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Multi-objective regulations on transportation fuels: Comparing renewable fuel mandates and emission standards

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ABSTRACT

We compare two types of fuel market regulations — a renewable fuel mandate and a fuel emission standard — that could be employed to simultaneously achieve multiple outcomes such as reduction in fuel prices, fuel imports and greenhouse gas (GHG) emissions. We compare these two types of regulations in a global context taking into account heterogeneity in carbon content of both fossil fuels and renewable fuels. We find that although neither the ethanol mandate nor the emission standard is certain to reduce emissions relative to a business-as-usual baseline, at any given level of biofuel consumption in the policy region, a mandate, relative to an emission standard, results in higher GHG emissions, smaller expenditure on fuel imports, lower price of ethanol-blended gasoline and higher domestic fuel market surplus. This result holds over a wide range of values of model parameters. We also discuss the implications of this result to a regulation such as the US Renewable Fuel Standard given recent developments within the US such as increase in shale and tight oil production and large increase in average vehicle fuel economy of the automotive fleet.

1. Introduction

Governments all over the world have enacted policies in support of alternatives to crude oil (see Martinot and Sawin, 2009 for a list of countries). These policies aim to simultaneously reduce petroleum imports, help the rural economy, support domestic infant industries, and reduce greenhouse gas (GHG) emissions (CARB, 2009; CBO, 2010; Sobrino and Monroy, 2009). One popular regulation is a biofuel mandate, which specifies either a target quantity of biofuel (as in the United States (US) with the Renewable Fuel Standard[1] (RFS)) or a target market share for biofuel (as in the case of several European countries). An alternative type of regulation is an emission intensity standard, which specifies an upper limit on the average GHG intensity of fuel(s). Examples include the California Low Carbon Fuel Standard[2] (LCFS) and the European Union's Fuel Quality Directive.[3] The two types of regulation can be considered equivalent when there is only one type of fossil fuel and one alternative fuel and each has a fixed GHG intensity. Otherwise, the two regulations present different trade-offs between different potential policy objectives. In this paper we show how the two policies differ when they apply only to a portion of the global market for affected fuels. The political economic literature suggests that public policies are selected based on multiple performance measures (see Rausser et al., 2011). We therefore analyze alternative fuel policies based on their ability to influence multiple objectives as opposed to a single criterion such as efficiency or cost-effectiveness. We compare the two different approaches — a biofuel share mandate (SM) and a fuel-emission intensity standard (ES) to each other and also to a third policy that targets

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[1] http://www.epa.gov/otaq/fuels/renewablefuels/.

[2] http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

[3] http://ec.europa.eu/environment/air/transport/fuel.htm.

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emissions but also affects energy prices and energy imports, namely, a fuel carbon tax (CT). Our objective is to illustrate the differences between these policies with respect to different outcome variables that are invariant to both parametric uncertainty and policy stringency. Our modeling effort is not aimed at predicting the absolute impact of biofuels or any given policy.

This paper contributes to an expanding literature on the economics of biofuel policies, only a small sample of which we summarize. One set of papers develops simple analytical models to illustrate stylized facts about the net economic benefits or the cost-effectiveness of GHG emission reduction under different biofuel policies. One insight from this literature is that biofuel mandates lead to larger net social benefit when implemented in conjunction with a GHG tax rather than with a biofuel subsidy (de Gorter and Just, 2009; Khanna et al., 2008; Lapan and Moschini, 2009). Another message is that the currently commercial biofuels are not cost-effective for GHG mitigation (Creyts, 2010; Holland et al., 2009; Jaeger and Egelkraut, 2011) regardless of the policies used. Another set of papers rely on multi-market partial equilibrium and computable general equilibrium models to derive numerical estimates of the impact of biofuel policies on producers and consumers in different markets, the change in total surplus, and balance of trade and emissions (Bento et al., 2011; Cui et al., 2011; Rajagopal et al., 2010; Thompson et al., 2011). This literature suggests that worldwide, biofuel policies benefit food producers and biofuel producers and harm food consumers and suppliers of oil and oil products. Gasoline consumers benefit while consumers of the rest of oil products lose from ethanol policies. This literature demonstrates the multidimensionality of the policy objectives as well as policy tools. Individual studies mostly compare a mandate with a carbon tax or a subsidy, or compare an emission standard to carbon tax. However, the policy choice problem is selection of one or more policies from a set of inefficient policies. We contribute to this literature by emphasizing the differences between volumetric mandates and emission standards based on multiple explicit criteria.

Our work is related to two recent papers that analyze both emission standards and share mandates. Chen and Khanna (2012)—in contrast to most studies—found that either type of regulation reduces GHG emissions relative to a no-policy, business-as-usual scenario. Huang et al. (2013) simulated a policy scenario incorporating both the RFS and the LCFS and concluded that stacking these policies would lead to a greater GHG emission reduction than would occur under either policy alone, and more generally that biofuel policies tend to confer net economic benefits. The findings of both studies are predicated on achieving a level of cellulosic ethanol consumption that meets or exceeds the Energy Security and Independence Act 2010 target of 16 billion gallons of advanced biofuels. However, according to the US Energy Information Administrations Annual Energy Outlook 2014, the quantity of cellulosic biofuels consumed in the US in the year 2040 is predicted to be about 230 million gal, which accounts for less than 2% of the US annual biofuel consumption, while the prediction for first generation biofuels is one of no growth relative to current consumption. We focus on highlighting the differences between alternative policies for the currently mature, first-generation biofuels. Another distinction is that, since we do not model the land or food sectors (unlike Bento et al., 2011; Chen and Khanna, 2012; Huang et al., 2013), we analyze how different policies perform for a given level of domestic biofuel consumption.

Almost all the simulation-based studies mentioned above analyze results from only a few select combinations of values of their model's multiple assumed parameters such as the elasticity of supply and demand for different fuels in different markets, and the emission intensities of the various fuels. An exception is Rajagopal and Plevin (2013) who use a Monte Carlo simulation framework. Their simulations suggested that although either a biofuel mandate or an emission standard could reduce emissions relative to a no-policy baseline, a reduction occurred only within a narrow range of parameters. They focused on fuel rebound effects and GHG emissions. Here we extend their analysis to include economic variables including expenditure on fuel imports and the impact on fuel producers and consumers, and on biofuel suppliers.

2. Model and simulation

2.1. Model

We build on the model described in Rajagopal and Plevin (2013), a schematic diagram which is shown in Fig. 1. For a detailed description refer to the Supporting Information (SI) document. There are two regions — home and rest of the world (ROW), with each region having an open economy and competitive markets. There are two types of crude oil, namely, conventional crude oil and synthetic crude oil derived from Canadian oilsands. The two types of oil are perfect substitutes, but

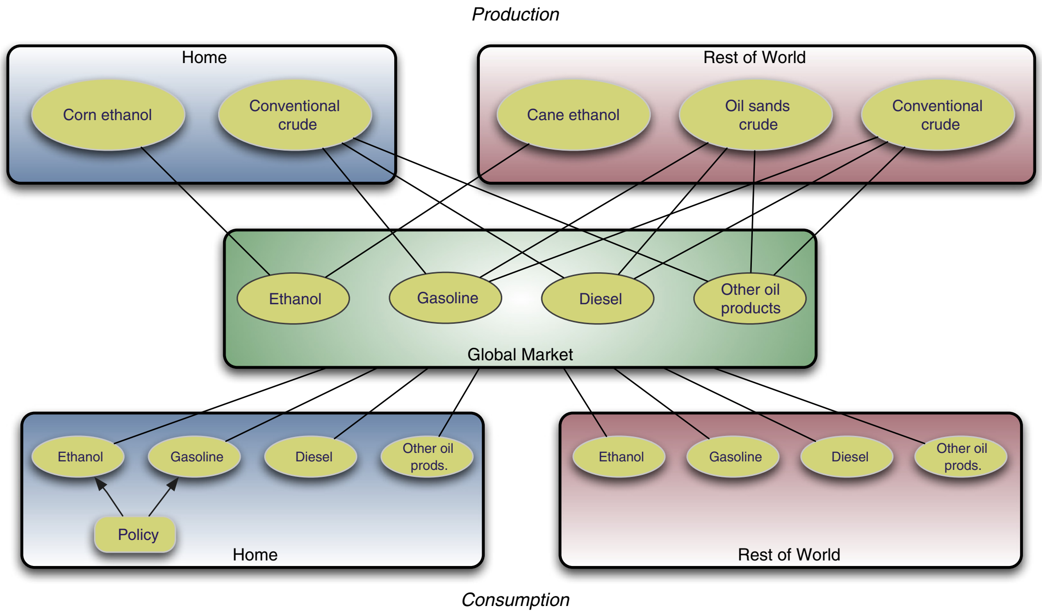

Fig. 1. Schematic diagram of the modeling framework.

Table 1
Input parameters used for the central case simulation and the uncertainty analysis using Monte Carlo simulation. (H) refers the region implementing the fuel policy and (R) refers to the rest of the world. We use data for the US for home region parameters. See the SI for a discussion of the assumed correlation between some of the parameters.

Model parameter	Central case	Assumed distrib.	Distribution parameter
Supply elasticity — Conventional crude oil (H)	0.2	Normal	(0.12,0.27)[a]
Supply elasticity — Conventional crude oil (R)	0.15	Normal	(0.08,0.23)[a]
Supply elasticity — Oilsands crude (R-*only*)	0.05	Normal	(0.03, 0.07)[a]
Demand elasticity — gasoline (H)	−0.5	Normal	(−0.6,−0.4)[b]
Demand elasticity — gasoline (R)	−0.65	Normal	(−0.8,−0.5)[b]
Demand elasticity — diesel (H)	−0.5	Normal	(−0.6,−0.4)[c]
Demand elasticity — diesel (R)	−0.65	Normal	(−0.8,−0.5)[c]
Demand elasticity — other oil products.(H)	−0.5	Normal	(−0.6,−0.4)[c]
Demand elasticity — other oil products (R)	−0.65	Normal	(−0.8,−0.5)[c]
Supply elasticity — corn biofuel, global	2	Uniform	(1,3)[d]
Supply elasticity — cane ethanol, global	2	Uniform	(1,3)[d]
GWI — Gasoline, conv. crude (g CO_2e MJ^{-1})	96	Lognormal	(91,104)[e]
GWI — Diesel, conv. crude (g CO^2e MJ^{-1})	95	Lognormal	(91,102)[e]
GWI — ROP conv. crude (g CO_2e MJ^{-1})	85	Lognormal	(79,94)[e]
GWI — Corn ethanol LCA (g CO_2e MJ^{-1})	69	Lognormal	(62,83)[f]
GWI — Cane ethanol LCA (g CO_2e MJ^{-1})	27	Lognormal	(25,33)[f]
GWI — Corn ethanol ILUC (g CO_2e MJ^{-1})	30	Lognormal	(15,51) [g]
GWI — Cane ethanol ILUC (g CO_2e MJ^{-1})	46	Lognormal	(6,95)[g]
Annual growth rate of fuel demand (H)	0.0015	Uniform	(0.001,0.002)
Annual growth rate of fuel demand (R)	0.006	Uniform	(0.005,0.007)

[a] Average of short- and long-run values from Greene (2010). Range represents the 95% confidence interval (CI).

[b] Avg. of short- & long-run values from Brons et al. (2008). Range is the 95% CI.

[c] We assume the same distributions as for gasoline. Range is the 95% CI.

[d] We are not aware of econometric estimates of elasticity for biofuel supply. Following previous literature Holland et al. (2009), we use a range of 1–3.

[e] Mean values from CARB's (2012) carbon intensity look-up tables for LCFS, http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf. Distributions based on 90% confidence intervals from Venkatesh et al. (2011) expressed as percentages and applied to CARB's mean values. When the oil products are derived by refining oilsands, we simply scale the emissions intensity of each product 15% relative to its emissions intensity when derived from conventional crude oil.

[f] Mean values from CARB's (2012) LCFS look-up tables. No distributions were available for LCA values; we assumed a range of [−10%, +20%] based roughly on Plevin (2010).

[g] Mean values from CARB's (2012) LCFS look-up tables. Distributions were adapted from CARB's "Initial Statement of Reasons" for LCFS re-adoption, which can be accessed at http://www.arb.ca.gov/regact/2015/lcfs2015/lcfs2015.htm.

the latter is more GHG intensive. Crude oil refining yields three products — gasoline, diesel and an aggregate consisting of all other refined products and a renewable fuel, which is ethanol. It is derived from two sources — corn and sugarcane, which are perfect substitutes, but the former is more GHG intensive. Gasoline and ethanol are also substitutes—once adjusted for difference in energy density—but only up to a limit. This limit is the so-called "blend wall", which is an upper limit on the fraction of ethanol in gasoline permitted for non-flexible fuel automobiles, currently assumed to be 10% for the older models. The GHG intensity of ethanol is modeled as the sum of two quantities: (1) the direct life cycle emission intensity, which represents emissions traceable to the biofuel supply-chain, and (2) emission from indirect land use change (ILUC) caused by biofuel expansion. For oil products, their GHG intensity is simply their direct life cycle emission intensity. These are fixed for each fuel. The extensions to Rajagopal and Plevin (2013) are our economic analysis of change in surplus to different groups in different markets and expenditure on imports for the policy region and the disaggregation of the emissions impacts into substitution and price effects and into those due to changes in consumption of different types of fuels in different regions. In the next section we describe how our numerical simulation scenarios differ from Rajagopal and Plevin (2013).

We model three different policies: biofuel share mandate, fuel emission intensity standard, and fuel carbon tax. The biofuel share mandate specifies the minimum share of ethanol, by volume, in domestic total gasoline consumption. The emission intensity standard specifies a maximum average fuel GHG intensity for the home region. Under this policy, each type of ethanol is assigned a "nominal" GHG intensity rating that is used to determine compliance with the regulation. The third type of policy is a fixed tax on fuel GHG emissions on a life cycle basis, including emissions from ILUC. The algebraic formulations of the equations representing the equilibrium under each of the above policies and the solution procedure are described in Sections S-1 and S-2 of the SI, respectively.

2.2. Numerical simulation

We perform numerical simulations to illustrate some qualitative differences between policies with respect to each different criterion. We assume a linear function for the supply of each of the two types of crude oil (in Rajagopal and Plevin, 2013 oilsand supply was fixed), the two types of ethanol and for the demand for the different products in the model — ethanol-blended gasoline, diesel, and the rest of oil product aggregate in each region. The functional specifications and the calibration procedure are described in Section S-3 of the SI.

For the numerical analysis, we assume that conventional crude oil is produced both at home and abroad while crude from oilsand is supplied only by the ROW region. We assume that corn ethanol is supplied only by the home region while sugarcane ethanol is supplied only by the ROW region. The various assumed inputs to the model are shown in Table 1. The distributions we assign are somewhat arbitrary for these are not available in the literature and we draw data from different studies. See Sections S-4 and S-5 of the SI for a discussion of assumptions underlying the numbers in Table 1. Our justification is that our goal is not to analyze the outcome under any single policy but to reveal systematic differences between policies with respect to certain policy relevant variables such as domestic fuel prices and expenditure on fuel imports and emissions. To illustrate the sensitivity of our results to the assumed values, we perform a Monte Carlo simulation where we evaluate each policy scenario 2500 times for different randomly chosen combinations of the various model inputs. The same set of 2500 different input combinations is used to compare different policies. The distributions of these inputs are also specified in Table 1. For those parameters assigned a normal distribution, the range column in the table denotes the 95% confidence interval and the span for the uniform distributions. Since the range for normal distributions extends from $-\infty$ to $+\infty$, we checked to ensure that our calculations did not involve negative values for the price elasticity of supply and other positive inputs and also did not involve positive values of price elasticity of demand.

Table 2
Base year (2007) data used in model calibration. We use data for the US for home region. mbpd = million barrels per day, gal denotes gallons. See Table 12 in the Appendix A for the sources of data in this table.

Fuel	Variable	Units	World	US	ROW
Oil	Total production	mbpd	84.6	8.5	76.1
	Conv. crude prod.	mbpd	83	8.5	74.5
	Oilsands prod.	mbpd	1.6	0	1.6
	Producer price	$/barrel	73	73	73
Gasoline	Consumption	mbpd	21.2	7.8	13.4
	Producer price	$/gal	2.3		
	Consumer price	$/gal		2.8	3.6
Diesel	Consumption	mbpd	23.7	4.1	19.5
	Producer price	$/gal	2.4		
	Consumer price	$/gal		2.9	3.3
Rest of oil products	Consumption	mbpd	39.8	4	36
	Producer price	$/gal	1		
	Consumer price	$/gal		1.5	2.1
Corn ethanol	Production	mbpd	0.4	0.4	0.0
	Consumption	mbpd	0.4	0.4	0.0
	Producer price	$/gal	2.2	2.2	
Cane ethanol	Production	mbpd	0.5	0.0	0.5
	Consumption	mbpd	0.5	0.0	0.5
	Producer price	$/gal	1.7		1.7

The US Energy Security and Independence Act which adopted the federal RFS targets for the year 2015 and beyond[4] and the Governor of California's Executive order adopting the LCFS targets for 2011 and beyond,[5] were both passed in 2007. Although we are not simulating these exact policies, this is one reason for calibrating the model to the year 2007. The data for 2007 is shown in Table 2. We also performed a second set of simulations in which we calibrated the model to 2010 (the last year for which we are able to find all the necessary data) and then simulated outcomes for 2015 under the different policy scenarios. The parameter distribution, base year data and results for the central case (defined in Section 3.1) for this exercise are shown in Appendix A (see Tables 9–11). Between 2007 and 2010, annual US ethanol consumption more than doubled from 6.6 to 13.3 billion gal (its share doubled as well from 5% to 10%), and the average world oil price increased from $73 to $81/barrel. During the same time, the average annual price of corn ethanol in the US declined from $2.1 to $1.9 per gal, while that of cane ethanol was almost unchanged (see Table 10). Interestingly, after calibrating to 2010, the model predicts that the level and share of ethanol in domestic consumption of gasoline in the year 2015 under BAU is, respectively, 19.2 billion gal and 14% (see Table 11). Therefore, the minimum stringency for a share mandate to be binding in 2015 is 14%, which exceeds the blend wall.[6] This also implies that a 15 billion gal volumetric target for 2015 is non-binding. This prediction accords with the current situation in the U.S. wherein the attainment of the RFS targets is constrained by the lower than estimated levels of gasoline consumption for 2015, the 10% blending limit for non-flex fuel vehicles and the limited diffusion of flex-fuel vehicles.[7] In light of the above, and since the primary motivation of this paper is to illustrate the differences between a binding biofuel mandate and a binding emission performance standard, we focus on simulations with the model calibrated to 2007. The results for 2010 base year confirm that the comparative performance of the different policies is not affected by the base year chosen for model calibration or the model inputs. In the concluding section, we, however, discuss the implications of recent developments that are not part of the formal analysis.

Table 3
Table shows the policy scenarios we simulate. Each type of policy is simulated for different levels of stringency within the range shown. These represent policy targets for the year 2015. For the emission standard (ES), the range represents the reduction in the emission intensity of ethanol–gasoline blend relative to its value in the base year to which the model is calibrated, which is 2007.

Policy type	Policy level in 2015
Ethanol share mandate (SM)	10.5%–14.5%
GHG emission intensity standard (ES)	2.5%–3.5%
Fuel carbon tax ($ per tonne CO_2e) (CT)	5–50

Table 4
Global warming intensity (GWI) rating of various fuels for determining compliance with policy. These values are chosen from the California Air Resources Board's lookup table for GWI intensity of gasoline and fuels that substitute for gasoline, which can be accessed here http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf.

Fuel	Rating (g CO_2e/MJ)
Gasoline from conventional crude	95.8
Ratio of GHG intensity of oilsand products relative products of conventional crude	1.15
Corn ethanol (supply chain only)	69.4
Corn ethanol ILUC	27.4
Cane ethanol (supply chain only)	30
Cane ethanol ILUC	46

2.3. Policy scenarios

Table 3 lists the policy scenarios that we simulate in the home region. We first simulate the outcome in a future year, which we choose as 2015. We refer to this as a business-as-usual (BAU) scenario. Under this scenario, the only policy in effect is the fuel oxygenate mandate, which stipulates a minimum 5% ethanol blend level in gasoline. For reference, the ethanol blend level in the U.S. in 2007 was approximately 8%. We then simulate three different types of policies — ethanol share mandate (SM), GHG emission intensity standard (ES), and fuel carbon tax (CT), each at different levels of stringency within a chosen range for each. For the discussion, we focus on one specific level of each policy. We focus on the 11.5% SM (SM11.5) and the 2.7% ES (ES2.7). These levels of stringency result in approximately 15.4 billion gal of ethanol being consumed within the US in the year 2015 under either policy (see Table 5). For the carbon tax, we chose $20 per tonne CO_2 simply because this value lies within the range of carbon price discussed in US Congressional Budget Office reports and in the literature.[8]

Table 4 shows the global warming intensity (GWI) rating (also referred to as GHG intensity of a fuel) of different fuels used either for determining compliance in the case of the emission-standard or computing the carbon tax to be levied on a fuel. Because of the substantial uncertainty in estimates of fuel GWI, we model the actual emission intensity based on a sample from the parameter distributions shown in Table 1. For the "central case" simulation (described below) the two sets of values are identical. Note that since the sum of the GWI ratings for corn ethanol's supply chain and ILUC emissions exceeds the GWI rating of gasoline from conventional crude, corn ethanol becomes unviable at home under an emission standard, which is what we find in the central case.

3. Discussion of results

We discuss first the results for a single model run in which each input parameter takes a central value, which is shown in Table 1. We refer to this particular run as the "central case". We would like to point out that for certain variables the impact of a policy shock, all else

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[4] http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf.

[5] www.arb.ca.gov/fuels/lcfs/eos0107.pdf.

[6] The blend wall faced by US gasoline retailers is a weighted average of the maximum permissible level of E10 and E85 consumption given a mix of non-flex fuel and flex fuel vehicle fleet and this is generally considered to be below 14% in the 2015 time frame.

[7] http://www.eia.gov/todayinenergy/detail.cfm?id=11671.

[8] https://www.cbo.gov/publication/44223.

Table 5
Mean case outcomes in the BAU and three main policy[a] scenarios. Note: We depict the levels for the base year and BAU but depict the change with respect to the BAU for the three policies. *Abbreviations*: B = billion, bbl = barrel, d = day, gal = gallons, geq = gasoline equivalent, H = Home, M = million, ROW = Rest of the world, t = metric tonne, W = World, y = year.

Model outputs	Units	2007	BAU 2015	CT20	SM11.5	ES2.7
Producer price[b]				*Change wrt. BAU*		
Oil (W)	\$/bbl	73.0	100.5	−1.19	−0.10	−0.13
Gasoline (W)	\$/gal	2.3	3.0	−0.07	−0.01	−0.02
Diesel (W)	\$/gal	2.4	3.4	−0.02	0.00	0.00
Corn eth. (W)	\$/gal	2.2	2.0	−0.04	0.22	−0.01
Cane eth. (W)	\$/gal	1.7	2.0	−0.01	0.22	0.32
Eth.–gas. blend geq. (H)	\$/gal–geq	2.9	3.0	0.17	−0.02	0.00
Consumption				*Change wrt. BAU*		
Oil (W)	Mbbl/day	84.6	89.7	−0.22	−0.02	−0.02
Corn eth. (W)	Bgal/yr	6.6	5.2	−0.26	1.30	−0.06
Cane eth. (W)	Bgal/yr	7.7	11.8	−0.11	2.99	4.34
Corn eth. (H)	Bgal/yr	6.6	5.2	−5.20	1.30	−5.20
Cane eth. (H)	Bgal/yr	0.0	5.9	4.77	2.98	9.46
Total eth. (H)	Bgal/yr	6.6	11.1	−0.43	4.29	4.26
GHG emissions				*Change wrt. BAU*		
World	Mt/yr	13,926	14,765	−38.19	21.92	18.67
Home	Mt/yr	2812	2841	−147.84	18.41	−34.20
Other variables				*Change wrt. BAU*		
Eth. share in gas. (H)		5%	9%	0%	3%	3%
Import outlay (H)	\$B/y	728	941	−50	15	56
Change in surplus		Units		Change wrt. BAU		
i) Fuel consumer (H)		\$B/y		−120.1	35.9	33.0
ii) Oil producer (H)		\$B/y		−10.9	−0.9	−1.2
iii) Eth. producer (H)		\$B/y		−0.6	3.5	−0.1
iv) Fuel market (H) = i + ii + iii		\$B/y		−131.5	38.6	31.6
v) Govt. revenue (H)		\$B/y		141.8	4.8	4.6
vi) Fuel consumer (ROW)		\$B/y		76.7	5.5	7.2
vii) Oil producer (ROW)		\$B/y		−95.8	−8.1	−10.6
viii) Eth. producer (ROW)		\$B/y		−0.3	8.0	12.2
ix) Fuel market (ROW) = vi + vii + viii		\$B/y		−19.4	5.5	8.9

[a] For the three policies, we report the change with respect to BAU for the variables.
[b] Producer price is consumer price less the sales tax in each region.

fixed, could be positive or negative. For instance, the price of pure gasoline would decline under any of the policies considered. However, the price of ethanol-blended gasoline in the home region, could either increase or decrease under an ethanol mandate or emission standard while it always increases under a carbon tax (see Section S-6 of SI). For both the ethanol mandate and the emission standard, the total emissions could either increase or decrease, while it always declines under a carbon tax. For these reasons, when discussing the central case, we emphasize only the differences between the policies and not the absolute impact under any single policy. Section 3.2 illustrates the robustness of the differences we observe in the central case for certain key variables over a wide range of model inputs.

Following the discussion of the central case, we discuss the disaggregation of the total change in GHG emissions into a fuel substitution effect and a fuel price effect to highlight their relative importance in the total change in emissions (Section 3.1.1). We also illustrate the shuffling of pollution between regulated and unregulated regions (Section 3.1.2). In Section 3.2, we summarize results from 2500 simulations involving different combinations of values of model parameters chosen randomly from the distributions shown in Table 1. This, as mentioned above, is aimed at illustrating the robustness of differences between policies observed in the central case for select variables.

3.1. Central case

Table 5 shows the results for the base year (year 2007, which is also the model calibration year), the future BAU scenario (year 2015), and the three policies for the central case. For the BAU, the model projects that, due to growing demand, world oil price increases from \$73/barrel (bbl) in 2007 to \$100.5/bbl in 2015 while global oil consumption increases from 85 to about 90 million barrels per day (Mbbl/d). The price of all fuels increases in the home region (and in ROW as well). Global consumption of corn ethanol decreases from 6.6 to 5.2 billion gal per year (Bgal/y) and consumption of cane ethanol increases from 7.7 to 11.8 Bgal/y. Despite an increase in oil prices from 2007 to 2015, global corn ethanol consumption declines on account of elimination of the ethanol excise tax credit and ethanol import tariff in the home region, which in the case of the US, expired in the year 2011. The share of ethanol in the home region increases from 5% to 9%, on account of greater imports of cane ethanol. Global GHG emissions increase from 13.9 to 14.7 billion tonnes/y with relatively little change in home emissions. Home expenditure on fuel imports increases from 728 to 941 B\$/y on account of greater imports of oil and cane ethanol. We next discuss outcomes under the three different policies. For the sake of brevity, we discuss the impact on select variables only.

> *Impact on fuel prices:* Relative to the BAU, world oil price is lower under each of the policies considered, and so are both world oil production and consumption. A fuel carbon tax decreases the world price of all oil products but increases the cost of all refined oil products in the home region (see Rajagopal and Plevin, 2013 for discussion of impact on non-gasoline products). World gasoline price declines under both SM11.5 and ES2.7 as ethanol supply increases. For the ethanol-gasoline blend, we discuss its price in units of US dollars per gasoline equivalent gallon.[9] The price of ethanol blended

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[9] This involves adjusting the price per gallon of ethanol–gasoline blend to reflect its lower energy content relative to a gallon of pure gasoline. Essentially, if the proportion of ethanol in the blend is α and η is ratio of energy per gallon of ethanol and energy per gallon of pure gasoline (which is 0.67), then $P^{geq}_{blend} = \frac{P_{blend}}{1-(1-\eta)\alpha}$.

Table 6
Decomposition of the change in emissions into substitution and price effect under the different policies. Changes are computed relative to BAU and are shown for the "central case". Emissions are in units of million tonnes of CO_2e per year (Mt/y).

	CT20-BAU	SM11.5-BAU	ES2.7-BAU
Net global change	−37	15	8
Substitution effect	0	−9	−13
Price effect or IFUE	−38	24	21

Table 7
Decomposition of the change in emissions relative to BAU under the different policies for the "mean case". We decompose the total change into that attributable to the change in consumption of finished fuel products from the different primary sources. Emissions are in units of million tonnes of CO_2e per year (Mt/y).

	CT20		SM11.5		ES2.7	
	World	Home	World	Home	World	Home
Conv. crude products	−35	168	−17.0	−36.6	−19.5	224
Oilsand products	−0.2	−306	−0.1	−0.1	−0.1	−306
Corn ethanol	−1.8	−36.4	14.6	14.6	−2.1	−36.4
Cane ethanol	−0.4	25.7	17.1	16.8	29.7	55.5
Net change	−37	−148	14.6	−5.3	7.9	−63

gasoline at home is lower under SM11.5 and higher under ES2.7. For an analytical proof of the fact that mandating new fuels could either raise or lower fuel prices see Section S-6 of the SI.

Impact on fuel imports: Expenditures on fuel imports by the home region decline under the tax but increase under both SM11.5 or ES2.7 on account of greater imports of cane ethanol relative to BAU. As mentioned earlier, the elimination of the ethanol excise tax and ethanol import tariff increases the cost of corn ethanol both absolutely and also relative to cane ethanol. ES2.7 results in greater domestic demand for cane relative to corn ethanol on account of its lower cost per unit of GHG emissions avoided. For a similar level of total biofuel consumption at home, ES2.7 results in larger expenditure on fuel imports relative to SM11.5.

Impact on ethanol consumption: Home ethanol consumption increases by similar amounts under both SM11.5 and ES2.7, with both resulting in a similar share in the domestic market, which as mentioned earlier, is the basis for comparing these specific instances of SM and ES. Home ethanol use increases relatively less under the tax. However, different policies lead to different effects on the two types of ethanol. Global cane ethanol consumption increases more than corn ethanol under all policies and accounts for almost the entire increase under the ES2.7 and CT20, which suggests that corn ethanol is less cost effective relative to cane ethanol in reducing GHG emissions.

Impact on emissions: Global GHG emissions are lower relative to the BAU in the case of CT20 (and it would be so for any positive level of fuel carbon tax) but are higher under both SM11.5 and ES2.7, suggesting that biofuels prove counterproductive to GHG reduction goals. It is worth reminding that the GWI ratings we use for the central case prevents corn ethanol consumption under ES2.7 (or any generic ES for that matter) and it partially explains the higher emissions under the SM11.5. Interestingly, although cane ethanol's total GWI rating i.e., supply chain and ILUC combined, is lower than that of gasoline, the net effect again is an increase in global emissions under ES2.7 as well. However, with a sufficiently small GHG intensity of ethanol relative to gasoline result either of these policies could lead to lower global emissions. Also, ES2.7 reduces home emissions more than SM11.5 but this is essentially on account of shuffling of GHG-intensive oil sands from the home region in BAU to ROW. For a more detailed discussion of these effects see Section 3.1.2.

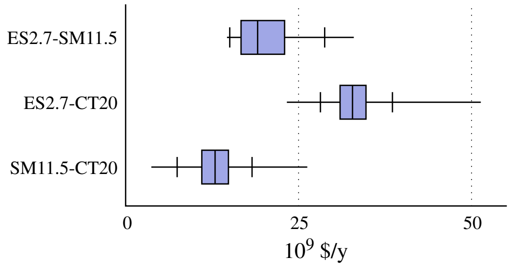
Impact on home fuel market surplus: Fuel consumers always lose under a carbon tax but, under SM11.5 and ES2.7, gasoline consumers gain while consumers of other oil products lose (not shown in Table 5). Relative to BAU, net fuel consumers' surplus is higher under SM11.5 or ES2.7 and lower in the case of CT20. Oil producers lose under all policies due to the decline in global oil price. Home ethanol producers (i.e., corn ethanol producers) gain under the SM and lose under CT20 or ES2.7. Total domestic fuel market surplus, which is the sum of the surplus accruing to fuel consumers and fuel producers at home, is lower under the carbon tax and higher under the other two policies relative to BAU.

Impact on ROW fuel market surplus: The decline in world oil price benefits ROW fuel consumers and harms oil producers worldwide. The ROW ethanol producers gain under both biofuel policies, but gain more under ES2.7 since this policy increases the demand for cane ethanol produced outside the home region. The ROW fuel market surplus declines under CT20 on account of the loss to oil producers, but it increases under the ethanol-based policies on account of the increase in ethanol producer surplus.

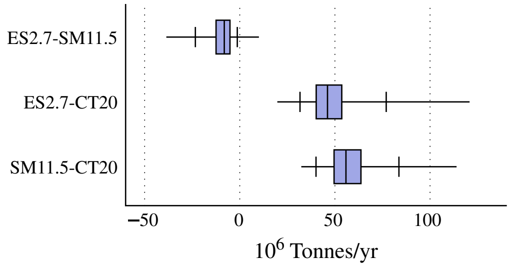
Summarizing the central case for the three policies, we find that the carbon tax, CT20, results in the greatest reduction in both global GHG emissions and the home region's expenditure on fuel imports but also results in the smallest fuel market surplus. The biofuel mandate, SM11.5, increases global GHG emissions but it also leads to the largest increase in fuel consumers' and ethanol producers' surplus and a small

Table 8
Comparison of the impact of share mandate (SM) and emission standard (ES) at similar levels of biofuel consumption for the central case. *Abbreviations*: B = billion, gal = gallons, t = metric tonne, y = year, Q_E^H — Home ethanol consumption. The column 'Target' shows the target share for ethanol under the share mandate and the target level for reduction in GHG intensity under the emission standard.

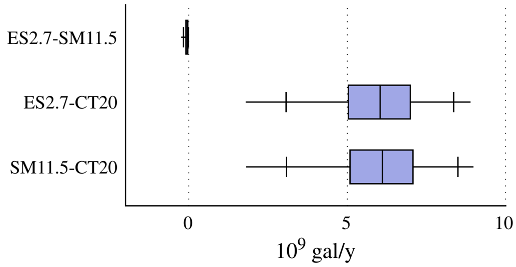
SM		ES		Difference between SM and ES			
Target	Q_E^H (B gal/y)	Target	Q_E^H (B gal/y)	Q_E^H (B gal/y)	Fuel imports ($B/y)	Global Emissions (Mt/y)	P_{blend} ($/gal)
.5%	13.8	2.50%	13.4	0.32	−44.9	5.1	−0.016
.0%	14.4	2.60%	14.2	0.19	−48.5	5.9	−0.018
.5%	15.1	2.70%	15.1	0.06	−52.3	6.7	−0.021
.5%	16.5	2.80%	15.9	0.63	−58.2	9.3	−0.030
.0%	17.2	2.90%	16.7	0.51	−62.3	10.3	−0.034
.5%	17.9	3.00%	17.5	0.40	−66.7	11.3	−0.038
.0%	18.6	3.10%	18.3	0.30	−71.2	12.4	−0.043
.5%	19.3	3.20%	19.1	0.20	−75.9	13.6	−0.048



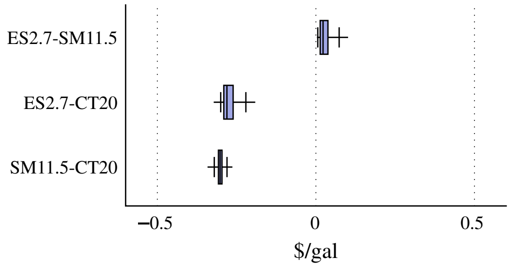
(a) Expenditures on imports



(b) Global CO_2 emissions



(c) Global ethanol consumption



(d) Price of blended gasoline

Fig. 2. Frequency distributions of differences in policy outcomes for (a) expenditures on imports, (b) global CO_2 emissions, (c) global ethanol consumption, and (d) price of blended gasoline. Results are based on 2500 trials. BAU = business-as-usual; ES2.7 = 4% emission reduction standard; and SM11.5 = 11% share mandate; CT20 = \$20/metric tonne CO_2 carbon tax. In this figure, the box width represents the interquartile range, and the central vertical line represents the median value. The crosshatch marks identify the 95% confidence interval, and the ends of the whiskers identify the minimum and maximum values for each distribution.

increase in expenditure on fuel imports. The emission-standard, ES2.7, which leads to a similar level and share of biofuels at home as SM11.5, reduces emissions, but by less than what is achieved by the carbon tax, CT20. ES2.7 also leads to the largest increase in expenditure on imports and a much smaller increase in fuel market surplus relative to SM11.5.

3.1.1. Disaggregating emission changes into substitution and price effects

Table 6 shows a decomposition of the change in emissions under the different policies relative to the BAU in the central case trial. We disaggregate the change in emissions into two effects, namely, a substitution effect and a price effect. The substitution effect refers to the change in emissions (ΔZ_{subs}) that would arise from a one-to-one replacement of gasoline with ethanol, including all direct and market-mediated effects other than those related to fuel prices. The price effect refers to the change in the quantity of petroleum products consumed, resulting from fuel price changes induced by increased production and use of biofuels. Following Rajagopal et al. (2011), we refer to the price effect as the Indirect Fuel Use Effect (IFUE). The change in emissions associated with IFUE is designated ΔZ_{IFUE}. We calculate these two effects as follows:

$$\Delta Z_{subs} = \sum\nolimits_{b \in B} \Delta q_b \left(z_b - z_g\right) \tag{1}$$

$$\Delta Z_{IFUE} = \Delta Z_{total} - \Delta Z_{subs} \tag{2}$$

where, $B \in$ {corn ethanol, cane ethanol}, g is gasoline, q is quantity, Z is emissions, and Δ denotes change. When multiple biofuels are in use, the total substitution effect is the aggregate of the individual substitution effects.

There is relatively little change in ethanol consumption under the carbon tax CT20; the reduction in emissions arises primarily from reduction in fuel consumption. For the other two policies, the substitution effect plays a larger role. In both SM11.5 and ES2.7, the substitution effect contributes to emission reduction. However, for both these policies, the substitution effect is mitigated by the price effect: world oil price declines, causing consumption to rebound and this effect overwhelms the substitution effect. Similar effects of fuel price changes on emissions have been suggested by others (Bento et al., 2011; Chen and Khanna, 2012; de Gorter and Drabik, 2011; Thompson et al., 2011).

3.1.2. Decomposing change in emissions: by fuel source

Table 7 disaggregates the change in emissions into effects attributable to the change in consumption of products derived from different primary sources — conventional crude oil, oil sands, corn ethanol and cane ethanol at home and globally. For brevity, we leave out ROW, which can be inferred. For CT20, and a carbon tax in general, emissions decline both at home and globally. A negative sign in the column for carbon tax denotes a decrease in emissions. The reduction in global emissions under the carbon tax is driven by a reduction in global crude oil consumption, which accounts for almost all the change in emissions. The slight increase in global consumption of cane and corn ethanol under this policy explains their positive contribution to total emissions. We discuss oil sands separately below. Under SM11.5, emissions increase both globally and for the home region in total (see the last row). Therefore, positive values in the column for SM11.5 represent an increase in emissions. Global emissions increase under ES2.7 while emissions at home are decline. The latter is essentially due to the shuffling of oilsand products and corn ethanol consumed at home in the BAU with lower GWI-products from conventional crude and cane ethanol consumed abroad in the BAU.

The global consumption of oilsands changed by relatively small amounts in all of the scenarios we examined. This is attributable to our assumption of a highly price-inelastic supply of oilsands. However, regional consumption of oilsands is policy dependent. Both the carbon tax and the emission standard render oil sands uneconomical in the home region on account of their higher GHG intensity relative to conventional crude oil, resulting in a greater than 100% contribution of oil sands to the reduction in emissions in the home region under these two policies. This suggests that emission-sensitive policies lead to more shuffling than do renewable fuel mandates.

3.2. Robustness analysis

To illustrate the robustness of the differences we observe between SM11.5 and ES2.7, we first compare different pairs of SM and ES when both attain a similar level of biofuel consumption at home, the policy region. Table 8 shows the results for seven such pairs — (SM10.5, ES2.5), (SM11, ES2.6), (SM11.5, ES2.7), (SM12.5, ES2.8), (SM13, ES2.9), (SM14, ES3.1), and (SM14.5, ES3.2). In each case, when compared to ES, SM results in higher home ethanol consumption, smaller expenditure on fuel imports, higher global emissions and lower price of ethanol–gasoline blend at home.

Next, we explore whether the differences we observe among policies in the central case for SM11.5 and ES2.7 are robust to assumptions about the model parameters listed in Table 1. Fig. 2 shows the frequency distribution across the 2500 trials of the difference in the outcomes in a given trial for each of the three policy pairs — SM11.5 and CT20, ES2.7 and CT20, and ES2.7 and SM11.5. Let us focus on the difference between SM11.5 and ES2.7 since these two policies achieve a similar level of biofuel consumption at home. Relative to SM11.5, ES2.7, leads to: higher expenditure on fuel imports, lower global emissions, lower total ethanol consumption, and higher gasoline price in the home region. The lower total ethanol consumption is on account of the lower GHG intensity of cane ethanol, while higher expenditure on imports is because cane ethanol is produced abroad. The higher price of blended gasoline is on account of lower total ethanol consumption, for in our simulations increasing ethanol consumption is associated with lower fuel price in the home region. Comparing SM11.5 and CT20, SM11.5 leads to a lower domestic price of gasoline. However, while both emissions and expenditure of fuel imports are almost always lower under CT20, it is possible that they are higher under some conditions. Likewise for ES2.7 relative to CT20.

4. Policy implications and conclusion

Policies such as renewable energy mandates are adopted for multiple reasons which include reducing petroleum imports, supporting the rural economy, supporting domestic infant industries, and reducing environmental externalities. That such polices are neither efficient nor cost-effective with respect to any single objective is well established. Our motivation instead is to compare a renewable fuel mandate to a fuel GHG emission standard, which can also achieve multiple objectives, and in theory, is less prescriptive than the former. We also compare these two regulations to a fuel carbon tax. Our approach has been to simply delineate the impact of the three policies on different policy-relevant variables and identify systematic differences between them that are robust to uncertainty in model parameters. Different from two recent related studies, Chen and Khanna (2012) and Huang et al. (2013), we focus only on ethanol from corn and sugarcane and not on cellulosic ethanol. We derive the following main conclusions.

Firstly, relative to an ethanol mandate, an emission standard results in lower global emissions while requiring less biofuel, but results in slightly higher fuel price in the home region. The difference between an ethanol mandate and an emission standard with regard to reduction in fuel-import expenditure depends on the cost effectiveness of home region's sources of low GHG fuels relative to those from abroad. Since, in our model, the home region produces corn ethanol, our model predicts that a biofuel mandate will result in lower expenditure on imports relative to an emission standard. A biofuel mandate increases domestic fuel market surplus (the sum of fuel consumer, oil producer, and ethanol producer surplus for the home region) more than an emission standard.

Secondly, some intended benefits of renewable fuel policies could be undermined by their effect on global oil price. We show that the inclusion of ILUC in the GWI rating of biofuels does not guarantee that emissions decline absolutely. The reduction in world oil price by the home region's policies causes a rebound in oil consumption. For currently available biofuels, emissions attributable to the rebound effects could completely offset the direct effect of substituting gasoline with a less GHG intensive fuel. In terms of absolute impact, while in theory policies supporting ethanol could either increase or decrease global emissions, we conjecture that if the GWI rating of different ethanols under regulations such as the LCFS or RFS approximates their true GWI, then such regulations could prove counterproductive. The potential of such an outcome is, however, diminished under some conditions. Biofuels with a substantially lower lifecycle GHG intensity (ILUC GWI included) relative to that for oil products could make the substitution effect dominate the IFUE so that total emissions decline. Furthermore, as the global coverage of regions with ethanol policies increases, the scope for shuffling and leakage diminishes, which also mitigates IFUE. Our model accounted for ethanol demand abroad but to the extent that we under-estimated it, we might be over-estimating IFUE.

We conclude by discussing the implications of two recent trends, that are not part of our formal analysis, to the conclusions above. One is the rapid increase in oil extraction from shale and tight oil formations since 2009, which currently is confined mainly to the US.[10] This positive supply shock has been a contributing factor to the recent declining trend in both the quantity of and the expenditure on fuel imports for the US.[11] However, global GHG emissions are still increasing.[12] This implies that on account of its better environmental performance, the benefits (costs) of an emission standard are now larger (smaller) relative to a biofuel mandate. Complementing the positive oil supply shock is a negative demand shock experienced by the US since the adoption of the RFS II regulations in 2007[13] and here we are not referring to the effect of the so called great recession from 2007 to 2009.[14] Instead, the automobile fuel economy targets adopted in 2010, which raised the minimum average fuel efficiency for cars and light trucks produced by each manufacturer to the equivalent of 35.5 miles per gal (mpg) in 2016,[15] have led to a declining trend in US gasoline demand further constricting the capacity to absorb greater quantities of ethanol into domestic gasoline supply resulting in the blend wall being reached.[16] This increases the relative benefits in switching to a national fuel carbon emission standard from an ethanol mandate as a given emission target can be achieved using less biofuel through this regulation, although with first generation biofuels there appears to be little benefits if any under either policy. With breakthroughs in the second-generation biofuels, electric vehicles and natural gas vehicles, however, the GHG and other benefits of an emission standard might be higher relative to a fixed biofuel mandate, and absolutely positive as well.

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[10] http://www.eia.gov/forecasts/aeo/er/early_production.cfm.

[11] http://www.eia.gov/todayinenergy/detail.cfm?id=18351.

[12] http://infographics.pbl.nl/website/globalco2/.

[13] http://www.eia.gov/todayinenergy/detail.cfm?id=16871.

[14] http://www.nber.org/cycles/sept2010.html.

[15] These targets were subsequently further raised to 54.5 mpg by 2025. See http://www.whitehouse.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-mpg-fuel-efficiency-standard.

[16] http://www.eia.gov/todayinenergy/detail.cfm?id=3070.

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Appendix A

Tables 9–11 show the parameter distribution, base year data and results for the central case when the base year is 2010 instead of 2007 as in the main paper. The policy targets and the future business-as-usual are, however, unchanged, and fixed as of the year 2015. Given that the time span from base year 2010 to 2015 is half that from 2007 to 2017, we decided that it was more appropriate to use elasticities of smaller magnitude for the 2010 base year simulations. For this, we simply took the original 2500 random combinations of input parameters and divided the elasticities in half, while leaving the other input parameters unchanged.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2015.02.020.

Table 9
Input parameter ranges used for Monte Carlo simulation. (H) refers to the region implementing the fuel policy and (R) refers to the rest of the world. We use data for the US for home region parameters, but we do not mean to imply this as an exact representation of the US fuel market.

Model parameter	Central value	Assumed distrib.	Distribution parameter
Supply elasticity — Conventional crude oil (H)	0.12	Normal	(0.06,0.13)[a]
Supply elasticity — Conventional crude oil (R)	0.7	Normal	(0.04,0.11)[a]
Supply elasticity — Oilsands crude (R-*only*)	0.02	Normal	(0.01,0.03)[a]
Demand elasticity — gasoline (H)	−0.25	Normal	(−0.3,−0.2)[b]
Demand elasticity — gasoline (R)	−0.32	Normal	(−0.4,−0.25)[b]
Demand elasticity — diesel (H)	−0.25	Normal	(−0.3,−0.2)[c]
Demand elasticity — diesel (R)	−0.32	Normal	(−0.4,−0.25)[c]
Demand elasticity — other oil products.(H)	−0.25	Normal	(−0.3,−0.2)[c]
Demand elasticity — other oil products (R)	−0.32	Normal	(−0.4,−0.25)[c]
Supply elasticity — corn biofuel, Global	1	Uniform	(0.5,1.5)[d]
Supply elasticity — cane ethanol, Global	1	Uniform	(0.5,1.5)[d]
GWI — Gasoline, conv. crude (g CO_2e MJ^{-1})	96	Lognormal	(91,104)[e]
GWI — Diesel, conv. crude (g CO_2e MJ^{-1})	95	Lognormal	(91,102)[e]
GWI — ROP conv. crude (g CO_2e MJ^{-1})	85	Lognormal	(79,94)[e]
GWI — Corn ethanol LCA (g CO_2e MJ^{-1})	69	Lognormal	(62,83)[f]
GWI — Cane ethanol LCA (g CO_2e MJ^{-1})	27	Lognormal	(25,33)[f]
GWI — Corn ethanol ILUC (g CO_2e MJ^{-1})	30	Lognormal	(15,51)[g]
GWI — Cane ethanol ILUC (g CO_2e MJ^{-1})	46	Lognormal	(6,95)[g]
Annual growth rate of fuel demand (H)	0.0015	Uniform	(0.001,0.002)
Annual growth rate of fuel demand (R)	0.006	Uniform	(0.005,0.007)

[a] Average of short- and long-run values from Greene (2010). Range represents the 95% confidence interval (CI).

[b] Avg. of short- & long-run values from Brons et al. (2008). Range is the 95% CI.

[c] We assume the same distributions as for gasoline. Range is the 95% CI.

[d] We are not aware of econometric estimates of elasticity for biofuel supply. Following previous literature (Holland et al., 2009), we use a range of 1–5 for sugarcane ethanol, although we assume a narrower range of 1–3 for corn ethanol.

[e] Mean values from CARB's (2012) carbon intensity look-up tables for LCFS, http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf. Distributions based on 90% confidence intervals from Venkatesh et al. (2011) expressed as percentages and applied to CARB's mean values.

[f] Mean values from CARB's (2012) LCFS look-up tables. No distributions were available for LCA values; we assumed a range of [−10%, +20%] based roughly on Plevin (2010).

[g] Mean values from CARB's (2012) LCFS look-up tables. Distributions were adapted from CARB's "Initial Statement of Reasons" for LCFS re-adoption, which can be accessed at http://www.arb.ca.gov/regact/2015/lcfs2015/lcfs2015.htm.

Table 10
Base year (2010) data used in model calibration. We use data for the US for home region. mbpd = million barrels per day, gal denotes gallons. See Table 12 in Appendix A for the sources of data in this table.

Fuel	Variable	Units	World	US	ROW
Oil	Total production	mbpd	87.6	9.7	77.9
	Conv. crude Prod.	mbpd	85.6	9.7	75.9
	Oilsands prod.	mbpd	2.0	0	2.0
	Producer price	$/barrel	80.8	80.8	80.8
Gasoline	Consumption	mbpd	21.9	8.5	13.4
	Producer price	$/gal	2.37		
	Consumer price	$/gal		2.87	3.67
Diesel	Consumption	mbpd	24.5	4.2	20.3
	Producer price	$/gal	2.5		
	Consumer price	$/gal		3.0	3.4
Rest of oil products	Consumption	mbpd	41	4.5	36.6
	Producer price	$/gal	1.35		
	Consumer price	$/gal		1.85	2.45
Corn ethanol	Production	mbpd	0.87	0.87	0.0
	Consumption	mbpd	0.87	0.87	0.0
	Producer price	$/gal	1.9		
Cane ethanol	Production	mbpd	0.53	0.0	0.53
	Consumption	mbpd	0.53	0.0	0.53
	Producer price	$/gal	1.7		

Table 11
Mean case outcomes in the BAU and three main policy scenarios. Note: We depict the levels for the base year and BAU but depict the change with respect to the BAU for the three policies. *Abbreviations*: B = billion, bbl = barrel, d = day, gal = gallons, geq = gasoline equivalent, H = Home, M = million, ROW = Rest of the world, t = metric tonne, W = World, y = year.

Model outputs	Units	2010	BAU 2015
Producer price			
Oil (W)	$/bbl	80.8	117.7
Gasoline (W)	$/gal	2.4	3.1
Diesel (W)	$/gal	2.5	3.8
Corn eth. (W)	$/gal	1.9	2.0
Cane eth. (W)	$/gal	1.7	2.0
Eth.–gas. blend (H)	$/gal	2.8	3.1
Eth.–gas. blend geq. (H)	$/gal–geq	2.9	3.1
Consumption			
Oil (W)	Mbbl/d	87.6	90.7
Corn eth. (W)	Bgal/yr	13.3	14.0
Cane eth. (W)	Bgal/yr	8.1	9.6
Corn eth. (H)	Bgal/yr	13.3	14.0
Cane eth. (H)	Bgal/yr	0.0	3.7
Total eth. (H)	Bgal/yr	13.3	17.7
GHG emissions			
World	Mt/yr	14,473	14,991
Home	Mt/yr	3035	3019
Other variables			
Eth. share in gas. (H)		10%	13%
Import outlay (H)	$B/y	734	922

Table 12
Sources of data for prices and quantities consumed in the base year.

Data	Source
Oil price	http://www.eia.gov/dnav/pet/pet_pri_fut_s1_a.htm
Oil consumption (US, Global)	http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=53&aid=1
Canadian oilsands	http://statshb.capp.ca/SHB/Sheet.asp?SectionID=3&SheetID=85
Price of gasoline–ethanol blend (US)	http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0524
Quantity of gasoline consumed (US)	http://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_a.htm
Price of diesel (US)	http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0524
Quantity of diesel consumed (US)	http://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_a.htm
Price of rest of oil products	Imputed using data on diesel and gasoline and refining fractions
Quantity of rest of oil products	Imputed using data on diesel and gasoline and refining fractions
Price of corn ethanol	http://www.neo.ne.gov/statshtml/66.html
Quantity of corn ethanol consumed (US)	http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=M_EPOOXE_YOP_NUS_1&f=A
Quantity of corn ethanol consumed (ROW)	http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=m_epooxe_eex_nus-z00_mbbl&f=a
Price of cane ethanol	http://www.ers.usda.gov/media/183470/feature5_fig05_1_.gif
Quantity of cane ethanol consumed (US)	http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=79&pid=79&aid=1
Quantity of cane ethanol consumed (ROW)	http://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_epooxe_im0_mbbl_a.htm

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