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D. Rajagopal_, G. Hochmany, and D. Zilbermanz

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D. Rajagopal*, G. Hochman†, and D. Zilberman‡

Abstract

We develop a two-region partial equilibrium model of the global market for liquid fuels to analyze different fuel policies based on multiple criteria, including greenhouse gas (GHG) emissions, expenditure of fuel imports, and the impact on fuel consumers and producers. We find that while ethanol policies may lower gasoline price in the home region, they increase the price of other oil products. A carbon tax increases prices of all fuels. For current sources of ethanol, reduction in GHG emissions due to the substitution of gasoline with ethanol in domestic markets may be dominated by the increase the global emissions because of price effects. Policy makers' preference for ethanol mandates reveals a desire to lower the cost of gasoline and to support the domestic biofuel sector while the selection of an emission-standard reveals a desire to reduce GHG emissions and minimize the impact on fuel consumers.

Keywords: climate change, transportation, energy security, renewable energy, biofuel, carbon tax, mandate, GHG standard

*Institute of Environment, University of California, Los Angeles, rdeepak@ioe.ucla.edu (corresponding author)

†Department of Agriculture, Food, and Resource Economics and Rutgers Energy Institute, The State University of New Jersey, Rutgers

‡Department of Agricultural and Resource Economics, University of California, Berkeley

1 Introduction

Governments world over have enacted policies in support of alternatives to crude oil. These policies aim to achieve multiple objectives, such as reduce energy imports, lower energy price, reduce greenhouse-gas (GHG) emissions, support infant domestic industries etc. (CBO, 2007; Sobrino and Monroy, 2009; CARB, 2009b). Currently, a predominant number of such policies are biofuel-based. The most popular policy is a biofuel mandate, which specifies either a target quantity of biofuel (as in the United States (US) with the Renewable Fuel Standard (RFS)) or a target market share for biofuel (as is the case in several countries in Europe) (Martinot and Sawin, 2009). An alternative type of regulation is an emission intensity standard, an example of which is California's Low Carbon Fuel Standard (LCFS) and which is under consideration in the European Union (EU) and China. Whereas a biofuel mandate may explicitly or implicitly specify the type and quantity of biofuel to be consumed, an emission-standard simply specifies an upper limit on the average GHG intensity of gasoline (and/or diesel) for a region. The two types of regulations can be considered equivalent when there is only one type of fossil fuel and one alternative fuel and both have a fixed GHG intensity. Otherwise, and when regulations do not cover the entire market, they may lead to a different trade-off between the various policy objectives. The political economic literature suggests that policies are selected based on multiple performance measures (see Rausser et al. (2011)). An evaluation of such policies should, therefore, compare their performance taking various criteria into consideration.

We analyze different policy instruments that are either being used or have been suggested. We model three main types of policies, namely, market share mandate (SM) for biofuel; fuel-emission intensity standard (ES), which is a policy with features akin to the LCFS; and fuel carbon tax (CT). We model generic policies and, hence, do not refer to the mandates and standards as RFS or LCFS, respectively. We also analyze two variants of mandates and emission-standards, namely, a market share mandate specific to corn ethanol (SMC), which is a policy with features akin to the US RFS; a variant of the emission-standard in which the so-called "indirect land use change" (ILUC) emissions are ignored; and a combination of SM and CT. We develop a two-region partial equilibrium model of the global market for liquid fuel and simulate the above policies under different assumptions about the model parameters, such as price elasticities, fuel emission intensities, etc.

This paper contributes to a growing literature that evaluates biofuel policies on different criteria. Using an open-economy, general-equilibrium model to compare various policies, Lapan and Moschini (2009) show that a combination of biofuel mandates and fuel GHG taxes would result in a higher fuel-market surplus than mandates along with subsidies. Cui et al. (2011) find that US mandates and subsidies do not contribute to GHG reduction but contribute to fuel security and improve farmers' welfare. de Gorter and Just (2009) argue that the decrease in corn market surplus and taxpayer cost of biofuel excise tax credits dwarf the welfare gain from reduction in farm subsidies. Focussing on the GHG emissions and the cost of congestion from driving, Khanna et al. (2008) find that biofuel subsidies lead to marginal reduction in GHG emissions, an increase in vehicle miles driven, and a net loss in social welfare. Other studies employing the cost effectiveness criterion to evaluate current biofuel policies conclude that biofuels are not cost effective as a GHG mitigation strategy relative to a carbon tax (Creyts, 2007; Holland et al., 2009). Jaeger and Egelkraut (2011) evaluate different policy interventions in terms of their cost effectiveness for achieving two objectives, namely, reducing GHG emissions and reducing fossil fuel use, and find biofuel policies costly. Holland (2009) finds that an ES-like policy may yield higher welfare than an emission tax either in the presence of incomplete regulation of GHG emissions or when there is market power. In one of the first studies to analyze US biofuel mandates in a global context and simulate their impact on both the fuel and food sector, Rajagopal et al. (2007) suggested that the total gain to consumers and food producers worldwide could exceed the total loss to oil producers and food consumers. Their study, however, does not quantify the effect on emissions. Bento et al. (2011) and Thompson et al. (2011) analyze US biofuel mandates in a global context and show that biofuel mandates are likely to raise emissions. Focusing on the energy security related impact of biofuels, Leiby (2008) estimates that the US RFS regulation confers a monopsony benefit of \$7.86 per barrel of renewable fuel and a benefit of \$6.56 per barrel due to reduced macroeconomic risk from oil-price shocks.

The rich literature on biofuel policies recognized and demonstrated the multidimensionality of the policy objectives as well as policy tools, but individual papers mostly compare either a mandate with a tax or a subsidy or compare an emission-standard to tax. The contribution of this paper is in analyzing mandates, emission-standards, and fuel carbon tax with respect to multiple criteria, such as emissions, expenditure on fuel imports, fuel market surplus, etc. We do so taking into account heterogeneity in GHG intensity of both fossil fuels and renewable fuels, limits on blending biofuels in the near to medium term (referred to as the "blend wall"). We analyze them in global context.Chen and Khanna (2012) simulate all three policies, namely, mandate, emissions standard, and fuel carbon tax and derive similar results to ours in terms of the relative performance of different policies with respect to one another. We differ in that, by modeling multiple types of crude oil and multiple sources of biofuels, we are able to identify the pollution-shuffling effect of different policies. Additionally, we simulate these policies for a broad distribution of uncertain inputs and show that, while the impact on different variables such as prices, emissions etc. may be positive or negative relative under a mandate or emission-standard, the relative performance of one policy with respect to another is consistent. For instance, we find that the emission-standard approach leads to lower global emissions, higher expenditure on fuel imports, and lower domestic fuel surplus for a similar share of biofuel in domestic consumption (see Table 10). Huang et al. (2012) find a combination of a biofuel mandate and emission-standard leads to lower emission relative to a mandate alone.

2 Model and simulation

2.1 Model

We develop a microeconomic framework that builds on Fischer (2010) and is capable of analyzing different types of fuel policies in a multi-region partial context. Our model has two regions – home and rest of the world (ROW). We assume open economy and competitive markets. Our model includes three different types of fuels, namely, crude oil, refined oil products, and biofuel. We consider two types of crude oil namely, conventional crude (CC) oil and synthetic crude oil from sources such as oil sands (OS), which are perfect substitutes, but differ in their GHG emissions. We consider three refined oil products, namely, gasoline, diesel and an aggregate, which is the rest of the oil products. We model biofuels from two sources: ethanol from corn and from cane, which are perfect substitutes. Gasoline and ethanol are also substitutes once adjusted for difference in energy density but only up to a limit. Tglobal warming intensityhis limit, referred to as the blend wall', represents an upper bound on the fraction of ethanol in gasoline permitted for gasoline cars. The GHG intensity of each of the different fuels is fixed. The GHG intensity of each type of ethanol is represented as the sum of two quantities: (1) the direct life cycle emission intensity, which represents emissions traceable to the processes involved in the production and use of biofuel, and (2) emission from ILUC.

We model three different types of policies: biofuel share mandate, emission intensity standard, and fuel carbon tax. The biofuel share mandate specifies the minimum share, by volume, of ethanol in domestic gasoline consumption. The emission intensity standard regulation specifies a maximum average fuel GHG intensity for the home region. Under this policy, each distinct combination of feedstock and fuel-production process is assigned a "nominal" GHG rating that is used to determine compliance with the regulation. The third type of policy is an exogenous carbon tax on fuel life cycle GHG emissions.

We describe the mathematical formulation of these policies next. We use the following notation. Let superscripts h, a, and w denote the home, ROW, and the world, respectively. Let subscripts, o, cc, os, g, d, x, ce, and se denote oil, CC, OS , gasoline, diesel, rest of oil products, corn ethanol, and sugarcane ethanol, respectively. Let gcc and gos denote gasoline from CC and gasoline from OS, respectively. Let $R = \{h, a\}$ denote the set of regions, $G = \{gcc, gos, ce, se\}$ the set of gasoline substitutes, $F = \{gcc, gos\}$ the set of gasoline from the two different types of oil, $B = \{ce, se\}$ the set of biofuels. Let p denote the fuel price, q denote the quantity of fuel, z denote the life cycle GHG intensity of fuel, and Z denote GHG emissions. η is a constant, which represents the ratio of energy density of ethanol to the energy density of gasoline and α_{max} represents the blend wall, i.e., the maximum feasible volume share of ethanol in the home region's consumption of ethanol-blended gasoline. Let D and D^{-1} denote the demand and inverse demand functions, respectively. Let S and S^{-1} denote fuel supply function and the inverse supply function, respectively. We assume that the functions are well behaved and that the inverse function exists. Transportation costs are assumed to be a negligibly small component of the price of fuel and, hence, zero. We assume that the blending of fossil fuel and renewable fuel is costless.

Renewable fuel volumetric mandate (α_{SM}): Under this policy, the total quantity of renewable fuel consumed within the home region is such that its share in total fuel consumption is not less than α_{SM}. The system of equations describing the equilibrium under an SM are:

Home ethanol mandate constraint

$$\alpha_{SM}^h \leq \alpha \leq \alpha_{max}^h, \text{ where } \alpha = \frac{\sum_{b \in B} q_b^h}{\sum_{f \in F} q_f^h + \sum_{b \in B} q_b^h} \tag{1a}$$

Equilibrium price constraint

$$p_{gb}^h \leq (1-\alpha)p_g + \alpha(p_b - s_b^h + \tau_b^h), \forall b \in B \tag{1b}$$

Biofuel price

$$\frac{p_b}{\eta} \geq p_g, \forall b \in B \tag{1c}$$

Biofuel supply

$$p_b \leq S_b\left(\sum_{r \in R} q_b^r\right), \forall b \in B \tag{1d}$$

Home gasoline demand

$$\sum_{f \in F} q_f^h + \eta \sum_{b \in B} q_b^h = D_g^h(p_{gb}^h + t_g^h) \tag{1e}$$

ROW gasoline demand

$$\sum_{f \in F} q_f^a + \eta \sum_{b \in B} q_b^a = D_g^a(p_g + t_g^a) \tag{1f}$$

Quantity of gasoline supplied as a fixed proportion of total quantity of crude oil

$$q_g^h + q_g^a = \beta_g q_o \tag{1g}$$

Quantity of diesel supplied as a fixed proportion of total quantity of crude oil

$$q_d = \beta_d q_o \tag{1h}$$

Quantity of other oil products supplied as a fixed proportion of total quantity of crude oil

$$q_x = \beta_x q_o \tag{1i}$$

Diesel demand

$$D^h_d(p_d + t^h_d) + D^a_d(p_d + t^a_d) = q_d \tag{1j}$$

Other oil products demand

$$D^h_x(p_x + t^h_x) + D^a_x(p_x + t^a_x) = q_x \tag{1k}$$

Zero oil refining profit condition

$$\beta_g p_g + \beta_d p_d + \beta_x p_x = p_o \tag{1l}$$

Oil supply

$$q_o = S^h_o(p_o) + S^a_o(p_o), \text{, where } S^r_o = S^r_{cc} + S^r_{os} \forall r \in R \tag{1m}$$

ROW ethanol constraint

$$\frac{\sum_{b\in B} q^a_b}{\sum_{f\in F} q^a_f + \eta \sum_{b\in B} q^a_b} = \alpha^a_0 \tag{1n}$$

Equation (1a) is the constraint on the volume share of ethanol in the home region under the policy. The upper limit on this share is the ethanol blend wall, α_{max}.

Equation (1b) represents the competitive-blending condition under the ethanol share mandate for each pair of renewable fuel and fossil fuel. The equality holds when $q^h_b > 0$ else the inequality applies. The left-hand side cannot be greater than the right-hand side for it would imply that there are positive profits in blending biofuel b with gasoline, which cannot be an equilibrium.

Equation (1c) says that if a given type of ethanol is consumed in abroad, then the price of biofuel equals the world price of gasoline. Since there is no biofuel policy in the ROW, biofuels compete with gasoline in a free market. Therefore, the price of biofuel (adjusted for energy equivalence) equals the price of gasoline in the ROW whenever a positive amount of a biofuel is consumed.

Equation (1d) is the supply equation for biofuel that says that the energy equivalent price of biofuel is equal to or greater than the price of gasoline. The left-hand side cannot be less than zero in equilibrium else it would suggest ethanol is cheaper compared to gasoline.

Equation (1e) represents the demand for gasoline in the home region, which is function of the consumer price of blended gasoline, p_{gb}.

Equation (1f) represents the demand for gasoline in the ROW.

Equation (1g) relates the global gasoline consumption, $q_g^h + q_g^a$, to the quantity of gasoline derived from refining of crude oil, which is a fixed proportion, β_g, of crude oil.

Equation (1h) relates the global diesel consumption, q_d, to the quantity of diesel derived from refining of crude oil, which is a fixed proportion, β_d, of crude oil.

Equation (1i) relates the global consumption of rest of oil products, q_x, to the quantity of these products derived from refining of crude oil, which is a fixed proportion β_x of crude oil.

Equation (1j) relates the global diesel consumption to demand function for diesel in the two regions.

Equation (1k) relates the global consumption of the rest of oil products to the demand function for these products in the two regions.

Equation (1l) is a condition similar to the competitive blending condition that says that in equilibrium there is zero profits in oil refining.

Equation (1m) relates the global oil consumption to the global oil supply, which is the sum of oil supply from region.

Equation (1n) is an additional constraint that we impose on ethanol consumption in ROW. Our initial simulations without this constraint predicted that ROW ethanol consumption would decline to zero in response to biofuel policies in the home region. The reality however is that there exist ethanol mandates in ROW – the most important example being the ethanol mandate in Brazil, which ranged between 20% and 25% during 2001 to 2010. We, therefore, introduced an additional constraint that the share of ethanol in the ROW region does not fall below its level in the baseline, α_0^a. Under the assumption that ROW ethanol consumption is essentially confined to Brazil and that Brazilian fuel consumption is a constant fraction of ROW fuel consumption, a constant share for biofuel in Brazilian fuel consumption translates into a constant share of ethanol in ROW biofuel consumption.

Emission intensity standard (z_{ES}): Under this regulation, the average GHG rating across all fuel consumed within the policy region cannot exceed the standard, z_{ES}. The system of equations describing the equilibrium under an ES are identical to that for the SM with the exception of the first two equations, which are shown below:

Emission standard constraint

$$z = \frac{\sum_{f \in F} z_f q_f^h + \eta \left(\sum_{b \in B} z_b q_b^h \right)}{\sum_{f \in F} q_f^h + \eta \left(\sum_{b \in B} q_b^h \right)} \leq z_{ES} \tag{2a}$$

Equilibrium price constraint

$$p_{gb}^h \leq ((1 - \alpha_b) p_f + \alpha_b (p_b - s_b^h + \tau_b^h)), \forall b \in B \tag{2b}$$

Equation (2a) represents the overall constraint on the emission intensity imposed by the ES for the home region. Similar to the SM, equation (2b) represents the competitive-blending condition under the ES for each pair of renewable fuel and fossil fuel. The difference is that the proportion in which the two fuels are blended is specific to each clean fuel and fossil fuel pair, i.e., $\alpha_b = \frac{z_g - \bar{z}}{z_g - z_b}$, $\forall b \in B$. If ILUC emissions of biofuel are included in the policy GHG rating of biofuels then, z_b represent the sum of both direct life cycle GHG and ILUC GHG else it represents direct life cycle GHG of any given biofuel.

Fuel carbon tax(t): The fuel carbon tax denotes a tax on fuel GHG emissions. The system of equations describing the equilibrium under a share mandate or an emission-standard with the exception of the first two equations which are shown below:

Relationship between home motor gasoline price and gasoline price

$$p^h \leq p_f + t z_f, \forall f \in F \tag{3a}$$

Relationship between home motor gasoline price and biofuel price

$$p^h \leq \frac{p_b + t z_b - s_b + \tau_b}{\eta}, \forall b \in B \tag{3b}$$

Equation (3a) expresses the relationship between the world gasoline price, p_f, and the domestic price of motor gasoline, p^h. $t z_f$ is the tax on gasoline in the home region. If $p^h > p_f + t z_f$, then gasoline suppliers in the home region can earn positive profits. The equality holds whenever a positive amount of gasoline is consumed in the home region. A similar interpretation holds for every other fuel, including the biofuels, taking into account subsidies and tariffs as applicable. If ILUC emissions of biofuel are included in the policy, the GHG rating of biofuels then z_b represent the sum of both direct life cycle GHG and ILUC GHG else it represents direct life cycle GHG of any given biofuel.

Let Z denote emissions, CS denote the consumer surplus, PS denote the producer surplus, G denote the change in government revenue, and W denote the fuel market surplus. Then,

$$
\begin{aligned}
Z^r &= \sum_{r\in R} \tilde{z}_k q_k^r && (4)\\
CS^r &= \int_0^{\sum_{k\in L} q_k^r} D^{r-1}(q)dq - p^r \sum_{k\in L} q_k^r \ , \forall r \in R && (5)\\
PS_k^r &= p_k S_k^r(p_k) - \int_0^{S_k^r(p_k)} S_k^{r-1}(q)dq \ , \forall k \in L \ , \forall r \in R && (6)\\
G^h &= t\sum_{k\in L} \tilde{z}_k q_k^h - \sum_{b\in B} s_b q_b^h + \sum_{i\in I} \tau_i(q_i^h - S_i^h(p_i)) && (7)\\
W^h &= CS^h + \sum_{k\in L} PS_k^h + G^h && (8)
\end{aligned}
$$

where, $\tilde{z}_k$, is the actual average emission intensity of fuel of type k. This value is however unknown to the policy maker, who chooses a value z_k, and $\tilde{z}_k = z_k + \epsilon$, where ϵ is an error term with $\sim [0, \sigma^2]$. Therefore, $z_k = E[\tilde{z}_k]$.

The surplus of oil sands producers is,

$$
\begin{aligned}
PS_{os} &= p_{oil} * q_{os} - \int_o^{q_{os}} p * dq \\
&= p_{oil} * q_{os} - \int_o^{q_{os}} \left(\beta(\bar{Q} - q)^\alpha + \gamma\right) * dq \\
&= p_{oil} * q_{os} - \left(\frac{\beta\bar{Q}^\alpha}{\alpha+1} - \frac{\beta(\bar{Q} - q_{os})^\alpha}{\alpha+1} + \gamma q_{os}\right) && (9)
\end{aligned}
$$

2.2 Some Analytical Findings

Proposition 1: Under regional policies, the world price of fossil fuel, domestic fossil fuel consumption, and global fossil fuel consumption all decline or remains unchanged while fuel consumption in ROW increases or remains unchanged. Whereas, under a carbon tax, domestic fuel price increases, and domestic fuel consumption, global total fuel consumption, and global emissions all decrease, the direction of impact on these variables is ambiguous under biofuel share mandate or emission-standard.

Proof: See the Appendix for the mathematical proof for the statements that follow and for derivation of the results shown in Table1. Also for the sake of brevity, we only derive the equations only for the tax and the mandate.

Table 1: Comparative static analysis for biofuel mandate

	Base case (no extra assumptions)	Perfectly elastic fossil fuel supply, $h = 0^*$	Perfectly inelastic fossil supply, $h = \infty^*$	Perfectly elastic biofuel supply, $g = 0^*$	Perfectly inelastic home fuel demand, $f = \infty^*$	Perfectly inelastic ROW fuel demand, $i = \infty^*$	Perfectly elastic ROW demand, $i = 0^*$
$\frac{dp^w}{d\bar{\alpha}}$	-	0	-	-	-	-	0
$\frac{dp^h}{d\bar{\alpha}}$	+/- **	+	+/-	+/-	+/-	+/-	+
$\frac{dp_b}{d\bar{\alpha}}$	+/-	+/-	+/-	0	+	+/-	+/-
$\frac{dq_f^h}{d\bar{\alpha}}$	-	-	-	-	-	-	-
$\frac{dq_f^a}{d\bar{\alpha}}$	+	0	+	+	+	0	+
$\frac{dq_r^h}{d\bar{\alpha}}$	+/-	+/-	+/-	+/-	+	+/-	+/-
$\frac{dq_t^h}{d\bar{\alpha}}$	+/-	-	+/-	+/-	0	+/-	-
$\frac{dq_f^w}{d\bar{\alpha}}$	-	-	0	-	-	-	0
$\frac{dq_t^w}{d\bar{\alpha}}$	+/-	-	+/-	+/-	+	+/-	+/-

* See the system of equations (22) for definitions of f, h, g, and i.
** +/- implies that the change may be either positive or negative.

Table 1, shows that $\frac{dp^w}{d\bar{\alpha}} \leq 0$, $\frac{dq_f^h}{d\bar{\alpha}} < 0$, and $\frac{dq_f^a}{d\bar{\alpha}} \geq 0$, and global fossil fuel consumption, $\frac{dq_f^w}{d\bar{\alpha}} = \frac{dq_f^h}{d\bar{\alpha}} + \frac{dq_f^a}{d\bar{\alpha}} \leq 0$. By reducing demand for domestic fossil fuel, domestic carbon policies and renewable fuel policies reduce the world price of fossil fuel except when the supply of fossil fuel is perfectly elastic, in which case the world price of fossil fuel is unchanged. The impact of the biofuel mandate on domestic fuel price, $\frac{dp^h}{d\bar{\alpha}}$; the price of renewable fuel, $\frac{dp^b}{d\bar{\alpha}}$; domestic renewable fuel consumption, $\frac{dq_r^h}{d\bar{\alpha}}$; total domestic fuel consumption, $\frac{dq_t^h}{d\bar{\alpha}} = \frac{dq_f^h}{d\bar{\alpha}} + \frac{dq_r^h}{d\bar{\alpha}}$; and total global fuel consumption, $\frac{dq_t^w}{d\bar{\alpha}} = \frac{dq_f^h}{d\bar{\alpha}} + \frac{dq_r^h}{d\bar{\alpha}} + \frac{dq_f^a}{d\bar{\alpha}}$ are all ambiguous.

Only when the fossil fuel supply is perfectly elastic, does total global fuel consumption unambiguously declines and thereby guarantee global emission reduction. Under all other conditions, the impact of global emission reduction is ambiguous.

Similarly, completely differentiating a system of similar equations for an emission-standard, we can show a similar directional impact on different variables as under a biofuel mandate.

Proposition 2: When fuel transport cost is negligible (or high), an emission-standard will result in the same (or higher) domestic fuel price, lower domestic emissions, and the same (or lower) global emissions relative to a biofuel mandate when both policies attain the same market share of renewable fuels. The world price of oil may be the same (or higher or lower) under the emission-standard relative to the biofuel mandate.

Proof: Since the emission-standard imposes additional constraints on the supply of fossil fuels to the home region, it cannot possibly result in a lower price in the home region than when such a constraint does not exist. The biofuel mandate, however, does not impose differential constraints on different fossil fuels; all fossil fuels are equally viable in the home region.[1] If the fuel transport cost is negligible, then an emission-standard policy simply leads to realignment of fossil fuel supplies such that the dirtier fuels are consumed by ROW. In that case both emission-standard and biofuel mandate result in the same domestic fuel price and the same world oil price when both policies attain the same market share of renewable fuels. The world price of fuel is also the same under both policies. While domestic emissions will be lower under the emission-standard, global emissions will be the same under emission-standard and biofuel mandate.

If fuel transportation cost is not negligible, then the emission-standard clearly shifts the excess supply curve faced by the home region to the left relative to that under the biofuel mandate. So long as the excess demand in the home region is not perfectly inelastic, this will lead to a higher domestic price under the emission-standard than under

[1]Note that, under a biofuel mandate, $\alpha_{cc} = \alpha_{sc} = \bar{\alpha}$. Therefore, the equations representing the blending condition for both types of fossil fuels are identical. In this case, all types of fossil fuels are priced the same in the home country regardless of their carbon intensity. The revised system of equations for emission-standard is shown in the Appendix.

the biofuel mandate. The impact on world price is, however, ambiguous since the impact depends on whether the emission-standard increases fossil fuel supply to the ROW. If the fossil fuels that become uneconomical in the home region entail a high transportation cost to ROW, then global oil supply shifts to the left. This increases the world price of oil. However, if these fuels are now available to ROW, then that shifts supply faced by ROW to the right, which decreases the world price of oil.

2.3 Numerical simulation

To illustrate the difference between policies, particularly with respect to variables for which the direction of impact is shown to be ambiguous above (Section 2.2), we perform numerical simulation. We first describe the specific functional forms assumed for the supply and demand functions and the procedure for their calibration and subsequently discuss the various simulations we perform.

We assume a linear function for the supply of conventional crude oil and ethanol. Given a price elasticity of supply, ϵ^s and the price and quantity of a fuel supplied at a given time, $t0$, a linear supply (or demand) function of the form $q = a + bp$, can be calibrated as follows:

$$b_f^r = \epsilon_f^r \frac{q_{f,t0}^r}{p_{t0}} \text{ , } \forall f \in \{cc, cb, sb\} \text{ , } \forall r \in R \tag{10}$$

$$a_f^r = q_{f,t0}^r - b_f^r p_{t0} \text{ , } \forall f \in \{cc, cb, sb\} \text{ , } \forall r \in R \tag{11}$$

For OS, which currently comprise a small but growing share of total oil supply, we assume a hockey-stick shaped supply function. We chose such a function so as to reflect the situation that OS extraction is characterized by an almost constant marginal cost up to a capacity that is growing at an exogenous rate each year but fixed in any given year. Hence, so long as the world price of oil exceeds the minimum price that renders OS extraction profitable, OS supply occurs close to capacity that year. Mathematically, the hockey-stick shape supply curve can be represented as,

$$p = \beta(\bar{Q} - q)^\alpha + \gamma \tag{12}$$

Given the capacity for OS supply at $t0$, $\bar{Q}_{os,t0}$, the minimum price of oil above which OS are produced, $\underline{p}_{os}$, and the elasticity of supply of OS (since the oil sand industry is assumed to be operating close to capacity, this is a small number, less than 0.05), ϵ_{os}^{t0}, we calibrate, α, β and γ as follows

$$\alpha_{os} = -\frac{\bar{Q}_{os,t0}/q_{os,t0} - 1}{\epsilon_{os}^{t0}} \tag{13}$$

$$\beta_{os} = \frac{(p^w - \underline{p}_{os}}{(\bar{Q}_{os,t0} - q_{os,t0})^{\alpha_{os}} - \bar{Q}_{os,t0}^{\alpha_{os}}} \tag{14}$$

$$\gamma_{os} = \underline{p}_{os} - \beta_{os}\bar{Q}_{os,t0} \tag{15}$$

As capacity expands, for any given year in the future we re-compute the parameter γ_{os}, such that the function is still characterized by the same minimum marginal cost of $\underline{p}_{os}$. Therefore, we recalculate $\gamma_{os} = \underline{p}_{os} - \beta_{os}\bar{Q}_{os,t}$, where $\bar{Q}_{os,t} = \bar{Q}_{os,t0}(1 + \delta_{os})^{t-t0}$. The cost and capacity constraints were chosen based on projections reported in (Timilsina et al., 2005).

The supply of the three petroleum products, namely, gasoline, diesel, and the rest of oil products aggregate, is each assumed to be a fixed proportion of the supply of oil. Based on the quantity of gasoline and diesel consumed and the quantity of crude oil consumed globally in the base year, the computed values for the volume fractions of gasoline and diesel derived per unit of oil are 0.25 and 0.28, respectively. The of rest of oil products comprise the remaining 47%.

We assume that the demand function for each of the different products, namely, ethanol-blended gasoline, diesel, and the rest of oil products aggregate, is linear, and is calibrated in manner similar to the linear supply function of crude oil and the biofuels.

For the numerical analysis, we assume that conventional crude oil is produced both at home and abroad while OS is supplied by only 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 2. To illustrate the sensitivity of our results to the assumed values, we perform a Monte Carlo simulation-type analysis where we simulate each policy scenario 5,000 times for different randomly chosen combinations of the various model inputs. The same set of 5,000 different input combinations is used to compare different policies. The distributions of these inputs

Table 2: Input parameter ranges used for Monte Carlo simulation. "Home" refers the region implementing the fuel policy; We use data for the US for home region parameters, but we do not mean to imply this is a model of the US.

Model parameter	**Distribution**	**Range**
Elasticity of supply of crude oil, Home	Normal	(0.12, 0.27)[a]
Elasticity of supply of crude oil, ROW	Normal	(0.08, 0.23)[a]
Elasticity of supply of corn biofuel, Global	Normal	(1, 3)[b]
Elasticity of supply of cane ethanol, Global	Normal	(1, 5)[b]
Elasticity of demand for gasoline, Home	Normal	(-0.6, -0.4)[c]
Elasticity of demand for gasoline, ROW	Normal	(-0.85, -0.5)[c]
Elasticity of demand for diesel, Home	Normal	(-0.6, -0.4)[d]
Elasticity of demand for diesel, ROW	Normal	(-0.85, -0.5)[d]
Elasticity of demand for rest of petroleum products, Home	Normal	(-0.6, -0.4)[d]
Elasticity of demand for rest of petroleum products, ROW	Normal	(-0.85, -0.5)[d]
Gasoline GWI, conv. crude (gCO_2e/MJ)	Lognormal	(86, 97)[e]
Diesel GWI, conv. crude (gCO_2e/MJ)	Lognormal	(90, 101)[e]
"Other" GWI, conv. crude (gCO_2e/MJ)	Lognormal	(73, 88)[e]
Corn ethanol GWI (gCO_2e/MJ)	Uniform	(55, 70)[f]
Corn ethanol ILUC (gCO_2e/MJ)	Uniform	(5, 100)[g]
Cane ethanol GWI (gCO_2e/MJ)	Uniform	(10, 30)[h]
Cane ethanol ILUC (gCO_2e/MJ)	Uniform	(5, 50)[i]
Oil sand multiplier (rel. to conv. crude)	Normal	(1.1, 1.2)[j]
Minimum price for oil sand supply ($\$ \ bbl^{-1}$)	Normal	(45, 55)[k]
Annual growth rate of fuel demand, home	Normal	(0.1%, 0.2%)[l]
Annual growth rate of fuel demand, ROW	Normal	(0.5%, 0.7%)[m]

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

[b] 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.

[c] Average of short- and long-run values from Brons et al. (2008). Range represents the 95% CI.

[d] We assume the same distributions as for gasoline.

[e] Venkatesh et al. (2011). Range represents the 90% CI. The authors do not identify distribution shapes, but as all are slightly right-tailed, we assume lognormal distribution.

[f] Plevin (2009, 2010).

[g] Plevin et al. (2010).

[h] Taken from the range in CARB (2012), accounting for potentially higher N_2O emissions (Lisboa et al., 2011).

[i] Approximation of the range from estimates by USEPA (4 gCO_2e/MJ) and CARB (46 $CO_2e \ MJ^{-1}$) (USEPA, 2010; CARB, 2012).

[j] Brandt (2011).

[k] Timilsina et al. (2005); National Energy Board, Canada (2011).

[l] Energy Information Administration Annual Energy Outlook 2012 (see page 2)

[m] International Energy Agency World Energy Outlook Factsheet 2010 forecasts imply an average growth of 0.6% per annum in global oil use

are also specified in Table 2. The range column in the table denotes the 95% confidence interval for the 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.

We assume that some of the input parameters are correlated. For instance, we assume that the emission intensity of all three oil products are correlated since they are all derived from oil and jointly produced. We also assume that ILUC emissions for corn and sugarcane ethanol are correlated since they compete for land, and estimates of ILUC for the two fuels are estimated either simultaneously or using the same or similar modeling assumptions. We also assume that projections of demand growth for US and ROW are also correlated for a similar reason. The values that we chose for these correlations are subjective and as follows. The correlation coefficient for the emission intensities for each pair of oil product is 0.8, that for ILUC emission intensity of the two types of ethanol is 0.6, and that between the growth rates of demand of US and ROW is 0.25. Sensitivity analyses to alternative correlations, including zero correlation, suggest that our conclusions about the policies are robust. We calibrate the model to the year 2007. The data for the base year are shown in Table 3.

2.4 Policy scenarios

Table 4 lists the policy scenarios for the home region we simulate. We first simulate the outcome in a future year, which we choose as 2017. 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. The ethanol blend level in the U.S. in 2007 was approximately 5% and this we maintain as a lower-bound on ethanol share in the home region. We then simulate three different policies, namely, SM, ES, and CT. The stringency level of the ethanol mandate is chosen as 15% since this represents the ethanol blend limit for gasoline cars. For the emission-standard, we chose a 5% reduction in GHG intensity of gasoline as the target, since this level of stringency results in a similar ethanol blend level as the ethanol mandates, which

Table 3: Base year (2007) data used in model calibration. We use data for the US for home region. mbpd = million barrels per day.

Fuel	**Variable**	**Units**	**World**	**US**	**ROW**
Oil	Production	mbpd	84.9	6.9	78
	Price	\$/barrel	68	68	68
Conventional Crude	Production	mbpd	83.5	6.9	76.6
Oilsands	Production	mbpd	1.4	0	1.4
Corn ethanol	Production	mbpd	0.4	0.4	0.0
	Consumption	mbpd	0.4	0.4	0.0
	Producer price	\$/gal	1.800		
Cane ethanol	Production	mbpd	0.3	0.0	0.3
	Consumption	mbpd	0.3	0.0	0.3
	Producer price	\$/gal	1.576		
Gasoline	Consumption	mbpd	21	9	13
	Producer price	\$/gal	2.388		
	Consumer price	\$/gal		2.888	3.688
Gasoline+ethanol blend	Consumption	mbpd	22	9	13
	Producer price	\$/gal	2.340		
	Consumer price	\$/gal		2.840	3.688
Diesel	Consumption	mbpd	24	4	20
	Producer price	\$/gal	2.388		
	Consumer price	\$/gal		2.888	3.688
Rest of oil products	Consumption	mbpd	40	12	28
	Producer price	\$/gal	0.757		
	Consumer price	\$/gal		1.257	1.857

Table 4: Simulated policy scenarios

Policy	**Level**	**Notation**
Future business-as-usual baseline: Year-2017		BAU17
Ethanol share mandate	15%	SM15
GHG emission intensity standard	5%	ES5
Carbon tax (\$ per tonne CO_2e)	20	CT20
Policy Variations		
Corn ethanol share mandate	15%	SMC15
Emission standard-without ILUC	5	ES5-NoILUC

facilitates its comparison to a biofuel mandate. For the tax, we chose \$20 per tonne CO_2 tax since this lies within a frequently cited range of price on carbon and also the price observed under the EU Emission Trading Scheme.[2]

We also analyze one variant each of the mandate and the standard. One is a corn ethanol share mandate, denoted as SMC15 – the motivation for which is to analyze the implications of biofuel policy that supports only domestic biofuels (which is corn ethanol in our case). We also simulate an emission-standard in which ILUC emission intensity excluded from regulatory accounting (denoted as ES5-NoILUC) given the controversy and other challenges surrounding regulating ILUC.

Table 5: Assumed emission intensity rating of various products for determining compliance with policy.

Fuel	**Rating (gCO_2e/MJ)**
Gasoline from conventional crude	89[a]
Ratio of GHG intensity of oilsand products relative products of conventional crude	1.1[a]
Corn ethanol (supply chain only)	62.5[b]
Corn ethanol ILUC	25[c]
Cane ethanol (supply chain only)	25[c]
Cane ethanol ILUC	25[d]

[a] Venkatesh et al. (2011)
[b] Plevin (2009)
[c] Approximately the values estimated by CARB (2009a).
[d] The average of CARB's 46 gCO_2e/MJ and USEPA's 4 gCO_2e/MJ CARB (2009a); USEPA (2010).

Table **??** shows the GHG rating 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. Actual emissions under any scenario are, however, always calculated using the randomly chosen "actual" emission intensity parameter for any given model run and not the "rated" GHG emission intensity. The rated GHG emission intensity values lie within the assumed range for the actual emission intensity shown in Table 2.

[2] http://www.eea.europa.eu/data-and-maps/figures/eu-ets-future-contract-prices-200520132009

3 Simulation results

We begin with a discussion of the results for a single trial in which each input parameter assumes the mean value of it's distribution. We refer to this trial as the "mean case" for each policy, and this case illustrates the main differences between policies. The impacts of the policies on GHG emission will be broken down into two components to highlight the relative importance of fuel substitution effect and fuel price effect on emissions (see Section 3.1.1). We then discuss the effect of different policies in shuffling pollution between regulated and unregulated regions. Finally, we discuss how the outcome in the mean case compares with the range of predicted outcomes across 5,000 simulations involving different combinations of randomly chosen values of model parameters. Indeed, all policies are simulated for the same set of combinations of values of the model parameters. As we show later in Section 3.2, the qualitative conclusions about the impact of one policy relative to another on any given variable as suggested by the mean case are robust.

3.1 Mean case

Table 6 shows the results for the base year (2007), the BAU scenario, and three policies for the mean case. Note that, for the base year, the prices and quantities of different fuels are fixed across all 5,000 runs and not dependent on the various assumed parameters. Emissions, however, depend on the chosen value of fuel emission intensities in a given model run. The model predicts that, due to growing demand, world oil price increases from \$68/barrel (bbl) in 2007 to \$104/bbl in 2017 under BAU while global oil consumption increases from 85 to 92 million barrels per day (Mbbl/d). Global consumption of corn ethanol increases from 6.5 to 9.8 billion gallons per year (Bgal/y) and consumption of cane ethanol increases from 5 to 11.5 Bgal/y. The share of ethanol in the home region increases from 5% to 10%. Global CO_2 emissions from oil and ethanol consumption increases 9% from 12.7 to 13.8 billion tonnes/y while home emissions increase 3%. Home region's expenditure on fuel imports increases 44% from 321 to 461 B\$/y. For the sake of brevity, we discuss the impact of different policies on select key 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. The effect

Table 6: 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, H = Home, M = million, ROW = Rest of the world, t = metric tonne, W = World, y = year.

	Units	2007	BAU 2017	CT20[a]	SM15[a]	ES5[a]
Producer Price[b]						
Oil (W)	\$/bbl	68.0	104.0	-1.07	-0.37	-0.65
Gasoline (W)	\$/gal	2.4	3.4	-0.08	-0.04	-0.08
Diesel (W)	\$/gal	2.4	3.8	-0.02	0.00	0.01
Corn eth. (W)	\$/gal	1.8	2.3	-0.01	0.48	-0.57
Cane eth. (W)	\$/gal	1.6	2.3	0.05	0.48	1.21
Gasoline-eth. blend (H)	\$/gal	2.3	3.4	0.14	-0.14	-0.07
Consumption						
Oil (W)	Mbbl/d	84.9	92.0	-0.21	-0.07	-0.13
Corn eth. (W)	Bgal/y	6.5	9.8	-0.08	3.49	-4.10
Cane eth. (W)	Bgal/y	5.0	11.5	0.47	4.60	11.54
Corn eth. (H)	Bgal/y	6.5	9.8	-0.08	3.49	-9.82
Cane eth. (H)	Bgal/y	0.0	5.9	0.40	4.55	17.18
GHG Emissions						
World	Mt/y	12717	13822	-32	39	-13
Home	Mt/y	2610	2683	-109	29	-94
% Ethanol share in gas. (H)[c]		5%	10%	11%	15%	15%
%Δ in gas. GHG intensity (H)[d]		–	-4%	-3%	-4%	-5%
Expenditure on fuel imports (H)	\$B/y	321	461	-29	5	48
Surplus			Units	CT20[a]	SM15[a]	ES5[a]
a) Fuel consumer (H)			\$B/y	-36.1	20.3	9.0
b) Oil producer (H)			\$B/y	-2.8	-1.0	-1.8
c) Eth. producer (H)			\$B/y	-0.4	5.6	-4.4
d) Fuel market (H) = a + b +c			\$B/y	-39.4	24.9	2.8
Govt. Revenue (H)			\$B/y	51.8	3.2	2.4
e) Fuel consumer (ROW)			B\$/y	23.4	6.8	12.3
f) Oil producer (ROW)			B\$/y	-31.4	-11.2	-20.1
g) Eth. producer (ROW)			B\$/y	0.2	6.7	20.9
h) Fuel market (ROW) = e+ f +g			B\$/y	-7.9	2.3	13.1

[a] Change with respect to BAU

[b] Producer price is consumer price minus sales tax in each region

[c] Ethanol blend level is reported as absolute values. SM15 results in an ethanol share of 15% in the home region, which is the policy target.

[d] The percentage reduction in gasoline average emission intensity relative to base year. We can see that ES5 results in 5% emission reduction, which is the policy target.

on the price of oil products is, however, both product specific and policy dependent. A carbon tax decreases the world price of all oil products but increases the cost of consuming oil products in the home region. The reduction in oil supplied notwithstanding, world gasoline price declines under SM and ES as ethanol supply increases. However, the world price of nongasoline oil products increases under SM and ES due to the reduction in oil supplied.

Impact on ethanol consumption: Total global ethanol consumption decreases under the carbon tax and increases under SM and ES. Different policies lead to different effects on the two types of ethanol. Whereas global cane ethanol consumption is higher under all three policies, global corn ethanol consumption is higher with SM, it is lower both with the ES and CT, which suggests corn ethanol is less cost effective compared to cane ethanol in reducing GHG emissions. The ethanol price impact exhibits a pattern opposite to that exhibited by the quantity consumed of each. Home consumption of each type of ethanol exhibits a pattern similar to the pattern for global consumption of that type of ethanol under any policy relative to BAU.

Impact on emissions: Global GHG emissions are lower relative to the BAU in the case of CT and ES but are higher under SM, suggesting, biofuels may prove counterproductive to GHG reduction goals. The CT reduces emissions principally by reducing oil consumption rather than increasing biofuel consumption unlike with SM or ES. Home emissions exhibit a similar pattern as global GHG emissions for all three policies. One reason for the much larger decline in home emissions under CT or ES relative to the decline in world emissions is that these policies lead to shuffling of the more GHG-intensive source of oil, namely oil sands from the home region in BAU to ROW under both of these policies.

Impact on fuel imports: Expenditure on fuel imports by the home region declines under the tax but increases under SM or ES due to greater demand for cane ethanol, which is produced outside the home region. For a similar level of total biofuel consumption at home, ES leads to higher expenditure on fuel imports relative to SM.

Impact on home fuel market surplus: Fuel consumers always lose under a carbon tax but, under SM and ES, gasoline consumers gain while consumers of other oil products lose. Relative to BAU, net fuel consumers' surplus is higher under SM or ES and lower in the case of CT. Oil producers lose under all policies due to the fall in global oil price. The direction of impact on home ethanol producers (corn ethanol producers), depends on the impact on global corn ethanol consumption. 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 oil producers worldwide. The ROW ethanol producers gain under biofuel policies and gain more under an emission-standard since this policy increases the demand for cane ethanol produced outside the home region. The ROW fuel market surplus declines under the carbon tax 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.

The impact of the policies fuel market surplus cannot be considered in isolation from their impact on food and agricultural commodity markets, which are beyond the scope of this paper.

Summarizing the mean case, among the three policies, we find that the carbon tax leads to the largest reduction in both global emissions and the home region's expenditure on fuel imports and also results in the largest reduction in fuel market surplus. The biofuel mandate, SM15, increases emissions but it also leads to the largest increase in fuel consumers' and ethanol producers' surplus and a small increase in expenditure on fuel imports. The emission-standard, ES5, which leads to an almost identical share of biofuels at home as SM15, reduces emissions but by less than the carbon tax, CT20. It also leads to the largest increase in expenditure on imports and a much smaller increase in fuel market surplus relative to SM15.

3.1.1 Disaggregating change in emissions into a substitution and a price effect

Table 7 shows a decomposition of the change in emissions under the different policies relative to the BAU in the mean case trial. It disaggregates the change in emissions into two effects, namely, a substitution effect and a price effect (Rajagopal et al., 2011; Chen and Khanna, 2012). The substitution effect refers to the change in emissions (ΔZ_{subs}) arising from a one-to-one replacement of gasoline with ethanol. The price effect accounts for the rest of change in emissions, and it is the change in emissions attributable to the change in quantity of various petroleum products consumed. This is an effect akin to ILUC but one that occurs in the fuel market. Following Rajagopal et al. (2011), we refer to the price effect as the Indirect Fuel Use Effect (IFUE). The price effect or IFUE would not exist if biofuels did not affect fuel prices. We calculate these two effects as follows:

$$\Delta Z_{subs} = \sum_{b \in B} \Delta q_b (z_b - z_g) \tag{16}$$

$$\Delta Z_{ifue} = \Delta Z_{total} - \Delta Z_{subs} \tag{17}$$

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

Table 7: 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 "mean case". Numbers in parentheses denote share of the two effects in total change in emissions.

	CT	SM15	ES5
Global change (Mt/y)	-32 (100%)	39 (100%)	-13 (100%)
Substitution effect (Mt/y)	-1 (3%)	-8 (-21%)	-47 (363%)
Price effect or IFUE (Mt/y)	-31 (97%)	47 (121%)	34 (-263%)

We can see that, since 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 SM15 and ES5, the substitution effect contributes to emission reduction. However, for these policies the price effect counteracts the substitution effect, which is due to the fact that world price declines causing oil consumption to bounce back. It overwhelms the substitution effect in the case of the biofuel mandate. For the emission-standard ES5, the price effect substantially mitigates the GHG benefits adopting biofuels. Similar effects of fuel price changes on emissions have been calculated by Bento et al. (2011), de Gorter and Drabik (2011), Thompson et al. (2011), and Chen and Khanna (2012).

Table 8: Decomposition of the change in emissions relative to BAU under the different policies for the "mean case". Disaggregation is by the change in emissions due each change in consumption of oil products from different types of crude and the two types of ethanol. Total for each column is 100%

	CT20		SM15		ES5	
	World	Home	World	Home	World	Home
Oil products (conv. crude)	92%	-131%	-27%	-70%	147%	-193%
Oil products (oilsand)	0%	228%	0%	0%	1%	266%
Corn ethanol	10%	3%	83%	111%	292%	96%
Cane ethanol	-2%	0%	45%	60%	-339%	-69%

3.1.2 Decomposing change in emissions: By fuel source

Table 8 shows an alternative decomposition of the change in emissions. It disaggregates the change in emissions for each region into that attributable to the change in consumption of oil products from the two types of crude oil, CC and OS, and the two types of ethanol, corn and cane, within each region. For brevity, we only discuss the decomposition at the worldlevel and for the home region, leaving out ROW.

The reduction in emissions under the carbon tax (refer Table 6) is driven essentially by the reduction in global crude oil consumption, which accounts for 92% of the total change. Reduction in corn ethanol consumption accounts for 10% of the reduction. The negative value of -2% for cane ethanol means that increase in global cane ethanol consumption served to increase emissions. We discuss oil sands separately below.

For the ethanol mandate, unlike with the carbon tax, emissions increase both globally and in the home region (refer to Table 6). Therefore, for this policy, positive entries represent an increase in emissions. Global increase in corn and cane ethanol account for 83% and 45%, respectively, of the increase in emissions under the mandate SM15. Like the carbon tax, the emission-standard, ES5, also leads to a reduction in global emissions relative to the BAU, in the mean case. Although this policy leads to significant reduction in global conventional crude oil use, similar to the ethanol mandate, it also leads to significant changes in global consumption of corn ethanol (decreases) and cane ethanol (increases), which explains the large contribution of these fuels to the change in global emissions.

In all of our calculations, global consumption of oil sands changes only by relatively small amounts. This is attributable to our representation of oil sands supply, which is characterized by almost constant marginal cost and a rigid capacity constraint in any given year. With the world price oil exceeding the marginal cost of oil sands extraction (assumed to lie between \$45–55/bbl), oil sands production is always near capacity and hence global oil sands consumption changes negligibly in our simulations. Therefore, emissions attributable to oil sands change negligibly. However, regional oil sands consumption is policy dependent. Both carbon tax and emission-standard render oil sands uneconomical in the home region on account of their higher GHG intensity relative to conventional crude oil. This explains the greater than 100% contribution of oil sands to the reduction in emissions in the home region under these two policies (see Table 8). Different policies lead to different levels of pollution shuffling and leakage (Bushnell et al., 2008). Emission-based policies, such as carbon tax and emission-standard, lead to more shuffling than a biofuel mandate.

3.2 Monte Carlo simulation

Table 9: Summary statistics of difference in outcomes in each trial with respect to BAU. Table shows the mean value of the difference followed by the 2.5% and 97.5% quantile values of the difference in outcomes in parentheses.

Variable	CT20 – BAU	SM15 – BAU	ES5 – BAU
Price of eth-gas. Blend \$/gal (H)	0.14 (0.13,0.15)	-0.13 (-0.16,-0.09)	-0.04 (-0.11,0.1)
Ethanol qty. Bgal/y (W)	-0.2 (-0.4,0.02)	7.7 (-3,13.6)	7 (-3.7,12.83)
Corn ethanol qty. Bgal/y (W)	-0.3 (-0.5,-0.17)	3.6 (-1.1,8.47)	-4.2 (-9,-1.69)
Cane ethanol qty. Bgal/y (W)	0.1 (0,0.24)	4.1 (-2.2,8)	11.2 (3.4,15.22)
Global emissions (Mt/y)	-32 (-43,-20)	36 (3,77)	-19 (-64,12)
Expenditure on imports	-29 (-35,-24)	4 (-16,28)	53 (33,89)
Fuel market surplus (B\$/y)	-39 (-40,-38)	25 (20,30)	-1 (-28,10)

We now discuss the results of the Monte Carlo simulation (5,000 runs with different randomly chosen combinations of values for model inputs), to show that differences we observe between the different policies in the mean case appear to hold over a broad range of inputs. Table 9 shows the mean and the 2.5% and 97.5% quantile values of the difference in outcomes (shown in parentheses) for select variables. For the carbon tax, both the direction and order of magnitude of impact range of results over the 5,000 trials are similar in sign and magnitude to those in the mean case. However, for both the mandate and emission-standard, for some variables, the change relative to BAU may either be positive or negative. For instance, global total consumption of ethanol may be higher or lower under SM or ES. With regard to home price of gasoline-ethanol blend, we see that SM15 always results in lower price in the home region in our simulations, while it may be higher or lower relative to the BAU with the ES5. This, however, does not imply that mandates always lower the home price of blended gasoline. Simulations involving a more stringent, 20% ethanol mandate predict that home price of blend may be higher or lower (see Table 12 in the Appendix which shows the change with respect to BAU for SM20 and ES7.5).

Table 10 shows the summary statistics of the difference in each trial for select variables across the 5,000 different trials for the three policy pairs: SM15 and CT20, ES5 and CT20, and ES5 and SM15. We first focus on the difference between SM15 and ES5 since these two policies achieve a similar level of biofuel consumption at home. Compared to the biofuel mandate, SM15, the emission-standard, ES5, always leads to: lower total ethanol consumption, lower corn ethanol consumption, and higher cane ethanol consumption, both globally and at home; higher gasoline price in the home region; lower global emissions; higher expenditure on fuel imports; and lower fuel market surplus. Furthermore, while the mandate SM15 may result in higher or lower biofuel consumption relative to the tax; emissions, expenditure on fuel imports and fuel market surplus are all always higher while gasoline price in the home region is always lower. A similar comparison exists between the emission-standard and the carbon tax with the exception that emissions may be higher or lower under the ES5 relative to CT20.

Table 10: Summary statistics of difference in outcomes in each trial for different pairs of policies. Table shows the mean value of difference followed by the 2.5% and 97.5% quantile values of the difference in outcomes in parentheses.

Variable	SM15–CT20	ES5–CT20	ES5–SM15
Oil Price $/bbl (W)	0.7, (-0.3, 2.5)	0.3, (-1, 1.9)	-0.4, (-1, -0.1)
Price of eth-gas. Blend $/gal (H)	-0.3, (-0.3, -0.2)	-0.2, (-0.2, 0)	0.1, (0, 0.2)
Ethanol qty. Bgal/y (W)	7.9, (-2.8, 13.8)	7.2, (-3.5, 13)	-0.7, (-1.2, -0.5)
Corn ethanol qty. Bgal/y (W)	3.9, (-0.7, 8.8)	-3.9, (-8.5, -1.5)	-7.8, (-12.5, -4.2)
Cane ethanol qty. Bgal/y (W)	4, (-2.3, 7.9)	11.1, (3.3, 15.2)	7.1, (3.6, 11.4)
Global emissions Mt/y	69, (28, 113)	13, (-34, 47)	-55, (-114, -21)
Expenditure on imports B$/y (H)	91, (28, 167)	224, (161, 326)	133, (65, 268)
Fuel market surplus B$/y (H)	176, (164, 189)	104, (32, 136)	-72, (-151, -38)

3.3 Sensitivity to policy variations

Table 11 presents a comparison of the difference between two variants of the biofuel mandate and of the emission-standard over the 5000 runs. Comparing the ethanol share mandate to a corn ethanol share mandate, both at the 15% level, the home price of gasoline and global corn ethanol use are both always higher; expenditure on fuel imports is always lower; global ethanol consumption and global emission are both likely higher while global ethanol use is likely lower; all under the corn ethanol mandate. The increase in home gasoline price notwithstanding, home fuel market surplus increases under SMC due to the increase in home biofuel producer surplus, which can be inferred from the higher level of corn ethanol consumption under SMC15. Therefore, while a mandate specific to a fuel produced at home may help improve energy security and also support the domestic biofuel producers, it has a poor performance with regard to emission reduction.

Comparing the two variants of the emission-standard, both at the 5% level, exclusion of ILUC emission intensity from the policy rating of biofuels leads to lower home price of gasoline, higher consumption of corn ethanol and lower consumption of cane ethanol, higher emissions, lower expenditure on fuel imports and higher domestic fuel market surplus. This suggests that exclusion of ILUC emissions from the emission-standard has a similar directional impact as making the ethanol mandate to specific to corn ethanol.

Table 11: Summary statistics of difference in select variables in each trial for two variants of biofuel mandate and emission standard. Table shows the mean value of difference followed by the 2.5% and 97.5% quantile values of the difference in outcomes in parentheses.

Variable	SMC15 – SM15	ES-NoILUC5 – ES5
Oil Price $/bbl (W)	-0.8, (-1.6, -0.3)	0, (-0.4, 0.4)
Price of eth-gas. Blend $/gal (H)	0.1, (0, 0.3)	-0.1, (-0.2, 0)
Ethanol qty. Bgal/y (W)	0.7, (-1.1, 7.9)	3.3, (0, 7.8)
Corn ethanol qty. Bgal/y (W)	9.6, (5.4, 12.7)	10.6, (5.4, 17.7)
Cane ethanol qty. Bgal/y (W)	-8.9, (-13.7, 1)	-7.3, (-9.9, -5.3)
Global emissions Mt/y	31, (-7, 70)	70, (23, 149)
Expenditure on imports B$/y (H)	-130, (-218, -57)	-163, (-285, -96)
Fuel market surplus B$/y (H)	8, (-5, 32)	80, (35, 169)

4 Conculsion

Tinbergen's rule (Tinbergen, 1952) suggests that achieving the desired values of a certain number of targets requires the policy maker to control an equal number of instruments. A single instrument, such as a carbon tax, emission intensity standard, or renewable energy mandate cannot, therefore, achieve multiple independent goals, such as addressing externalities related to environment, concerns related to excess reliance on imports, distributional objectives, etc. Real-world policies are the outcome of a political process that reflects the power and influence of different interest groups rather than simple welfare maximization or cost minimization. Economic analysis can suggest ways of achieving better outcomes given various constraints and decipher which policy objectives are better served by various policies. This paper describes a simple framework to analyze existing and proposed fuel policies from these perspectives.

Partial (national or regional) policies are unable to capture the full benefit of reducing fossil fuel use or substituting fossil fuels with renewable fuels because of the global price effect or IFUE. Among the policies considered, a carbon tax has the clearest implications: It decreases global GHG emissions and fuel imports for the home region, and it increases the cost of all oil products and biofuel-blended gasoline. Global ethanol consumption can either increase or decrease. Both fuel consumers' and oil producers' surplus decline under a carbon tax. The impact on all these variables is ambiguous under both biofuel mandate and emission-standard. However, over a broad range of estimates for fuel supply and demand elasticities and GHG intensity of various fuels, and given constraints on blending biofuel with oil products, such as the 15% ethanol blend wall for gasoline vehicles, we find that ethanol mandates increase global emissions and decrease the price of gasoline and ethanol-blended gasoline and increase the price of nongasoline oil products, and they are expected to increase global ethanol consumption. Relative to a ethanol mandate, an emission-standard always results in lower global emissions while requiring less biofuel but results in higher fuel price in the home region. The difference between ethanol mandate and emission-standard with regard to reduction in fuel-import expenditure depends on the cost effectiveness of home region sources of low GHG fuels relative to those from abroad. Since, in our simulations, the home region produces corn ethanol, a less cost effective ethanol relative to cane ethanol in our simulations, we find that a biofuel mandate results in lower expenditure on imports relative to an emission-standard. An emission-standard would also lead to greater shuffling of pollution between markets relative to a biofuel mandate. 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 and increases it absolutely relative to the no-policy scenario, while a carbon tax reduces the same.

Therefore, the adoption of the US Renewable Fuel Standard suggests a greater weight on the objectives of lowering the cost of gasoline and supporting the domestic biofuel industry. Since emissions are expected to increase under biofuel mandates, it suggests a low or even negative weight on emission reduction. A preference for carbon tax would require that reducing emissions and expenditure on imports be the principal goals. The selection of an emission-standard is explained by a commitment to reducing emissions while also minimizing the impact on fuel consumers. A combination of two or all three types of policies might help achieve an intermediate outcome with respect to each of the multiple criteria and neither the best nor the worst outcomes with respect any single criterion that may result under any one policy alone.

A major controversy related to biofuel policies is the treatment of so-called ILUC emissions. While some argue that ILUC emissions should be considered when choosing a policy rating of the life cycle GHG intensity of a biofuel, others argue against the same.

Our results suggest that inclusion of ILUC in the GHG rating of biofuels leads to lower emissions but does not guarantee that emissions decline absolutely relative to the baseline. This is due to the rebound in oil consumption resulting from the decline in world oil price, which happens under any fossil-fuel reduction policy in the home region. For the current biofuels, emissions attributable to the price effect or IFUE counteracts the reduction in emissions from the substitution of gasoline with ethanol. Biofuels with a substantially lower life cycle GHG intensity relative to that for oil products would be required so that the substitution effect exceeds the IFUE effect in magnitude and ensures that biofuels reduce emissions.

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Appendix

Proof of Proposition 1: Without loss of generality and to simplify the mathematical exposition, we assume there are only two types of fuels, a fossil fuel (subscript 'f') and a renewable (subscript 'r') and that the two fuels are perfect substitutes. Let us also assume that the fossil fuel is more pollution intensive, i.e., $z_f > z_r$.

The system of equations for the carbon tax t become:

$$p^h = D^{h^{-1}}(q_f^h + q_r^h) \tag{18a}$$

$$p^w = D^{a^{-1}} q_f^a \tag{18b}$$

$$p^w = S_f^{-1}(q_f^h + q_f^h) \tag{18c}$$

$$p_r = S_r^{-1}(q_r^h) \tag{18d}$$

$$p^h = p^w + tz_f \tag{18e}$$

$$p^h = p^w + tz_r \tag{18f}$$

Completely differentiating the equations with respect to $p^h, p^w, p_r, q_f^h, q_f^a, q_r^h$ and t, while holding the emission intensities fixed we can write,

$$dp^h = mD^h * (dq_f^h + dq_r^h) \tag{19a}$$

$$dp^w = mD^a * dq_f^a \tag{19b}$$

$$dp^w = mS_f * (dq_f^h + dq_f^a) \tag{19c}$$

$$dp_r = mS_r * dq_r^h \tag{19d}$$

$$dp^h = dp_b + dt * z_f \tag{19e}$$

$$dp^h = dp_b + dt * z_r \tag{19f}$$

where,

$mD^a = \frac{\partial D^{a^{-1}}}{d(q_f^h + q_r^h)} < 0$, $mD^h = \frac{\partial D^{h^{-1}}}{dq_f^a} < 0$, $mS_f = \frac{\partial S_f^{-1}}{d(q_f^h + q_f^h)} > 0$, $mS_r = \frac{\partial S_r^{-1}}{dq_r^h} > 0$,

Solving the above system of equations we can write

$$\frac{dp^h}{dt} = \frac{Nr}{Dr} \tag{20}$$

where, $Dr = (mD^a * mD^h * mS_r + mD^a * mD^h * mS_f - mD^a * mS_r * mS_f - mD^h * mS_r * mS_f)$ and $Nr = mD^a * mD^h * mS_r * z_r + mD^a * mD^h * mS_f * z_r - mD^h * mS_r * mS_f * z_f$

Since $mD^a < 0$, $mD^h < 0$, $mS_f > 0$, and $mS_r > 0$,

$\Rightarrow Dr > 0$ and $Nr > 0$,

$\Rightarrow \dfrac{dp^h}{dt} > 0$

We thus prove that the carbon tax raises fuel price in the home region, which implies fuel consumption declines and therefore emissions decline.

Biofuel share mandate ($\bar{\alpha}$): The system of equations for a share mandate α in (1) now become:

$$p^h = D^{h^{-1}}(q_f^h + q_r^h) \tag{21a}$$

$$p^w = D^{a^{-1}}(q_f^a) \tag{21b}$$

$$p^w = S_f^{-1}(q_f^h + q_f^a) \tag{21c}$$

$$p_r = S_r^{-1}(q_r^h) \tag{21d}$$

$$p^h = (1 - \bar{\alpha})p^w + \bar{\alpha}p_r \tag{21e}$$

$$\frac{q_r^h}{q_f^h + q_r^h} = \bar{\alpha} \tag{21f}$$

As with the system of equations for the carbon tax, completely differentiating the system of equations (1) and solving of differential equations, we can write

$$\frac{dp^w}{d\bar{\alpha}} = \frac{-(ae - f + dg)\,hi}{\Delta} \tag{22a}$$

$$\frac{dp^h}{d\bar{\alpha}} = \frac{(aeh - aei - beh + bei + dgh + chi - dgi)\,f}{\Delta} \tag{22b}$$

$$\frac{dp_r}{d\bar{\alpha}} = \frac{(fgh - fgi - begh + begi + cghi)}{\Delta} \tag{22c}$$

$$\frac{dq_f^h}{d\bar{\alpha}} = \frac{-(fh - fi - aeh + aei - dgh + dgi)}{\Delta} \tag{22d}$$

$$\frac{dq_f^a}{d\bar{\alpha}} = \frac{-(aeh - fh + dgh)}{\Delta} \tag{22e}$$

$$\frac{dq_r^h}{d\bar{\alpha}} = \frac{(fh - fi - beh + bei + chi)}{\Delta} \tag{22f}$$

where,

$$\Delta = afh - afi - bfh + bfi + achi + bdgh - bdgi < 0$$

$$a = \frac{\bar{\alpha}(1-\bar{\alpha})}{q_r^h} > 0, \quad b = \frac{-\bar{\alpha}^2}{q_r^h} < 0, \quad c = (1-\bar{\alpha}) > 0$$

$$d = \bar{\alpha} > 0, \quad e = S_r^{-1} - S_f^{-1} > 0, \quad f = \frac{\partial {D^h}^{-1}(q^h)}{\partial q^h} < 0$$

$$g = \frac{\partial S_r^{-1}(q_r^h)}{\partial q_b^h} > 0, \quad h = \frac{\partial S_f^{-1}}{\partial q_f} > 0, \quad i = \frac{\partial {D^a}^{-1}(q^a)}{\partial q^a} < 0$$

By determining the sign for each term in right-hand side of every equation, we generate Table 1.

Table 12: Summary statistics of difference in outcomes in each trial for different pairs of policies. Table shows the mean value of difference followed by the 2.5% and 97.5% quantile values of the difference in outcomes in parentheses.

Variable	SM20 – BAU	ES10 – BAU
World oil	-1.75, (-4.18, 0.13)	-15.88, (-32.65, -1.59)
Home price	-0.07, (-0.21, 0.41)	3.12, (-0.15, 6.57)
World eth	15.98, (5.76, 21.55)	1.9, (-22.39, 24.48)
World corn	7.29, (-7.59, 22.24)	-2.84, (-11.47, 0.68)
World cane	8.69, (-8.57, 21.86)	4.75, (-18.88, 26.49)
Home Ethanol	15.79, (5.79, 21.29)	0.11, (-25.41, 24.14)
World emissions	46.08, (-73.37, 144.33)	-447.36, (-959.49, 23.54)
Import exp.	-4.55, (-309.26, 249.8)	-463.66, (-1273.3, 450.36)
Market surplus	62.97, (-150.21, 115.59)	-792.87, (-1623.9, 29.73)

Calculation of range for elasticities for numerical analysis

We choose the elasticities as follows: According to Greene (2010a), the short-run demand elasticity of oil supply for the US is 0.03 to 0.07, and that for ROW is 0.02 to 0.06. He states that if an adjustment rate of 0.15 is assumed, then long-run elasticities will be 6.7 times the short-run elasticities. This is one paper that we could find that divides the world into two regions, US and ROW and provides both short and long run. We average his range for short and long run to derive a range for the medium run for US and ROW and [0.12 0.27] and [0.08 0.23], respectively. The ROW oil supply is about 10 times larger than that of the US: US production was 6.9 million barrels per day (mbpd) in 2007, while ROW produced 78 mbpd. Since elasticity is $\dfrac{dq/q}{dp/p} = \dfrac{dq/dp}{p/q}$, given the larger denominator one can expect a smaller elasticity of ROW oil supply. For instance, say the ROW elasticity is 0.1 and the elasticity of the US is 0.15 and say oil price increases by 5%, ROW oil supply increase = 0.1*0.05*78 = 0.39 mbpd, while the increase in US oil supply = 0.15*0.05*6.9 = 0.05 mbpd. Therefore, despite the higher elasticity US oil supply increases by a much smaller amount, which seems plausible.

For elasticity of demand for gasoline a number of studies exist. Different studies employ different econometric techniques, analyze different time periods and different regions, and arrive at different results. A few studies exist that summarize this literature and perform a meta analysis of elasticity estimates. We rely on one such study by Brons et al. (2008), which is a comprehensive review of some of the most prominent studies. Table 6 of Brons et al. (2008) is summarized below.

Table 13: Elasticities reported by Brons et al. (2008)

	coefficient μ	std. error σ	$\mu - 2\sigma$	$\mu + 2\sigma$
Constant	0.49	0.06	0.37	0.61
US/Canada Dummy	0.17	0.04	0.09	0.25
long run	0.38	0.05	0.28	0.48

Based on Table 13, we compute a predicted range of short-run and long-run elasticities of gasoline for US and ROW. We then average the short-run and long-run range to derive the range for the medium-run, which we use in our simulations. These values are shown in Table 14.

Table 14: Gasoline demand elasticities imputed from Brons et al. (2008)

	Short run			Long run			Medium		
	mean	5th	95th	mean	5th	95th	mean	5th	95th
US	0.32	0.28	0.36	0.7	0.56	0.84	0.51	0.42	0.60
ROW	0.49	0.37	0.61	0.87	0.65	1.09	0.68	0.51	0.85

For lack of a better estimates, we use the same range for diesel and the other oil products aggregate as gasoline. Once again, our uncertainty importance analysis suggests that the range of our model results is not highly sensitive to the assumed range of the elasticities for diesel and other oil products.