	ILUC effect ^a (g CO ₂ e/MJ) (EPA, 2010)
Gasoline	93.05	1.54	–	–	–
Corn ethanol	58.35	1.76	9.68	3904	30.33 (19.91–43.60)
Sugarcane ethanol	25.12	1.70	75.2	6200	3.79 (–4.74 to 11.37)
Forest residue ethanol	21.40	2.75	–	–	–
Wheat straw ethanol	15.84	2.93	1.74	575	0
Corn stover ethanol	13.98	2.75	3.83	1265	0
Miscanthus ethanol	–19.29	2.85	23.48	7759	14.22 (8.53–21.80)
Switchgrass ethanol	–8.72	3.31	9.04	2988	14.22 (8.53–21.80)
Diesel	91.95	1.47	–	–	–
Soybean biodiesel	35.13	2.03	2.85	583	40.76 (14.22–72.04)
Wheat straw biodiesel	15.20	3.78	1.74	312	–
Waste grease biodiesel	12.87	2.01	–	–	0
Corn stover biodiesel	13.21	3.59	3.83	687	0
DDGS corn oil biodiesel	11.26	1.29	9.68	226	–
Forest residue biodiesel	7.36	3.59	–	–	–
Miscanthus biodiesel	–22.86	3.70	23.48	4211	14.22 (8.53–21.80)
Switchgrass biodiesel	–10.74	4.19	9.04	1622	14.22 (8.53–21.80)

^a These are ILUC estimates estimated by EPA (2010). The ILUC effect for biofuel from miscanthus is assumed to be the same as that for biofuel from switchgrass due to lack of estimates specific for miscanthus. This is likely to result in an overestimate for the ILUC effect of miscanthus derived biofuel because the yield of miscanthus per unit of land is substantially higher than that for switchgrass.

Table 2
Effects of alternative policies for the fuel sector in 2035.

Scenarios	BAU	RFS	RFS+LCFS	RFS+LCFS+CO ₂ price
Gas vehicle kilometers traveled (B km)	7067.3	7222.6	7174.3	6973.5
Diesel vehicle kilometers traveled (B km)	834.4	852.1	855.7	830.3
Biofuel consumption				
First generation ethanol (B l)	20.0	61.0	7.1	5.6
LE (B l)	0.0	85.0	129.8	131.2
Biodiesel and BTL (B ethanol equivalent liters)	0.0	33.1	51.3	51.5
Fossil fuel consumption				
Gasoline (B l)	510.3	437.9	440.4	425.5
Diesel (B l)	195.1	181.0	171.4	168.3

and by reducing the consumption of fossil fuels. The LCFS implicitly penalizes high carbon fuels and subsidizes low carbon fuels, with the magnitude of this subsidy increasing as the carbon intensity of the biofuel decreases (unlike the RFS which will provide the same implicit subsidy for all biofuels within a particular category). Since the LCFS penalizes high carbon fuels, it could result in a higher price of fuel for consumers than under the BAU and raise the cost of driving and hence lead to reduced VKT. Our simulation results indicate that adding the LCFS to the RFS has a significant impact on the mix of biofuels (Table 2). The production of the first generation biofuels under the RFS+LCFS is 7.1 B l in 2035, while that of cellulosic ethanol and BTL are 130 B l and 51 B ethanol equivalent liters, respectively. The total production of biofuels exceeds the level under the RFS alone. In addition, the high LE production required to meet the LCFS in this case crowds out the relatively more carbon intensive corn ethanol, in large part because the potential to absorb ethanol is limited by the vehicle fleet structure. The total production of biofuels is 6% higher under the RFS+LCFS as compared to the RFS alone in 2035; however the volume of ethanol (the first generation biofuels and cellulosic together) is lower under the RFS+LCFS than under the RFS in 2035, since the former induces greater production of BTL. As a result, the consumption of gasoline is slightly higher under RFS+LCFS as compared to the RFS alone while the consumption of diesel is only about 5% lower than the RFS in 2035. Thus the imposition of the LCFS has a limited impact on improving energy security beyond that achieved by the RFS.

A carbon price policy differs from an LCFS in that it would explicitly add to the cost of all fuels, including biofuels, based on their full CI; this is unlike the LCFS where the implicit price of carbon under the LCFS penalizes (subsidizes) high (low) carbon fuels based on the deviation of their CI being above (below) the desired intensity standard. Combining a carbon price policy with an LCFS reduces the stringency of the LCFS and the implicit carbon price needed to achieve the LCFS.

In the absence of low cost renewable fuel substitutes for fossil fuels, the carbon price will achieve GHG abatement primarily by reducing fuel consumption and VKT. It is expected to induce the production of cellulosic biofuels only if the price of carbon is extremely high. As expected, the addition of a carbon price to the RFS+LCFS policy primarily induces fuel conservation over and above levels achieved by the RFS+LCFS (Table 2). With the CO₂ price, the LCFS constraint will be binding in 2019 and onwards, suggesting that the carbon price induced reductions in fossil fuel consumption is not large enough to achieve the more stringent CI

reduction goal required by the LCFS. Relative to the RFS+LCFS alone, the addition of the carbon price reduces gasoline and diesel consumption by 2% each and gasoline imports by 3% in 2035. This combined policy reduces VKT with gasoline and diesel blends relative to the BAU since the carbon price increases the costs of all fuels and thus the cost of VKT. When compared to the BAU, gasoline imports under this combined policy are 22% lower, implying significant energy security benefits. The carbon price reduces the extent to which additional production of biofuels is needed to comply with the LCFS. The total amount of the first generation biofuels consumed is only slightly lower than under the RFS+LCFS but there is a further shift away from the first generation biofuels and towards LE with the total amount of biofuel production remaining the same as that with the RFS+LCFS. The addition of the carbon price lowers diesel consumption also and marginally reduces the need to blend high cost BTL to achieve the LCFS as compared to the RFS+LCFS policy.

Fig. 1 shows that significant reduction in the CI of gasoline blends is achieved under each of the policy scenarios, particularly around 2030 since biomass is primarily used for LE until then. BTL production starts in late 2020s or early 2030s depending on policy scenarios and reduces the CI of diesel blends after that. The CI of gasoline blends increases after that as the production of cellulosic ethanol declines somewhat while BTL production expands. This switch to BTL occurs around 2030 in large part because demand for ethanol becomes constrained by blend limits of the vehicle fleet.

Table 3
Food and fuel prices in 2035.

Scenarios	BAU	RFS	RFS+LCFS	RFS+LCFS+CO ₂ price
Corn (\$/MT)	125.06	174.78	134.06	135.05
Soybeans (\$/MT)	342.56	458.15	396.14	386.76
Biomass price (\$/MT)	0.00	67.04	67.63	65.04
Gasoline consumer price (\$/l)	1.01	0.90	0.94	1.09
Gasoline producer price (\$/l)	1.01	0.90	0.91	0.89
Diesel consumer price (\$/l)	1.09	0.98	0.95	1.11
Diesel producer price (\$/l)	1.09	0.98	0.90	0.88
Corn ethanol producer price (\$/l)	0.68	0.75	0.69	0.75
LE producer price (\$/l)	-	0.74	0.74	0.73
Ethanol consumer price (\$/l)	0.67	0.60	0.63	0.72
BTL producer price (\$/l)	-	1.21	1.12	1.1
BTL consumer price (\$/l)	-	0.96	0.93	1.09
Average carbon price (\$/metric ton CO ₂)	-	-	80	45
(Implicit price with LCFS) (2015–2035)	-	-	80	45

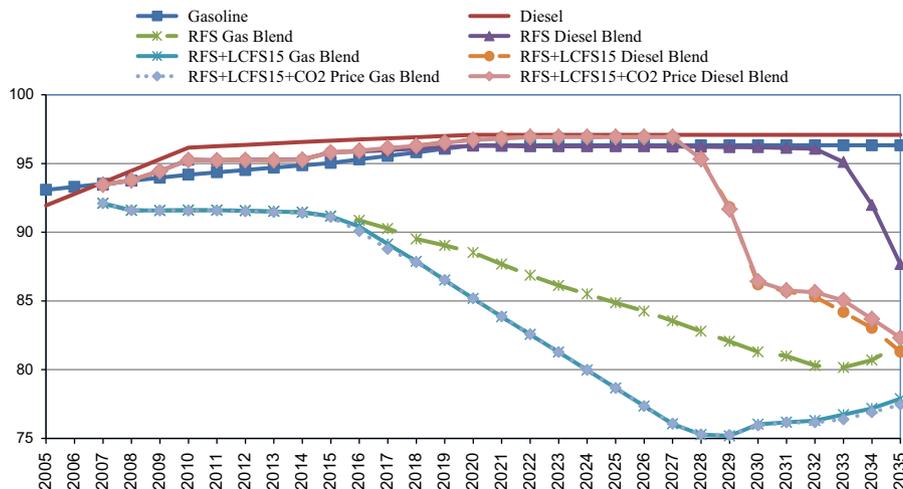


Fig. 1. Carbon intensities of gasoline and diesel blends under alternative policies.

Table 4
Effects of alternative policies on energy security and GHG emissions (2007–2035).

Scenarios	BAU	RFS	RFS+LCFS	RFS+LCFS+CO ₂ price
(a) GHG emissions from the fuel and agricultural sectors in the US (B Metric Tons)	64.0	60.9	58.7	57.0
% change in (a) relative to BAU		−4.8	−8.3	−10.9
(b) (a)+GHG emissions due to ILUC	64.3	62.0	59.6	58.0
% change in (b) relative to BAU		−3.6	−7.3	−9.8
(c) (b)+global rebound effect	64.3	63.6	61.4	60.1
% change in (c) relative to BAU		−1.1	−4.5	−6.5
Gasoline imports (B Liters)	9253	8255	8162	7945
% change in imports relative to BAU		−10.8	−11.8	−14.1

5.2. Effects of alternative policies on food and fuel prices

We now discuss the impact of the policies considered here on food and fuel prices in 2035 (Table 3). We find that the RFS raises corn prices by 40% and soybean prices by 34% relative to the BAU. With the addition of the LCFS, the impact of the RFS on corn and soybean prices is substantially tempered though these prices are still higher than in the BAU. Specifically, under the RFS+LCFS, the prices of corn and soybeans are 23% and 14% lower, respectively, than under the RFS alone, suggesting that an LCFS helps mitigate the food versus fuel competition by inducing a shift from corn ethanol to LE and BTL. The incremental impact of the imposition of a CO₂ price compared to the RFS+LCFS on food prices is modest; there is a marginal change in the price of corn and a reduction in the price of soybeans due to a slight shift from corn to soybean production resulting from reduced demand for first generation biofuels.

The decrease in fossil fuel consumption under the RFS translates into a reduction in consumer prices for both gasoline and diesel fuels by about 10% each relative to the BAU. With the addition of the LCFS to the RFS, the consumer price of gasoline is 6% lower than the BAU level but 4% higher than under the RFS alone. The consumer price of diesel under the RFS+LCFS is 13% and 3% lower than under the BAU and the RFS, respectively. We find that only in the presence of the carbon price will fuel consumer prices be higher than under the BAU (by about 8% for gasoline and 2% for diesel), since the carbon price raises the consumer price of gasoline and diesel and reduces the consumption of fossil fuels more than it increases the consumption of biofuels. These fuel consumer price changes under the biofuel and climate policies explain why compared to its BAU level, VKT is reduced only under the RFS+LCFS+CO₂ price.

Note that under the RFS consumer and producer prices of fossil fuels are the same but the producer price of biofuels is higher than the consumer price of biofuels (Table 3). With the introduction of the LCFS or the CO₂ price there is a price wedge between the consumer and producer price for fossil fuels and biofuels. The consumer prices of fossil fuels are higher than the producer prices, since the LCFS and the CO₂ price either implicitly or explicitly penalize the consumption of high CI fossil fuels. This price difference between the consumer and producer price under the RFS+LCFS is about \$0.03 per l for gasoline and \$0.05 per l for diesel. The price difference increases under the RFS+LCFS+CO₂ to \$0.20 and \$0.23 per l for the gasoline and diesel, respectively.

Table 3 also shows that there is a wedge between the producer prices of the different types of ethanol (and biodiesel) and their consumer price which is assumed to be the same as the energy equivalent prices of gasoline (and diesel). In the case of the RFS this reflects the implicit subsidy to biofuels paid by the blenders and is about \$0.16 per l for corn ethanol and LE in 2035. It is the same for both types of ethanol since the cost of producing LE is assumed to have decreased to the same level as that of corn ethanol due to learning by doing by 2035. This gap between the producer and the

consumer price of biofuels implies significant costs for blenders of biofuels. The imposition of the LCFS increases the amount of biofuel needed to lower the GHG intensity of transportation fuel to the targeted level beyond that provided by the RFS.

As a result, the RFS is no longer binding. Nevertheless, there is a wedge between the consumer and producer price of biofuels because the LCFS also implicitly subsidizes low carbon fuels in order to induce the additional production needed (beyond the levels required by the RFS) to meet the GHG intensity target with the extent of subsidy depending on the CI of the biofuel. The average implicit carbon price is \$80 per metric ton under the RFS+LCFS. The gap between the consumer and producer price of biofuels is lower than under the RFS alone. This is because the implicit tax on gasoline raises its price for consumers and thus the energy equivalent price of biofuels for consumers. The producer price of corn ethanol is lower under the RFS+LCFS because the reduced production of corn ethanol lowers the price of corn and the cost of producing corn ethanol relative to the RFS alone. The producer price of cellulosic biofuels is same or lower (despite higher levels of production than the RFS alone) because the RFS+LCFS induces greater cumulative production of these biofuels over the 2015–2035 period and thus greater reductions in processing costs compared to the RFS alone.

The addition of a CO₂ price policy reduces the consumption of fossil fuels and makes the LCFS constraint less stringent and therefore lowers the implicit carbon price to \$45 per metric ton. It also raises the consumer price of fossil fuels and reduces the gap between the producer and consumer prices of biofuels.

5.3. Effect of alternative policies on energy security and greenhouse gas emissions

Theoretically, the impact of the RFS on GHG emissions is ambiguous; while it induces a substitution of low carbon fuels for fossil fuels it also provides an implicit subsidy to biofuel consumers and lowers the price of fuel for consumers which increases VKT. The LCFS, on the other hand, penalizes high carbon fuels while subsidizing low carbon fuels, and thus could result in a higher price of fuel than under the BAU and raise the cost of driving. The LCFS is therefore likely to achieve greater reduction in GHG intensity than the RFS; its impact on overall GHG emissions, however, depends on the effect it has on overall fuel consumption. A CO₂ price will reduce GHG emissions because it induces both a substitution towards low carbon fuels and a reduction in VKT. We find that the cumulative GHG emissions from the fuel and crop sectors in the US, over the period 2007–2035 are reduced by 4.7% under the RFS, 8.3% under the RFS+LCFS and 10.8% under the RFS+LCFS+CO₂ price relative to the BAU (Table 4).

We also examine the impact of these policy combinations on global GHG emissions after considering the ILUC effect and the global rebound effect. When the ILUC effect is included, the reduction in the cumulative domestic GHG emissions relative to the BAU is now reduced to 3.6% for the RFS, 7.3% for the

RFS+LCFS, and 9.8% for the RFS+LCFS+CO₂ price (Table 4). Thus, the inclusion of the ILUC effect reduces the GHG savings achieved by 1%; however all of these policies still achieve substantial reduction in GHG emissions relative to the BAU. This result however is sensitive to the estimate of the ILUC effect included; if the ILUC effect is larger than that assumed here, the benefits of these policies on global GHG emissions will be further eroded. However, it is important to note that the RFS+LCFS and RFS+LCFS+CO₂ price policies will always result in a larger reduction in GHG emissions as compared to the RFS alone despite the ILUC effect because of their lower reliance on first generation biofuels that have much higher ILUC effects.

Addition of GHG emissions due to additional gasoline consumption by the ROW offsets some of the reduction in the contribution of these policies to global GHG mitigation. The reduction in cumulative GHG emissions over this period after including the increase in emissions due to increased gasoline consumption by the ROW due to these policies is 1.1% for the RFS, 4.5% for the RFS+LCFS policy and 6.5% for all three policies combined relative to the BAU (Table 4).

The impact of alternative policies on energy security, defined narrowly here as a reduction in cumulative US gasoline imports, is also shown in Table 4. We find that the RFS has the potential to reduce cumulative US gasoline imports by 10.8% relative to the BAU over the 2007–2035 period. Reduction in gasoline imports is larger than the reduction in US gasoline consumption since the world supply of gasoline is assumed to be more responsive to prices than the domestic production in the US. The addition of an LCFS policy to the RFS achieves a higher reduction in US gasoline imports by 11.8% compared to the BAU while imposition of a carbon price to this policy mix further increases the reduction to 14.1% relative to the BAU over the study period.

5.4. Costs and benefits of alternative policies

Compared to the BAU with no biofuel and climate policies, the policies considered here change consumer and producer behavior in the agricultural and fuel sectors and impose an efficiency cost on these sectors. These policies also differ in their impact on government revenue which consists of revenue from a fuel excise tax and any carbon tax revenue. The excise tax revenue changes across scenarios due to the change in the demand for fuel. However, in a dynamic setting they also stimulate innovation in biofuel technologies and lower costs of production as compared to the no-policy scenario. Moreover, they improve the terms of trade for the US, by lowering fuel (import) prices and raising agricultural (export) prices. Even without considering the environmental benefits of these policies, the net economic impact of these policies could be positive or negative and needs to be determined empirically.

We estimate the total discounted value of the net benefits to agricultural and fuel consumers and producers relative to the BAU over the period 2007–2035, using a discount rate of 4% (Table 5).

These net benefits are measured in 2007 dollars. Since fuel prices decrease by more under the RFS than under the RFS+LCFS over this period, the discounted net benefits for fuel consumers increase by 2.2% under the RFS and by 1.6% under the RFS+LCFS relative to the BAU. In contrast, when the RFS+LCFS is accompanied by a carbon tax, fuel consumers will lose 2% of net benefits relative to the BAU since the carbon tax raises fuel prices above the BAU level. The reduction in fuel prices for fuel producers under all these policy scenarios leaves fuel producers worse off relative to the BAU. They have 15% lower surplus under the RFS as compared to the BAU. However, they are better off under the RFS+LCFS compared to under the RFS alone, with a 11% reduction in surplus relative to the BAU, for reasons discussed above. The imposition of a CO₂ price reduces their net benefits relative to the RFS+LCFS and their surplus is 14% lower than in the BAU. The increase in crop prices over this period under each of the policy scenarios results in a loss to agricultural consumers relative to the BAU. The loss in consumer surplus is 5.1% under the RFS relative to the BAU. With the imposition of an LCFS and a CO₂ price their losses are smaller at 4% or lower relative to the BAU. Agricultural producers gain the most (20%) under the RFS due to higher crop prices and increased demand for biomass. They gain around 15% in the other policy scenarios, which is lower than under the RFS because of the lower crop prices due to reduced demand for corn ethanol, although it is offset to some extent due to increased demand for miscanthus as cellulosic biofuel feedstock. Overall, relative to the BAU case, agricultural and fuel consumers are better off under the RFS and the RFS+LCFS since the negative welfare effect of increased food prices under these two policies is offset by the positive effect due to reduced fuel prices. We also find that the addition of the LCFS to the RFS makes food and fuel consumers worse off than under the RFS alone because gains from reduced food prices are not large enough to offset the welfare loss arising from increased fuel prices. Food and fuel consumers will be made further worse off when a CO₂ price is imposed on the RFS+LCFS due to the increase in fuel prices.

Overall, all the policy scenarios in Table 5 lead to larger aggregate net benefits relative to the no-policy BAU. The economic impact of these policies is fairly modest though, with net benefits of the fuel and agricultural sectors combined increasing by about 1% relative to the level achieved under the BAU. The addition of an LCFS to the existing RFS lowers aggregate net benefits compared to the RFS alone. The net present value of the costs (over 2007–2035) is \$57 Billion. The imposition of a CO₂ price to the RFS+LCFS raises aggregate net benefits almost back to RFS levels, with the net present value of the gains in net benefits being \$343 Billion over the 2007–2035 period.

Fig. 2 shows that the annual change in net economic benefits under each of the policies is positive relative to the BAU. With the exception of a few years (2027–2030) net economic benefits are higher under the RFS than the other policy combinations, possibly because fuel prices are lower under the RFS. In some years, the net economic benefits under the RFS could be lower than under

Table 5
Domestic economic costs and energy security effects of alternative policies relative to the BAU over 2007–2035 period.

Scenarios	RFS	RFS+LCFS	RFS+LCFS+CO ₂ price
Net benefits for fuel consumers (\$ B)	\$557 (2.2%)	\$411 (1.6%)	–\$506 (–2.0%)
Net benefits for agricultural consumers (\$ B)	–\$127 (–5.1%)	–\$93 (–3.8%)	–\$95 (–3.9%)
Net benefits for agricultural and fuel consumers (\$ B)	430.81	318.09	–600.92
Net benefits for fuel producers (\$ B)	–\$484 (–14.7%)	–\$344 (–10.5%)	–\$448 (–13.6%)
Net benefits for agricultural producers (B)	342 (20.1%)	\$261 (15.3%)	\$268 (15.8%)
Net change in government revenue (\$B)	\$54	\$52	\$1124
Aggregate net benefits (\$B)	\$344 (1.02%)	\$287 (0.85%)	\$343 (1.02%)

Changes in costs and benefits are discounted value computed in 2007 dollars. Percentage changes are in parenthesis.

the other policy scenarios because the RFS leads to greater reliance on first generation biofuels and higher costs on food consumers.

6. Sensitivity analysis

We examine the sensitivity of our results to various assumptions about feedstock and biofuel costs, and land availability. Specifically, we examine the effects of (a) higher costs of energy crop production, (b) a 10% restriction instead of 25%, on the amount of land in each CRD that can be converted to energy crops (due to environmental concerns), (c) lower rate of growth of productivity of corn and soybeans (50% of historical trend rates), and (d) 30% lower cost of BTL conversion technology.

We summarize the effects of changing these assumptions for the outcomes under the RFS and the RFS+LCFS in Table 6. Columns 2 and 4 (labeled “Benchmark”) in Table 5 are the levels or percentage changes under the RFS and the RFS+LCFS policy scenarios in the benchmark case (described above) and show the percentage changes compared to the BAU. Columns 3 and 5

(labeled “Sensitivity”) show the range of levels or percentage changes in the two policy scenarios compared to the corresponding BAU when assumptions/parameters are changed as described above. Table 6 shows that with the assumption changes, the level of first generation biofuel production ranges between 41.3–62.2 B l under the RFS and 4.4–62.1 B l under the RFS+LCFS in 2035. Higher costs of energy crop production lead to the highest level of first generation biofuels production under the RFS alone, while lower costs of BTL conversion costs achieve the highest level of first generation biofuels production under the RFS+LCFS since cellulosic biofuels take the form of only BTL in this case and first generation biofuels can be blended with gasoline without any blending constraints. Overall, the production of second generation biofuels are less sensitive to the parameter changes considered here and range from 111.9 to 134.8 B l under the RFS. Production levels are always higher under the RFS+LCFS and range from 155.7 to 182.2 B l with not much deviation from their benchmark levels.

Under the RFS and the RFS+LCFS the change in food prices relative to the BAU varies between 23.4–43.1% and 5.3–48.3%, respectively for corn and 20.3–35.6% and 12.8–46.5%, respectively for soybeans, with lower BTL conversion costs leading to the largest increase in food prices compared to the BAU since large scale BTL production is accompanied by higher levels of corn ethanol production to be blended with gasoline. The variation in gasoline consumer prices ranges from –3.5% to –11.1% in the RFS case and –5.2% to 2.7% in the RFS+LCFS case, and the range of changes in corn ethanol producer prices is 7.9–10.9% and 0.9–13.5% in the two policy cases, respectively. We find that the consumer price of diesel is generally close to that in the benchmark case in each of the policy scenarios, except when the BTL conversion cost is assumed to be low, in which case the RFS could lead to a much larger reduction in the price of diesel (–37.8%) compared to the BAU. Similarly, the RFS+LCFS would result in a 44% reduction in the price of diesel relative to the BAU in the low BTL conversion cost scenario. Gasoline and diesel consumption levels are not very sensitive to changes in the assumptions considered here because demand is fairly inelastic. An exception is the case with lower BTL conversion costs which could reduce diesel consumption significantly relative to the BAU (–26.8% in the RFS and –37% in the RFS+LCFS policy scenario). We also find that the effects of RFS and RFS+LCFS on GHG emissions (with and without considering global effects) and on total net benefits are fairly robust to changes in parametric assumptions (see Table 6). Across all the scenarios considered, the RFS+LCFS achieves

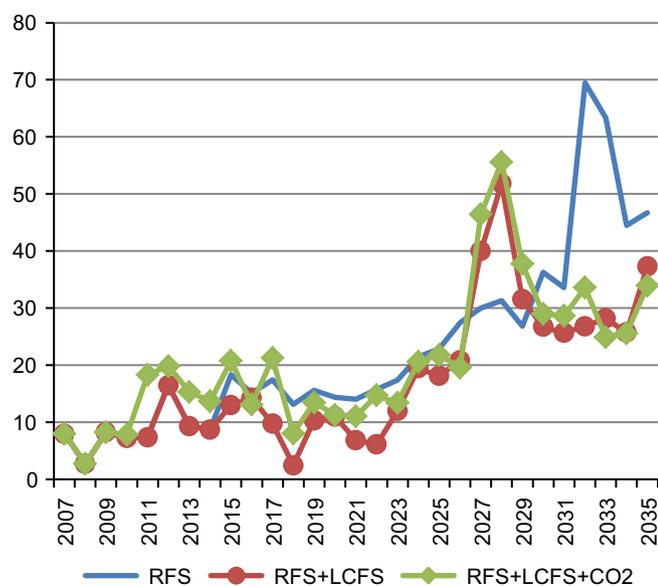


Fig. 2. Annual change in net economic benefits under alternative policies (\$ Million).

Table 6
Summary of sensitivity analysis.

Scenarios	RFS		RFS+LCFS	
	Benchmark	Sensitivity	Benchmark	Sensitivity
<i>Biofuel consumption in 2035 (B ethanol equivalent liters)</i>				
First generation biofuels	61.0	41.3–62.2	7.1	4.4–62.1
Second generation biofuels	113.8	111.9–134.8	180.3	155.7–182.2
<i>Food and fuel prices in 2035 (percentage change relative to corresponding BAU)</i>				
Corn price	39.8	23.4–40.5	7.2	5.3–48.3
Soybeans price	33.7	20.3–35.6	15.6	12.8–46.5
Gasoline consumer price	–10.3	–11.1 to –3.5	–6.3	–5.2 to 2.7
Corn Ethanol producer price	11.2	7.9–10.9	0.6	0.9–13.5
Diesel consumer price	–10.2	–37.8 to –7.1	–12.9	–44.0 to –11.1
<i>Fuel consumption in 2035 and GHG emissions (2007–2035) (percentage change relative to corresponding BAU)</i>				
Gasoline consumption	–14.2	–15.2 to –4.5	–13.7	–16.6 to –5.9
Diesel consumption	–7.2	–26.8 to –5.0	–12.2	–37.0 to –12.0
GHG emissions in US	–4.8	–5.5 to –4.0	–8.3	–9.1 to –7.9
Global GHG emissions (including ILUC and global rebound effect)	–1.1	–2.3 to –0.2	–4.5	–5.4 to –4.5
<i>Net present value of economic costs and benefits (2007–2035) (percentage change relative to corresponding BAU)</i>				
Net benefits	1.0	0.7–1.1	0.8	0.6–1.0

greater GHG reduction but lower net economic benefits as compared to the RFS alone.

We also examined the effects of alternative stringencies of 10% and 20% for the LCFS. These results are not reported here for brevity. We found that a 10% LCFS leads to outcomes that are very similar to those under the RFS alone (see *Khanna et al., 2011* for more details). When an LCFS with a 20% reduction target is added to the RFS, it would further stimulate the production of second generation biofuels in general and BTL in particular, with the production of cellulosic ethanol and BTL increasing to 138.1 B l and 52.4 B l in 2035, or by 6% and 76%, respectively, relative to the production level achieved under the LCFS 15%. The large increase in BTL production is stimulated by the limited potential to increase LE given the blend limits imposed by the vehicle fleet structure. Such a large scale production of second generation biofuels may not be feasible for the biofuel industry. With the increase in demand for land for cellulosic biofuel feedstock production, land rent and food and biomass prices would also increase substantially compared to those with LCFS 15%.

7. Conclusions

This paper examines the economic and GHG implications of going beyond the RFS by supplementing it with one or more low carbon fuel policies targeted specifically at reducing the GHG intensity of fuel and reducing GHG emissions. Our analysis shows that the addition of the LCFS to the RFS would significantly change the mix of biofuels by increasing the share of second generation biofuels. It would also have a large negative impact on diesel consumption because it would stimulate more production of BTL production than the RFS alone. The effect on gasoline consumption is similar to that under the RFS, primarily due to somewhat lower or similar production of ethanol compared to the RFS alone. The addition of a carbon price policy to the RFS and LCFS not only changes the mix of biofuels beyond the LCFS (overall biofuel production remaining about the same in quantity), but also encourages more fuel conservation. Thus, a carbon price policy and an LCFS when combined together with the RFS can be complementary policies and create incentives for both increased cellulosic biofuel production and reduced fossil fuel consumption.

One of the concerns with policies that promote biofuels is their implications for crop and fuel prices. We find that the RFS will raise corn and soybean prices by 30–40% in 2035 compared to the BAU scenario. An LCFS policy accompanying the RFS lowers crop prices (relative to the RFS alone) by shifting the mix of biofuels towards second generation biofuels. The addition of an LCFS also creates a wedge of \$0.03–0.05 per l between the consumer and producer price of fossil fuels. The consumer price of gasoline is 6% lower than the BAU level but 4% higher than the price under the RFS alone; the price of diesel, on the other hand, is 3% lower than the price under the RFS alone and about 13% lower than the price under the BAU scenario. When the RFS+LCFS policy is combined with a carbon price, corn prices remain almost unchanged and soybean prices decrease slightly relative to the price levels under the RFS+LCFS. The carbon price, however, increases consumer prices for fuels by about 16% compared to the RFS+LCFS.

Compared to the RFS alone scenario, the addition of the LCFS to the RFS will benefit food consumers and impose costs on fuel consumers. On the whole, however, they leave consumers worse off since the welfare losses due to increased fuel prices outweigh the gains from reduced food prices. The addition of the LCFS will benefit fuel producers but harm agricultural producers, leading to reduced aggregate net benefits. The addition of a carbon price, however, can impose costs on consumers and fuel producers while continuing to benefit agricultural producers compared to

the RFS+LCFS policy alone. These costs could be mitigated depending on the manner in which a carbon price policy is implemented, whether as a carbon tax or with carbon allowances and how tax revenues/profits are distributed since the aggregate net benefits including government revenues are higher than the RFS+LCFS alone and almost identical to the aggregate net benefits achieved under the RFS alone. The aggregate net benefits under each of the policy mixes considered here are higher than the BAU level. While a RFS+LCFS policy lowers aggregate net benefits compared to the RFS alone by \$57 B, the addition of a carbon price raises them to levels similar to those under the RFS alone.

Given that gains in aggregate economic benefits with the addition of an LCFS and a carbon price policy to the RFS are not substantially larger and could even be smaller (particularly to specific groups depending on the implementation of the carbon price policy) the rationale for preferring these additional policies will depend on the value attached to increased energy security and/or GHG emission reduction beyond levels achieved by the RFS alone. Here we find that the addition of an LCFS policy substantially decreases GHG emissions by the US compared to the RFS alone. Gasoline imports also decrease with the LCFS but not much beyond the levels achieved by the RFS. The addition of a carbon price policy achieves further reductions in US domestic GHG emissions and in gasoline imports. When global gasoline rebound effects are included, the reduction in global GHG emissions due to the addition of the LCFS or carbon price is still impressive compared to the RFS alone but smaller than the magnitude obtained for US domestic GHG reductions. As compared to the RFS which reduces domestic US emissions from the fuel and agricultural sectors by 4.8% and by 1% after including global effects, the combined policies reduce domestic GHG emissions by 8–11% and GHG emissions including global gasoline effects by 5–7% relative to the BAU over the 2007–2035 period.

Our analysis shows that the biofuel and climate policies and their combinations examined here differ in the trade-offs they offer for achieving the goals of GHG reduction, energy security and economic benefits. The RFS achieves the highest economic benefits but performs poorest in terms of GHG reduction. Its energy security benefits are higher than those with the addition of the LCFS but lower than those compared to those with the LCFS and a carbon price policy. The RFS and LCFS policy combination performs better in terms of GHG reduction and energy security but at an economic cost compared to the RFS alone. The addition of a carbon price to the RFS and LCFS combination, though imposing costs on fuel consumers, brings not only the level of GHG reduction and energy security to a significant new high compared to the RFS and LCFS combination but also the overall economic benefits close to the level achieved under the RFS alone. In sum, we find that the combination of the RFS, an LCFS and a carbon price can achieve the multiple objectives being pursued by the US energy and climate policies more effectively than the RFS alone. The analysis presented here can be used to infer the implications of other pair-wise combinations of these three policies. For example, an RFS+CO₂ price policy would increase production of cellulosic biofuels and reduce demand for corn ethanol leading to higher GHG mitigation compared to the RFS alone. *Khanna et al. (2011)* show that this policy combination will lead to lower GHG emissions and higher net economic benefits than the RFS alone. However, such a policy would not incentivize cellulosic biofuels, particularly BTL beyond the level achieved by the RFS alone. The level of cellulosic biofuels would also be smaller than that under the RFS+LCFS+CO₂ price policy. Thus the optimal mix of policies will depend on the weights attached to the multiple objectives of energy security, GHG mitigation, promoting innovation in low carbon fuels and economic benefits.

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