# Multi-objective fuel policies: Renewable fuel standards versus Fuel greenhouse gas intensity standards

Rajagopal, Deepak

2010-10-01

UNIVERSITY OF CALIFORNIA, LOS ANGELES

UCLA Institute of the Environment and Sustainability

**Working Paper Series**

# Multi-objective fuel policies: Renewable fuel standards versus Fuel greenhouse gas intensity standards

D. Rajagopal, G. Hochman, D. Zilberman

Oct 2010

WP#1

# Multi-objective fuel policies: Renewable fuel standards versus Fuel greenhouse gas intensity standards

D Rajagopal[*], G Hochman[†], D Zilberman[‡]

**Abstract**

Governments throughout the world have enacted policies to support the introduction of alternatives to crude oil. These policies are viewed as means to achieve multiple objectives such as energy independence and security, reduce greenhouse gas (GHG) emissions, protect fuel consumers and support infant industries. We evaluate the trade-offs presented by different policy instruments such as renewable fuel (biofuel) standards (RFS), fuel GHG intensity standards (FGIS) and fuel GHG tax in achieving these objectives. Using a two-region partial-equilibrium model, we find that the relative performance of the two policies, RFS and FGIS, relative to each other and relative to a fuel tax, depends on whether the policy is global or regional in scope. Whereas the FGIS has better environmental performance than RFS when applied globally, the two policies lead to similar environmental outcomes when the policy is regional. RFS leads to bigger marker share for non-crude oil fuels than both FGIS and fuel tax.

*Keywords*: climate change, transportation, energy security, biofuel, carbon tax, mandate, intensity standard

*JEL classifications*: Q42; Q48

## 1 Introduction

Governments throughout the world have enacted policies to support the introduction of alternatives to crude oil[Rajagopal et al.(2009)]. The policy debate and the wording of the policies themselves suggest that these policies are viewed as means to achieve multiple objectives such as energy independence and security, reduce greenhouse gas (GHG) emissions, protect fuel consumers, support infant industries and generate employment [CBO(2007), Sobrino and Monroy(2009), ARB(2009)].

---

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

[†] Energy Biosciences Institute, University of California, Berkeley

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

A predominant number of these policies take the form of biofuel regulations. There are two parallel types of regulations today. One popular type of regulation is biofuel mandate, henceforth referred to as renewable fuel standard (RFS), which specifies either a given share for biofuel or a given quantity of biofuel (as in the US) in domestic fuel consumption [Martinot and Sawin(2009)]. An alternative type of regulation that is being implemented in California (and is under consideration by the US federal government, the European Union and China) called the Low Carbon Fuel Standard (LCFS), henceforth referred to by the generic term fuel GHG standard (FGIS) [Holland et al.(2009)]. Unlike RFS, FGIS is a regulation that specifies a performance target, in this case an upper-bound on the average GHG intensity of fuel sold by a firm, without mandating any particular technology like biofuel to achieve this target. In other words firms are free to sell fuels regardless of their GHG emission intensity so long as the sales-weighted average of GHG intensity is below the upper-bound set by the regulation. Furthermore, the LCFS also permits trading on GHG emission credits.[1]. Since biofuels are the most cost-effective among alternatives to oil today the FGIS is de facto a RFS. Both types of regulations are also supported with direct subsidies like excise credits. In some countries domestic biofuels are protected from imports through trade tariffs, for instance the US.

In this paper we develop a framework to compare the performance of these regulations and lay out their distinctions with respect to different criteria of likely interest to policy makers such as fuel price, GHG emission (both domestic and global), and two indicators relevant to fuel security, namely, the share of alternatives to crude oil (both renewable fuels and unconventional petroleum) and the share of renewable fuel in domestic supply. We also compare them to a carbon tax, which can be viewed as either a first-best policy, if equal to the marginal social damage from GHG emissions, or a second-best policy if there exists a target of GHG reduction. Oil being a global commodity and GHGs being a global pollutant, we evaluate the performance of these policies under two set ups. One, if these policies were applied globally and two, when they are applied regionally as is happening in reality.

Economists have long known that to attain multiple targets, it is necessary that the number of policy instruments equal the number of targets [Tinbergen(1952)]. Normative economic studies that pursue efficiency or cost effectiveness in the presence of multiple market failures again attach a policy to correct each market failure. For instance, when there is both a negative environmental externality and under-investment in R&D, the optimal outcome is achieved through a price on emission and a subsidy for R&D [Fischer and Newell(2008)]. When additional constraints that

---

[1] The US RFS also is market-based in that it permits trading in renewable fuel credits. However these are likely to be generated only by biofuel producers

may be political constraints, market failures, or policy failures exist, multiple instruments may be required to achieve one target[Bennear and Stavins(2007)]. Bennear and Stavins cite several examples such as energy efficiency, toxics control and fisheries management, where multiple instruments are used to achieve one target. Sometimes however, there may not exist a one-to-one correspondence between instruments and targets, but rather a combination of instruments may be used to attain multiple targets and with fewer instruments than the targets. This is the case, for example, with biofuel mandates that aim to increase fuel security, reduce GHG emissions, generate employment and reduce the cost to consumers.

There exists a literature on evaluating biofuel policies, but this literature evaluates these policies based on a single criteria such as social welfare, market-surplus or the cost-effectiveness of GHG abatement. Comparing different biofuel policies using a general equilibrium framework and an open economy model, Lapan and Moschini (2009) show that combination of biofuel mandates and fuel GHG taxes would result in higher market surplus than biofuel mandates with biofuel subsidies. de Gorter and Just (2010) argue that the welfare loss taking into account corn market surplus and tax payer cost of biofuel excise tax credits dwarfs the welfare gain from reduction in farm subsidies. They do not however look at the change in fuel market surplus and do not monetize non-market impacts. Rajagopal et al. (2007) simulate the impact of US biofuel mandates and subsidies on food as well as fuel markets. Focussing on two externalities, GHG emissions and congestion from driving, Khanna et al. (2008) argue that biofuel subsidies lead to marginal reduction in GHG emissions, an increase vehicle miles driven and a net loss in social welfare. Several papers also conclude that biofuels are not cost-effective as a carbon mitigation strategy [Khanna et al.(2008), Holland et al.(2009)]. The imputed carbon price for biofuel policies is shown to be high compared to the cost of achieving carbon mitigation through improved energy/fuel efficiency, fuel-switching in the electricity sector etc. [Creyts(2007)]. Some argue that biofuel policies subsidize fuel consumption thereby negating the environmental benefits of switching to cleaner fuels [Rajagopal et al.(2007), De Gorter and Just(2009), Hochman et al. (2010a), Lapan and Moschini(2009)]. Focusing on energy security benefits of US biofuel mandates, Leiby depicts how increasing the usage of renewable fuels helps to reduce U.S. petroleum imports and consumption [Leiby(2008)].

We differ from the current literature in the following ways. Firstly, standard welfare economic literature evaluates policies from the criteria of efficiency or cost-effectiveness. If we can monetize variables and constraints relating to GHG emissions and energy security, such criteria can be used to benchmark the performance of different policies. However the difficulty to monetize these objectives suggests us to conduct multi-attribute analysis without imposing weights, which is the approach taken in this paper. Secondly, while the literature focusses either on RFS or on FGIS and compares them to a carbon tax, we compare RFS, FGIS and carbon tax (other biofuel policies such as subsidies and tariffs are assumed fixed) along the multiple dimensions, namely, fuel price, GHG emissions and market share of non-crude oil fuels. Thirdly, we assess regional policies in a global context by modeling emission leakage, which can occur in two ways: (i) an international rebound effect, which refers to an increase in fuel consumption abroad due to the domestic policy [Hochman et al. (2010a)], and (ii) a pollution shifting effect, which is an increase in the emission intensity of fuels consumed abroad[Bushnell et al.(2008)]. A policy that simply leads to reallocation of existing fuels in a manner such that less-polluting fuels are consumed at home and more-polluting fuels are consumed abroad while it may reduce domestic emissions may little global impact. Fourthly, different from much of the literature on renewable fuel policies, we take into account heterogeneity in GHG intensity among fossil fuels.

We find that the relative performance of the two policies, namely RFS and FGIS, relative to each other and relative to a fuel carbon tax, depends on whether the policy is global or regional in scope. When the policies are applied globally, a FGIS results in higher fuel price, lower fuel consumption, lower GHG emissions and smaller marker share for non-crude oil fuels (i.e, oilsand and biofuel) when compared a RFS when both policies target a fixed market share of renewable fuels. When the policies are applied in one region only, domestic fuel price is the same or higher under a FGIS than that under a RFS while world fossil fuel price is the same or lower under a FGIS than under a RFS, again when both policies target a fixed market share of renewable fuels. The FGIS results in lesser emissions domestically than RFS, but both policies lead to the same global emissions. In other words, the FGIS results in more emissions abroad than RFS. Unlike RFS, both FGIS and fuel carbon taxes lead to fuel/pollution shifting with the more-polluting fossil fuels being consumed abroad as opposed to home. The domestic market share of non-crude oil fuels is smaller under FGIS than RFS. Fuel subsidies reduce the burden of regulations like RFS and FGIS on domestic fuel consumers and fossil fuel suppliers. Numerical simulations indicate that the implicit carbon price of both renewable fuel policies is high, exceeding \$100 per ton $CO_2$. This also means that fuel carbon tax can achieve emission reduction at a lower cost but will not induce demand for renewable fuels. This provides one explanation for why policy makers choose renewable fuel policies.

We also find that a given quantity of renewable fuel does not simply replace an energy-equivalent quantity of fossil fuel but may replace more or less depending its impact on world price and domestic price of fuel. While the domestic price of fuel may increase or decrease depending on the policy regime and market conditions, the world price of oil declines unambiguously under any domestic clean fuel policy. Therefore while domestic emissions may decrease or increase, rest-of-the-world emissions certainly increase. Therefore, when using a lifecycle approach to calculating GHG benefits of a fuel or a policy, if leakage through phenomena like indirect land use change are accounted for then, so must leakage in the fuel sector. Simulations suggest this may be significant compared with both the direct lifecycle emissions and the indirect land use (ILU) emissions of biofuel and counter the effect of ILU.

## 2 The model

We develop a micro economic framework that extends Fischer (2010) and is capable of analyzing different energy and environmental policy instruments both within a regional and global context. We consider two regions, home and rest of the world (ROW). We assume an open economy and competitive markets. We consider two types of liquid fuels, namely, liquid fossil fuel and renewable fuel. While the former is produced in both regions and traded, similar to [Lapan and Moschini(2009)] we assume the latter is produced only at home and not traded.[2] We further classify fossil fuels as conventional crude oil (CCO) and synthetic crude oil (SCO). SCO refers to oil produced mainly from oilsands in Canada and relatively smaller amounts from Venezuelan extra heavy crude oil. SCO can also be produced through gas and coal liquefaction which tend to be costlier. According to the International Energy Agency's World Energy Outlook 2008, SCO is expected to comprise about 75% of the incremental supply between 2006 and 2030. While both type of fossil fuels can be considered perfect substitutes, they differ in their lifecycle carbon intensity. Since SCO requires significant amount of energy for processing the primary feedstock (oilsand, coal or gas) into useful fuel their lifecycle carbon intensity is reported to be 20% or more higher compared to conventional crude oil. For simplicity, we assume that each of the two types of crude oil have a fixed carbon intensity. Without loss of generality we assume there exists one type of renewable fuel, more specifically one type of biofuel[3] whose lifecycle GHG intensity is smaller than that of fossil fuels and is fixed.[4] For the sake of simplicity, we assume that fossil fuel and renewable fuel are perfect substitutes.[5].

---

[2] U.S. biofuels from corn and soy are inefficient compared to those from Brazilian cane or Malaysian oilpalm. At the same time, cane ethanol faces a prohibitively high import tariff of \$0.54/gallon

[3] This is reasonable because in the major biofuel consuming regions of the world today one type of biofuel appears more economical than other. For instance corn ethanol is the most economical biofuel in the US, while cane ethanol and rapeseed biodiesel are the most economical in Brazil and EU respectively.

[4] We are indeed aware the lifecycle carbon intensity of biofuel is matter of debate given the concerns regarding land use change and the associated emissions induced by increasing biofuel production. For the purpose of this paper we assume the lifecycle GHG intensity refers only to the direct lifecycle emission intensity which is generally accepted as being smaller than that of fossil fuels.

[5] While oil refining yields multiple products, gasoline and diesel are the main products driving the demand for oil and can be substituted by biofuel up to 10% by volume in existing fleet. In the longer run, flex fuel vehicle technology will allow complete substitution.

We use the following mathematical notations. Superscripts $h$, $a$ and $w$ denote the regions home, ROW and the world as whole respectively. The subscripts $c$, $os$ and $b$ refer to conventional crude oil, synthetic crude oil (oilsands) and biofuel respectively. $p$ denotes the fuel price, $q$ the quantity, $z$ the lifecycle GHG intensity of fuel (with, $z_b < z_c < z_{os}$) and $Z$ the emissions. We assume that transportation costs are a small component in the price of oil. Let $S$ and $S^{-1}$ denote fuel supply function (as a function price) and the inverse supply function (i.e, marginal cost as a function of quantity supplied). Similarly, $D$ and $D^{-1}$ denote the demand function and inverse demand function respectively.

The world fuel price is determined by the equilibration of global supply and global demand for fuel. The market clearing condition

$$S_c(p^w) + S_{os}(p^w) + S_b(p^w) = D^h(p^w) + D^a(p^w) \tag{1}$$

This can also be written as,

$$p^w = (<)S_c^{-1}(q_c^w) \text{ if } q_c^w > (=)0 \tag{2a}$$

$$p^w = (<)S_{os}^{-1}(q_{os}^w) \text{ if } q_{os}^w > (=)0 \tag{2b}$$

$$p^w = (<)S_b^{-1}(q_b^w) \text{ if } q_b^w > (=)0 \tag{2c}$$

$$p^w = D^{h^{-1}}(q^h) \tag{2d}$$

$$p^w = D^{a^{-1}}(q^a) \tag{2e}$$

$$q_c^w + q_{os}^w + q_b^w = q^h + q^a \tag{2f}$$

The inequalities hold when the quantity supplied is zero.

Total emissions is computed as,

$$Z^w = z_c S_c(p^w) + z_{os} S_{os}(p^w) + z_b S_b(p^w) \tag{3}$$

We assume that biofuels are not viable in the absence of policy.[6] Mathematically, if $p^*$ is the world price of oil in the absence of regulation, then $S_b(p^*) < 0$, indicating there is no biofuel supply.[7]

---

[6] Even in the absence of carbon or biofuel regulations, the presence of fuel oxygenate mandates and the ban on methyl tertiary butyl ether have given rise to a demand for ethanol as an oxygenate and octane enhancer. However, fuel oxygenate mandates will not bind under carbon or biofuel regulation as demand under the latter will far exceed the oxygenate mandate.

[7] In reality, the competitiveness of biofuels also depends on crop price. A decrease (increase) in price of agricultural commodities *ceteris paribus* shifts the supply of biofuel to the right (left) increasing (decreasing) its competitiveness. Simultaneously, biofuel policies increase demand for agricultural commodities. The impact of biofuels on food markets is a topic of controversy today. Since we do not derive the impact of biofuel regulations on food price in our model, we analyze different biofuel regulations when they attain a similar level of biofuel consumption.

We compare three types of regulations on fuel producers: a carbon tax, a RFS, which mandates a fixed market share ($\bar{\alpha}$) for renewable fuel and a FGIS ($\bar{z} < z_c$), which mandates a reduction in the average carbon intensity of fuel. Regulations such as RFS and FGIS tend to be supported through subsidies. Since the subsidy does not affect the qualitative comparison between the taxes, mandates and standards although it affects the actual outcomes, for simplicity and without loss of generality, we assume it is zero (An illustration with subsidy is in the Appendix). Since both the US RFS and the California LCFS policies permit trading in renewable fuel and emission credits respectively, we assume the same for the generic RFS and generic FGIS. Therefore, fossil fuel suppliers can meet their obligations either by blending renewable fuel themselves or by purchasing tradable permits. We assume that blending is perfectly competitive i.e, there are zero-profits from blending.

**Carbon tax ($t$)**: The carbon tax can either be interpreted as the marginal social cost of carbon or as the shadow price of a GHG emission target. The system of equations describing the equilibrium under a carbon tax is given below

$$p^w - tz_c = (<)S_c^{-1}(q_c^h) \text{ if } q_c^h > (=)0 \tag{4a}$$

$$p^w - tz_{os} = (<)S_{os}^{-1}(q_{os}^h) \text{ if } q_{os}^h > (=)0 \tag{4b}$$

$$p^w - tz_b = (<)S_b^{-1}(q_b^h) \text{ if } q_b^h > (=)0 \tag{4c}$$

$$p^h = D^{h^{-1}}(q_c^h + q_{os}^h + q_b^h) \tag{4d}$$

$$p^w = S_c^{-1}(q_c^a + q_c^h) \tag{4e}$$

$$p^w = S_{os}^{-1}(q_{os}^a + q_{os}^a) \tag{4f}$$

$$p^w = S_b^{-1}(q_b^a + q_b^h) \tag{4g}$$

$$p^w = D^{a^{-1}}(q_c^a + q_{os}^a + q_b^a) \tag{4h}$$

Equation (4a) relates domestic crude oil consumption $q_c^h$ to the marginal cost of the supplying of crude oil under the tax, which is world price less the tax per unit output i.e, $p^w - tz_c$. The equality holds if $q_c^h > 0$ else the inequality condition holds.[8] Equation (4b) and (4c) denotes the same for oilsands and biofuels respectively. Equation (4d) relates domestic fuel price to domestic consumption using the demand function. Equations (4e), (4f) and (4g) relate the world oil price to the marginal cost of each type of fuel. Equation (4h) relates ROW fuel price, i.e., the world fuel price to ROW consumption using the demand function for the ROW.

A fuel carbon tax, while it no doubt increases the relative cost of fossil fuels and makes biofuels

---

[8] The inequality condition cannot be $p^w - tz_c > S_c^{-1}(q_c^h)$ since this means price exceeds marginal cost, implying the market is not competitive which violates our assumption.

more competitive, it nevertheless also increases the cost of renewable fuels. Therefore whether biofuels get adopted depend on the level of the tax and carbon intensity of renewable fuel relative to fossil fuels. To give an example, assuming the carbon intensity of corn ethanol and gasoline from conventional crude oil is 75 $gCO_2/MJ$[9] and 95 $gCO_2/MJ$ respectively, a carbon tax of \$30 per tonne $CO_2$, increases the marginal cost of ethanol and gasoline by \$0.048 per gallon and \$0.091 per gallon. Therefore, if the marginal cost of ethanol exceeds that of gasoline by more than \$0.043 per gallon, this level of carbon tax will not lead to the adoption of biofuel.

**Renewable Fuel Standard (fixed market share, $\bar{\alpha}$)**: Under this policy, a fuel supplier is required to supply a quantity of renewable fuel (or possess credits) such that its share of all fuels he/she sold equals $\bar{\alpha}$. Unlike a carbon tax, which affects different fossil fuels differently depending on their carbon intensity, a RFS imposes the same obligation regardless of the carbon intensity of fossil fuel. We therefore drop the subscripts, $c$ and $os$ and denote with subscript $o$ aggregate the fossil fuel supply. The system of equations describing the equilibrium under a RFS is given below.

$$\frac{q_b^h}{q_o^h + q_b^h} = \bar{\alpha} \tag{5a}$$

$$p^h = (1-\bar{\alpha})p^w + \bar{\alpha} p_b \tag{5b}$$

$$p^h = D^{h^{-1}}(q_o^h + q_b^h) \tag{5c}$$

$$p_b = S_b^{-1}(q_b) \tag{5d}$$

$$p^w = S_f^{-1}(q_o^h + q_o^a) \tag{5e}$$

$$p^w = D^{a^{-1}}(q_o^a) \tag{5f}$$

Equation (5a) represents the blending standard imposed by the RFS. Equation (5b) represents competitive blending condition wherein the price at home is the blended price of world oil price and price of biofuel. This represents the marginal cost of supplying one more unit of fuel at home. Equations (5c) and (5f) represent the demand equations for home and ROW respectively. Equations (5d) and (5e) relate the price and marginal cost for each fuel. We have 6 equations in 6 unknowns, namely, $p^w, p^h, p_b, q_o^h, q_f^a$ and $q_b^h$. Given $p_w$ we can compute the global supply of conventional crude oil as $S_c(p_w)$ and the global supply of SCO as $S_{os}(p_w)$. We however cannot determine the spatial distribution of these quantities across the two regions.

---

[9] grams of carbon di oxide per megajoule

**Fuel GHG Intensity standard ($\bar{z}$)**: Under this policy, a fuel supplier is required to sell a quantity (or possess credits) of clean fuel (in this case biofuel) such that the sales-weighted average carbon intensity of all fuels he/she sold equals $\bar{z}$. Given $\bar{z}$, the blending obligation for the seller of conventional crude oil, $\alpha_c = \frac{z_c - \bar{z}}{z_c - z_b}$ and that for seller of oilsands, $\alpha_{os} = \dfrac{z_{os} - \bar{z}}{z_{os} - z_b}$. In other words, if a fuel supplier sells, $q_c$ units of crude oil and $q_{os}$ units of oilsands, he must sell an amount of biofuel $q_b$ (or possess an equivalent amount of permits) such that $q_b = \dfrac{\alpha_c}{1-\alpha_c} q_c + \dfrac{\alpha_{os}}{1-\alpha_{os}} q_{os}$. The equilibrium under the FGIS is defined by the following equations,

$$\frac{z_c q_c^h + z_{os} q_{os}^h + z_b q_b^h}{q_c^h + q_{os}^h + q_b^h} = \bar{z} \tag{6a}$$

$$p^h <= (1-\alpha_c)p^w + \alpha_c p_b \text{ if } q_c^h > (=)0 \tag{6b}$$

$$p^h <= (1-\alpha_{os})p^w + \alpha_{os} p_b \text{ if } q_{os}^h > (=)0 \tag{6c}$$

$$p_b = S_b^{-1}(q_b) \tag{6d}$$

$$p^h = D^{h^{-1}}(q_c^h + q_{os}^h + q_b^h) \tag{6e}$$

$$p^w = S_c^{-1}(q_c^h + q_c^a) \tag{6f}$$

$$p^w = S_{os}^{-1}(q_{os}^h + q_{os}^a) \tag{6g}$$

$$p^w = D^{a^{-1}}(q_c^a + q_{os}^a) \tag{6h}$$

Equation (6a) implies that the quantity weighted average of emission intensity of different fuels equals the FGIS $\bar{z}$. Equations (6b) and (6c) represent the competitive blending condition for CCO and SCO respectively. Equations (6e) and (6h) represent the demand equations for home and ROW respectively. Equation(6d) equates the price of biofuel to its marginal cost. Equations(6f) and (6g) relate the world oil price to the marginal cost of CCO and SCO respectively.

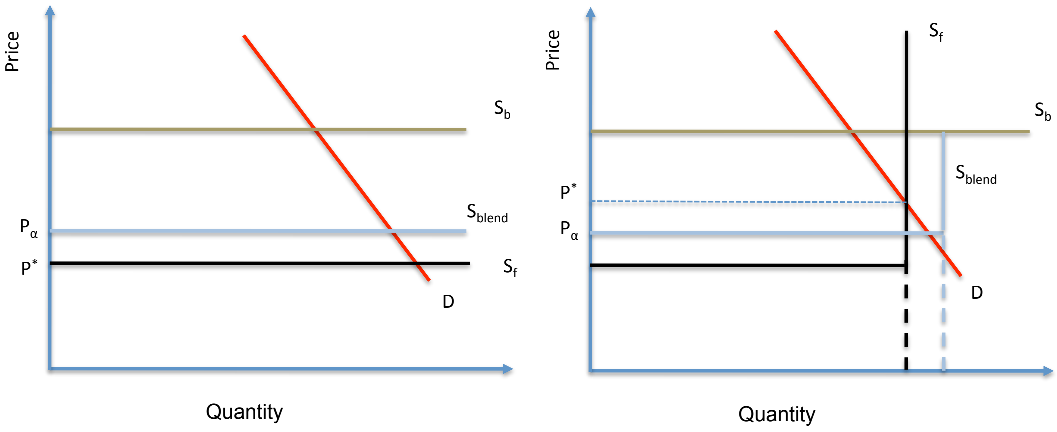
## 2.1 Global policies

We first analyze the policies single region context. The single region context can be taken to represent either that the policy is globally consistent or a single region under autarky. We therefore drop the superscripts $h$ and $a$ and rewrite the equations above. These are shown in the Appendix.

*Proposition 1*: Both renewable fuel standards and fuel GHG standards may increase or decrease fuel prices. If, $mc$ denotes marginal cost, $\eta$ denotes the fuel supply elasticity and subscript $f$ denotes fossil fuel, then fuel price increases (decreases) if $\dfrac{mc_f}{mc_b} < (>) \dfrac{\frac{1}{\eta_b}+1}{\frac{1}{\eta_f}+1}$. The elasticity fuel demand only affects the magnitude of the price change.

*Proof*: See appendix for mathematical derivation. The intuition is explained with the aid of figure

1 which depicts the RFS in a single region context.[10] When fossil fuel supply is inelastic, then blending a renewable fuel that is costlier (i.e, higher marginal cost than the market price of fossil fuel), may yet lower fuel price by increasing total supply, $p_{\bar{\alpha}} > p^*$. However, when fossil fuel supply is perfectly elastic then the RFS increases fuel price, $p_{\bar{\alpha}} > p^*$. For intermediate values of supply elasticity of fossil fuel, the direction of impact varies as mentioned above. From equation (11) shown in the appendix, we can see that $sign\left(\frac{dp}{d\bar{\alpha}}\right)$ does not depend on $d$, the term that represents the elasticity of demand.



(a) Perfectly elastic fossil fuel supply

(b) Perfectly inelastic fossil fuel supply

Figure 1: Price impact of renewable fuel standard (market share $\bar{\alpha}$) on fuel price

*Corollary*: More stringent the standard, the smaller the reduction in fuel price if any.

From figure 1, as the stringency of the RFS, $(\bar{\alpha})$, increases, the aggregate supply curve, $S_blend$, shifts up and to the right, and so the RFS reduces the price increase less i.e, $p_{\bar{\alpha}}$ begins to approach and then eventually exceed $p^*$. Similarly higher (lower) the elasticity of fossil fuel supply less (more) likely the reduction in fuel price under renewable fuel policies. Emissions may decrease or increase under clean fuel policies depending on whether fuel prices increase or decrease as a result of these policies. When a policy increase fuel price, it leads to both a reduction in total fuel consumption and a decrease in the average fuel carbon intensity and therefore unambiguously reduce emissions compared to the baseline scenario. However, when a policy lower fuel prices, it increases total fuel consumption, which offsets the benefits of adopting cleaner renewable fuel. To this end, biofuel subsidies, which lower the cost of biofuels, tend to mitigate any price increase that may result. (See appendix for an illustration of the comparative statics under a subsidy)Under

---

[10] In this figure, we depict the RFS as shifting the supply curve although in reality the biofuel regulation is a domestic consumption mandate. We do so because when there is only one region, a production and consumption mandate are equivalent and the intuition is more easily explained as a production mandate. In the mathematical model, the regulation is represented as a consumption mandate.

such circumstances, biofuel policies are less likely to reduce emissions.

*Proposition 2*: A FGIS imposes higher blending obligation of renewable fuel on the more polluting fossil fuels (say, oilsands) and lesser blending obligation on less polluting fossil fuels (say, conventional crude oil), i.e., $\alpha_{os} > \bar{\alpha}$ when compared to a RFS when both achieve the same market share of renewable fuels $\bar{\alpha}$.

*Proof*: Substituting the expression for $\bar{z}$ in the expression for $\alpha_{os}$ from the set equations for the FGIS we get,

$$\begin{aligned}
\alpha_{os} &= \frac{z_{os}-\bar{z}}{z_{os}-z_b} = \frac{z_{os}-\left[\frac{z_c q_c + z_{os} q_{os} + z_b q_b}{q_c+q_{os}+q_b}\right]}{z_{os}-z_b} \\
&= \frac{z_{os}-z_c}{z_{os}-z_b}\left[\frac{q_c}{q_c+q_{os}+q_b}\right] + \frac{q_b}{q_c+q_{os}+q_b} \\
&= \underbrace{\frac{z_{os}-z_c}{z_{os}-z_b}\left[\frac{q_c}{q_c+q_{os}+q_b}\right]}_{>0} + \bar{\alpha} \\
&> \bar{\alpha}
\end{aligned}$$

This shows that the blending obligation for oilsand is higher under the FGIS compared to the RFS. Similarly, substituting the expression for $\bar{z}$ in the expression for $\alpha_c$, we can show that the blending obligation for conventional crude oil is lower under the FGIS compared to the RFS, i.e., $\alpha_c < \bar{\alpha}$.

*Corollary*: If all fossil fuels have the same emission intensity then a RFS and FGIS are equivalent. In other words, for any given share mandate one can determine the equivalent FGIS that will result in an identical outcome as the share mandate. The impact of the policies are different when there is heterogeneity as we will show later.

Consider equation (6a). Dropping the subscript $h$ and assuming there is only one type of fossil fuel with emission intensity $z_c$, the emission intensity implied by a share mandate $\bar{\alpha}$ is $\bar{z}_{\bar{\alpha}} = (1-\bar{\alpha})z_c + \bar{\alpha} z_b$. Alternatively, given a FGIS $\bar{z}$, we can determine the implied share mandate, $\bar{\alpha}_{\bar{z}}$, as $(1-\bar{\alpha}_{\bar{z}})z_f + \bar{\alpha}_{\bar{z}} z_b = \bar{z}$ .

*Proposition 3*: Under a global policy, a FGIS results in higher fuel price, lower consumption, lesser emissions and slower adoption of dirtier fossil fuels and biofuels when compared a RFS that attains the same market share of renewable fuels.

*Proof*: Rewriting the equations for the FGIS (see appendix), and imposing the additional condition that it attain a given market share of biofuel, $\bar{\alpha}$, we get the following system of equations,

$$\begin{aligned}
\frac{z_c q_c + z_{os} q_{os} + z_b q_b}{q_c + q_{os} + q_b} &= \bar{z} \\
\frac{q_b}{q_c + q_{os} + q_b} &= \bar{\alpha} \\
p &= (1-\alpha_c) S_c^{-1}(q_c) + \alpha_c S_b^{-1}(q_b) \\
p &= (1-\alpha_{os}) S_{os}^{-1}(q_{os}) + \alpha_{os} S_b^{-1}(q_b) \\
p &= D^{-1}(q_c + q_{os} + q_b)
\end{aligned}$$

Completely differentiating the equations and rearranging yields the following:

$$\begin{aligned}
\frac{dp}{d\alpha_{os}} &= \frac{ad(1+g)}{a+c+(a+c)g+f(ac+(bc+ae)g)} > 0 \\
\frac{dq_{os}}{d\alpha_{os}} &= \frac{-d(1+g+f(a+bg))}{a+c+(a+c)g+f(ac+(bc+ae)g)} < 0 \\
\frac{dq_c}{d\alpha_{os}} &= \frac{d(1+g+bfg)}{a+c+(a+c)g+f(ac+(bc+ae)g)} > 0 \\
\frac{dq_b}{d\alpha_{os}} &= \frac{-adfg}{a+c+(a+c)g+f(ac+(bc+ae)g)} < 0
\end{aligned}$$

$a = (1-\alpha_c)\frac{\partial S_c^{-1}(q_c)}{\partial q_c} > 0, \qquad b = \alpha_c \frac{\partial S_b^{-1}(q_b)}{\partial q_b} > 0, \qquad c = (1-\alpha_{os})\frac{\partial S_{os}^{-1}(q_{os})}{\partial q_{os}} > 0$

$d = S_b^{-1}(q_b) - S_{os}^{-1}(q_{os}) > 0, \quad e = \alpha_{os}\frac{\partial S_b^{-1}(q_b)}{\partial q_b} > 0, \quad f = -\frac{\partial D}{\partial p} > 0$

$g = \frac{\bar{\alpha}}{1-\bar{\alpha}} > 0$ (since $\bar{\alpha} < 1$)

$a, b, c$ and $e$ are positive because, the supply function has a positive slope. $d > 0$ because of our assumption that policy is binding i.e., marginal cost of renewable fuel is higher than fossil fuels. $f > 0$ because demand function has a negative slope.

Global fuel consumption, $q^w = q_c + q_{os} + q_b$. Differentiating this with respect to $d\alpha_{os}$, and substituting from the expressions above we get,

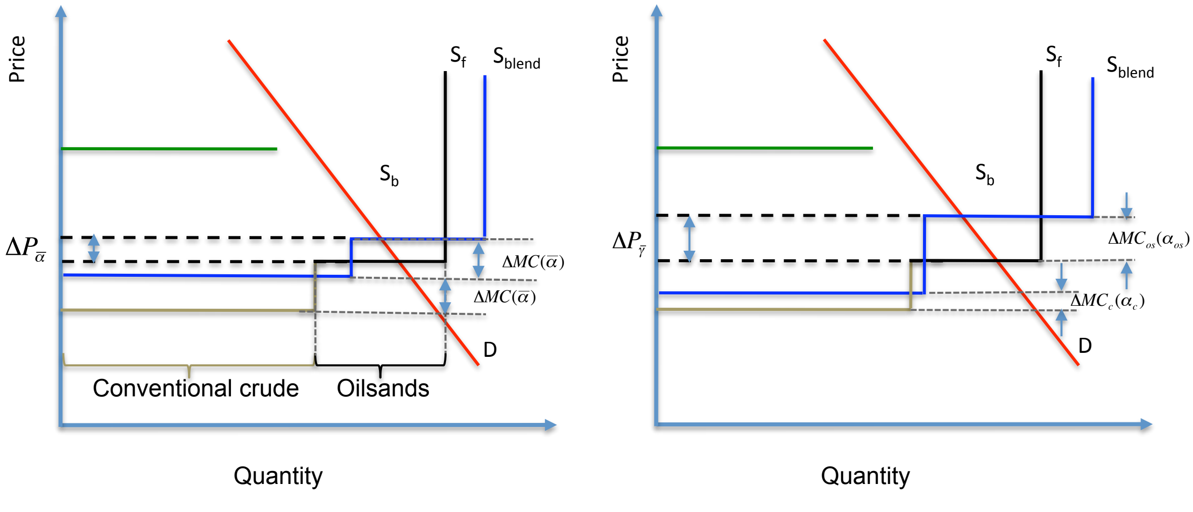
$$\frac{dq^w}{d\alpha_{os}} = \frac{dq_c}{d\alpha_{os}} + \frac{dq_{os}}{d\alpha_{os}} + \frac{dq_b}{d\alpha_{os}} = \frac{adf(1+g)}{a+c+(a+c)g-f(ac+(bc+ae)g)} < 0$$

Let $Z^w = \bar{z}q^w$, denote the total emissions. Differentiating this with respect to $d\alpha_{os}$, and substituting from the expressions above we get, $\frac{dZ^w}{d\alpha_{os}} = \bar{z}\frac{dq^w}{d\alpha_{os}} < 0$. Now combining with proposition

1, which shows that $\alpha_{os} > \bar{\alpha}$, we have proved that,

$$\begin{aligned} p^*|_{\alpha_{os}} &> p^*|_{\bar{\alpha}} \\ Z^{w*}|_{\alpha_{os}} &< Z^{w*}|_{\bar{\alpha}} \\ (q^*_{os} + q^*_b)|_{\alpha_{os}} &< (q^*_{os} + q^*_b)|_{\bar{\alpha}} \text{ (the share of non-crude fuels)} \end{aligned}$$

Therefore a FGIS results in higher prices, lower emissions and smaller share of non-crude oil fuels while achieving a given share of biofuels. A graphical interpretation is shown in figure 2.



(a) Renewable fuel standard $(\bar{\alpha})$

(b) Fuel GHG Intensity standard $(\bar{\gamma})$

*Note* : $\Delta MC$ denotes the increase in marginal cost due to blending of renewable fuel. Since $\alpha_c < \alpha_{os}, \Delta MC_c(\alpha_c) < \Delta MC_{os}(\alpha_{os})$

$\Delta P$ denotes the increase in fuel price

Figure 2: A comparison of RFS and FGIS

We can similarly also show that a FGIS results in higher prices, lower emissions and smaller share of non-crude oil fuels while achieving a total level of biofuel consumption.

## 2.2 Regional policies in a global context

We see that under a global policy there exists a clear distinction between RFS and FGIS. In the real world, policies are rarely global. For instance, the US RFS apply only to US fuel suppliers while the California LCFS is applies to fuel sales within the state of California. To analyze the implications when one region implements a fuel policy whereas the market for fuel is global, we return to the main model.

*Proposition 4*: Under any domestic policy that reduces domestic fuel consumption, world price of fossil fuel declines and world consumption of fossil fuel increases.

*Proof*: By reducing domestic demand, domestic renewable fuel policies and carbon standards reduce the world price of fossil fuel. Completely differentiating the system of equations for the RFS and the FGIS, we can show $\frac{dp^w}{d\bar{\alpha}} < 0$ and $\frac{dp^w}{d\bar{z}} < 0$ respectively. For the mathematical proof see the appendix.

*Proposition 5*: Under the domestic FGIS policy, the home region will not consume the more polluting fossil fuels whereas under a domestic RFS, all fossil fuels are equally viable in the home region.

*Proof*: By negation. Let us assume that oilsand, the more carbon-intensive fossil fuel, is consumed in the home region under the policy. This implies that the competitive blending condition for oilsand, $p^h = (1 - \alpha_{os})p^w + \alpha_{os}p_b$, is satisfied. But this also implies that $(1 - \alpha_c)p^w + \alpha_c p_b < p^h$ (since $\alpha_c < \alpha_{os}$ and given the assumption that the policy is binding i.e., $p_b > p^w$). This then implies that blending is not competitive, violating our original assumption. Now let us assume the blending condition for conventional crude oil, $p^h = (1 - \alpha_c)p^w + \alpha_c p_b$, holds. This implies, $(1 - \alpha_{os})p^w + \alpha_{os}p_b > p^h$. This implies that blending biofuel with oilsand is not viable since the marginal cost of the blend is higher than the fuel price in the home region. This is the only viable scenario and we have thus shown that oilsands are not viable in the home region under the FGIS policy. This also suggests that the FGIS policy may lead to shifting of more polluting fossil fuels abroad. Note that under a RFS, $\alpha_c = \alpha_{os} = \bar{\alpha}$ and therefore the equation 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 FGIS is shown in equation (19a) (shown in appendix).

*Corollary*: Domestic fuel price is the same or higher under a FGIS than that under a RFS when both policies attain the same market share of renewable fuels. Similarly, world fuel price is the same or lower under a FGIS than under a RFS.

Since the FGIS prohibits a part of the supply from become consumed in the home region, it cannot possibly result in a lower price in the home region than when this portion of the supply may be viable as is the case under the RFS. The impact on global emissions under either policy with respect to the baseline and for one policy relative to the other is ambiguous.

# 3 Numerical simulation and results

To illustrate the order of magnitude of the outcomes of the different types of policies, we perform simulation. Since our model is static and this being a reasonable approximation for short to medium term (say, 5 to 10 years), we simulate shocks that represent modest increase in biofuel consumption relative to the baseline. This implies mandates for 5% to 10 % market share of biofuels and emission intensity standards for 1% to 5% reduction in the average GHG intensity of transportation fuels. In fact the targets for 2015 to 2020 time frame set by the renewable fuel standard and California low carbon fuel standard lie within these ranges respectively. We assume a linear functional form for the supply function of conventional crude oil and biofuel and the also the demand for finished fuel. Given an elasticity (of supply or demand) and an observation of price and quantity, a linear function is specified. For oilsand supply we assume a hockey-stick shaped function, i.e., constant marginal cost until it reaches a rigid capacity constraint. We then simulate the policy shocks and compare outcomes relative to the baseline scenario. Biofuel consumption in the baseline scenario at a minimum equals the volume of ethanol requirements to meet the fuel oxygenate standards. The data used for model calibration and their sources are listed in the appendix in table 1.

Table 1: Sources of data

| **Parameter** | **Source of data** |
|---|---|
| Elasticity of supply of conventional crude oil | Based on range reported by [Cooper and Campus(2003)] |
| Elasticity of supply of biofuel | [Holland et al.(2009)][a] |
| Elasticity of demand for fuel | [Graham and Glaister(2004)] |
| Oil sand capacity and growth rates | Canadian Energy Research Institute ([Timilsina et al.(2005)]) |
| Fuel price, fuel consumption in 2007 and projections for future | US Energy Information Administration and International Energy Agency's World Energy Outlook 2008 |
| Cost of biofuel | USDA Survey of Ethanol Production facilities[b] |
| **GHG intensity of fuels** | |
| Conventional crude oil | US Environmental Protection Agency[c] |
| Oilsand | Based on [Bergerson and Keith(2006)]'s estimate that it is approximatey 20% higher than conventional crude oil |
| Biofuel | Based on [Farrell et al.(2006)] |

[a] We are not aware of econometrically estimates price elasticity of biofuel supply and hence use a representative similar to that assumed by [Holland et al.(2009)]

[b] *http://www.usda.gov/oce/reports/energy/usda_2002_ethanol.pdf*

[c] *http://www.epa.gov/grnpower/pubs/calcmeth.htm#oil*

Table 2 shows results for a one set of assumed elasticities and GHG intensity for biofuel (which is listed beneath the table). As the propositions show, domestic price of fuel increases and the world price of oil declines under any of the three types of policies. A 7.5% market share mandate, results in net global reduction of 100 million $tCO_2$ per year. An emission intensity standard that mandates a 3.5% reduction in the GHG intensity of liquid fuels results in the same outcome as the RFS with the difference that oilsands are not consumed domestically (the level of the emission intensity standard was computed as an outcome). With the exception of the RFS, oilsands are not consumed under domestic policies. A \$50 per $tCO_2$ fuel carbon tax achieves a similar level of emission reduction without inducing the adoption of biofuel. Even at \$100 per $tCO_2$ biofuels are not adopted suggesting that the implicit carbon price of biofuel policies is higher as several researchers have already argued before. For both the RFS and the emission intensity standard which reduce emissions by forcing the adoption of biofuels, the indirect effects on emissions are either similar in magnitude or larger compared to the direct emission reduction i.e, by one-to-one substitution of fossil fuel with biofuel. As the price impact of the policies increases, the indirect effect on emissions increases in magnitude relative to the direct emission reductions because total fuel consumption changes. We performed sensitivity analyses with respect to the various assumed parameters such as the elasticities and the GHG intensities of fuels and that found that these conclusions do not change significantly within a reasonable range of plausible values for these parameters. One interesting observation from the sensitivity analyses is that a reduction in the GHG intensity of biofuels, reduces the quantity of biofuels required under a performance-standard to achieve a given level of emission reduction compared to a mandate. A reduction in the GHG intensity of biofuel, ceteris paribus improves the viability of oilsands within the domestic region. In other words, cleaner biofuels may enable the coexistence of biofuel and oilsands even under FGIS.

## 4 Policy discussion

Economic intuition suggests performance standards like FGIS are likely to be more cost-effective compared to technology mandates like RFS because of the higher flexibility they offer in the range of actions that can be taken to achieve a given policy objective. We have shown that while this may be true when either policy is applied consistently globally or when a region is under autarky, it is not necessarily true when fuel policies are regional while the market for fuel is global. We show that a FGIS leads to both a greater reduction in domestic emissions and greater increase in emissions (and emission intensity) abroad than RFS, when both policies reach the same domestic share for renewable fuel. This implies that greater quantities of oilsands will consumed abroad while greater quantity of crude oil will be consumed at home under FGIS than under RFS. In other words

Table 2: Simulation results[*]

| Scenarios | 2007 | Baseline 2015 | RFS 7.5%[a] | FGIS[b] (RFS eq.) | FGIS[c] 5.0% | Ctax[d] 25 $/ton | Ctax 50 $/ton | Ctax 100 $/ton |
|---|---|---|---|---|---|---|---|---|
| **Oil Price** $/barrel | | | | | | | | |
| Domestic | 68 | 87.27 | 108.93 | 108.93 | 132.5 | 98.9 | 109.92 | 131.96 |
| ROW | 68 | 87.27 | 83.27 | 83.27 | 80.44 | 87.08 | 86.27 | 84.66 |
| **Fuel consumption** (mbpd)[e] | | | | | | | | |
| Domestic | 20.7 | 21.37 | 19.03 | 19.03 | 17.62 | 20.94 | 20.54 | 19.73 |
| ROW | 64.2 | 69.68 | 70.48 | 70.48 | 71.04 | 69.72 | 69.88 | 70.2 |
| Total | 84.9 | 91.05 | 89.51 | 89.51 | 88.66 | 90.66 | 90.42 | 89.93 |
| **Crude oil consumption** (mbpd) | | | | | | | | |
| Domestic | 19.3 | 19.04 | 16.64 | 19.03 | 17.62 | 20.94 | 20.54 | 19.73 |
| ROW | 64.2 | 69.68 | 70.48 | 68.09 | 68.65 | 67.33 | 67.49 | 67.81 |
| Total | 83.5 | 88.72 | 87.12 | 87.12 | 86.27 | 88.27 | 88.03 | 87.54 |
| **Oilsand consumption** (mbpd) | | | | | | | | |
| Domestic | 1.4 | 2.33 | 2.39 | 0 | 0 | 0 | 0 | 0 |
| ROW | 0 | 0 | 0 | 2.39 | 2.39 | 2.39 | 2.39 | 2.39 |
| **Biofuel consumption** (mbpd) | | | | | | | | |
| Domestic | 0.32 | 0.33 | 1.54 | 1.54 | 2.09 | 0.33 | 0.32 | 0.31 |
| **Oil outlay** ($ billion) | | | | | | | | |
| Domestic | 1407.6 | 1865 | 2073.2 | 2073.2 | 2334.1 | 2071.4 | 2257.7 | 2603.5 |
| **Emissions** (Gt $CO_2$/yr)[f] | | | | | | | | |
| Domestic | 3.66 | 3.81 | 3.58 | 3.5 | 3.33 | 3.66 | 3.59 | 3.45 |
| ROW | 11.08 | 12.03 | 12.17 | 12.24 | 12.34 | 12.11 | 12.14 | 12.2 |
| Total | 14.75 | 15.84 | 15.74 | 15.74 | 15.67 | 15.77 | 15.73 | 15.64 |
| Net change wrt 2015 baseline | | | -0.100 | -0.100 | -0.170 | -0.070 | -0.110 | -0.200 |
| Direct effect [g] | | | -0.051 | -0.051 | -0.070 | -0.011 | -0.011 | -0.010 |
| Indirect effect[h] | | | -0.049 | -0.049 | -0.100 | -0.059 | -0.099 | -0.190 |

[*] Elasticity of oil supply for US and ROW is 0.15 and 0.25 respectively, elasticity of US biofuel supply is 2, elasticity of fuel demand for US and ROW is -0.15 and -0.25 respectively. Emission intensity of corn ethanol, conventional crude oil and oilsand was assumed as 0.38, 0.47 and 0.55 tonnes of $CO_2$ per barrel of oil equivalent respectively

[a] Biofuel market share under RFS

[b] A fuel GHG standard that attains the same market share as the RFS in column 4

[c] Reduction in emission intensity mandated under an emission standard

[d] fuel carbon tax

[e] million barrels per day

[f] giga tonnes of carbon di oxide per year

[g] Direct effect is the reduction in emissions due to substitution of oil with biofuel. It equals the product of biofuel consumption and the difference in carbon intensity between crude oil and biofuel (in oil equivalent terms)

[h] Indirect effect is the difference between the net change in emissions with respect to baseline and the direct effect

GHG standards leads to more pollution shifting than RFS. To the extent that oilsands and other alternatives to crude oil such as off-shore petroleum, and coal/gas based liquids, can be considered better for energy security (say for the reason that these resources are concentrated outside of OPEC), RFS is better than FGIS because it results in more diversified fuel portfolio and global GHG emissions are similar.

A GHG tax while it may reduce GHG emissions cost-effectively, may not induce the adoption of biofuels unless the tax is large and it will exclude more GHG intensive fossil fuels like oilsands from domestic supply. A combination of GHG tax and RFS will be more cost-effective at both reducing GHG emissions and inducing adoption of renewable fuels although oilsands may remain uneconomical in the domestic market under this regime. However both GHG tax and regulations such as RFS and FGIS increase the domestic price of fuel which runs counter to a stated objective of energy policies. Biofuel subsidies are a response to this concern, which of course comes at a cost to the taxpayer. By reducing the marginal cost of driving, subsidies also reduce the GHG benefits of such policies and may also increase congestion externalities.

If policy makers hold biofuels accountable for emissions from land use change caused by biofuels, it would be consistent to take into account emissions from changes in fuel use caused by biofuels. Biofuel policies that raise domestic price have the secondary effect of reducing fuel consumption which amplifies the benefits of adopting of cleaner fuel. However, domestic biofuel policies lead to a rebound effect abroad which increases emissions. So long as biofuel policies do not lower domestic fuel price, there is a net reduction in global fuel consumption and hence a net reduction in global transportation emissions. In other words the rebound effect in ROW does not completely offset the domestic impact. There is a net indirect effect in transportation emissions, that suggests that the effective carbon intensity of biofuels is lower than that suggested by the direct lifecycle and this effect mitigates indirect emissions in agriculture. If biofuel policies lower domestic prices too, then global fuel consumption increases and there can even be a net increase in emissions. This suggests an indirect effect that amplifies indirect emissions in agriculture. While we recognize the complexity of attempting to compute the lifecycle carbon intensity taking into account indirect effects, consistency demands that either all such effects be considered.

One simplification in our model is that we assume there exists one type of clean alternative to oil, namely, biofuel and that there exists one type of biofuel. For instance, if import tariffs on ethanol are eliminated then the comparison is more complex and depends on the interpretation of the impact of biofuel imports on energy security. We will address this future work. Another assumption in our model that transportation cost is small relative to marginal cost of production. Most of the deposits of oilsands are located in Canada and a large part of investment in oilsand is aimed at meeting US demand for oil. If difference in oil transportation cost to US and to other markets is small, US policies that discourage oilsands will indeed result in these fuels being shipped to those other markets. However, if transportation costs are significant, then any carbon-based policy such as carbon standard or tax, will slow the rate of expansion in capacity for oilsand extraction. Under these conditions, the relative disadvantage of GHG tax and FGIS vis-a-vis RFS in terms of fuel shifting is diminished. Analyzing this effect requires a dynamic framework and is planed for future research. We also plan to extend the model to consider multiple types of biofuels. Another assumption is that the oil market is competitive while it is widely believed that OPEC cartel behaves like a dominant producer. Analyzing the impact of RFS under two different assumptions about OPEC behavior Hochman et al. [Hochman et al. (2010a)] show that OPEC mitigates the reduction in world price due to biofuels but does not alter the qualitative conclusions of the competitive model.

## 5 Conclusion

Biofuel policies are costlier than GHG tax for addressing climate change and reducing dependence on oil and reflect distributional considerations. Biofuel regulations represent a (large) implicit tax on domestic fuel consumers (at least in the short-run when they raise fuel prices) and on producers of fossil fuel and an implicit subsidy to biofuel and agricultural producers. Domestic fuel policies and GHG policies also represent an implicit subsidy for fuel consumers abroad who increase their fossil fuel consumption and therefore GHG emissions. This suggests the importance of striving for international agreement on climate change. Biofuel policies may also reflect a perspective that alternative fuels are an infant industry characterized by learning-by-doing externalities and supporting them will render these industries competitive in the long-run [Feder and Schmitz(1976)]. This is an area for empirical research.

**Acknowledgements** We thank the Energy Biosciences Institute for funding support. The views expressed herein are those of the authors only and do not reflect those of the institution supporting this research. We thank Richard Norgaard for insightful comments on a earlier draft which helped us in improving our paper.

## References

[ARB(2009)] ARB. Proposed Regulation to Implement the Low Carbon Fuel Standard, Volume I Staff Report: Initial Statement of Reasons. California Environmental Protection Agency and

Air Resources Board, 2009.

[Bennear and Stavins(2007)] L.S. Bennear and R.N. Stavins. Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics*, 37(1):111–129, 2007.

[Bergerson and Keith(2006)] J. Bergerson and D. Keith. Life cycle assessment of oil sands technologies. *Institute for Sustainable Energy, Environment and Economy, Univ. of Calgary*, 2006.

[Bushnell et al.(2008)] J. Bushnell, C. Peterman, and C. Wolfram. Local solutions to global problems: Climate change policies and regulatory jurisdiction. *Review of Environmental Economics and Policy*, 2(2):175, 2008.

[CBO(2007)] CBO. Energy Independence and Security Act of 2007: A Summary of Major Provisions , Congressional Research Service Report to Congress. Technical report, Congressional Budget Office, 2007.

[Cooper and Campus(2003)] J.C.B. Cooper and C. Campus. Price elasticity of demand for crude oil: estimates for 23 countries. *OPEC review*, 27:1–8, 2003.

[Creyts(2007)] J.C. Creyts. *Reducing US greenhouse gas emissions: how much at what cost?: US Greenhouse Gas Abatement Mapping Initiative.* McKinsey & Co., 2007.

[De Gorter and Just(2009)] H. De Gorter and D.R. Just. The welfare economics of a biofuel tax credit and the interaction effects with price contingent farm subsidies. *American Journal of Agricultural Economics*, 91(2):477–488, 2009.

[Farrell et al.(2006)] A.E. Farrell, R.J. Plevin, B.T. Turner, A.D. Jones, M. O'hare, and D.M. Kammen. Ethanol can contribute to energy and environmental goals. *Science*, 311(5760):506, 2006.

[Feder and Schmitz(1976)] G. Feder and A. Schmitz. Learning by Doing and Infant Industry Protection: A Partial Equilibrium Approach. *The Review of Economic Studies*, 43(1):175–178, 1976.

[Fischer and Newell(2008)] C. Fischer and R.G. Newell. Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2):142 – 162, 2008.

[Graham and Glaister(2004)] D.J. Graham and S. Glaister. Road traffic demand elasticity estimates: a review. *Transport Reviews*, 24(3):261–274, 2004.

[Hochman et al. (2010a)] G. Hochman, D. Rajagopal, and D. Zilberman. The Effect of Biofuels on Crude Oil Markets. *Agbioforum*, 2010(forthcoming).

[Holland et al.(2009)] S.P. Holland, J.E. Hughes, and C.R. Knittel. Greenhouse Gas Reductions under Low Carbon Fuel Standards? *American Economic Journal: Economic Policy*, 1(1): 106–146, 2009.

[Khanna et al.(2008)] M. Khanna, A.W. Ando, and F. Taheripour. Welfare effects and unintended consequences of ethanol subsidies. *Applied Economic Perspectives and Policy*, 30(3):411, 2008.

[Lapan and Moschini(2009)] H.E. Lapan and G.C. Moschini. Biofuels policies and welfare: Is the stick of mandates better than the carrot of subsidies? *Staff General Research Papers*, 2009.

[Leiby(2008)] Paul N. Leiby. Estimating the energy security benefits of reduced u.s. oil imports. Technical Report ORNL/TM-2007/028, Oak Ridge National Laboratory, 2008.

[Martinot and Sawin(2009)] E. Martinot and J. Sawin. Renewables Global status report: 2009 Update. *REN21 Renewable Energy Policy Network and Worldwatch Institute*, 2009.

[Rajagopal et al.(2007)] D. Rajagopal, SE Sexton, D. Roland-Holst, and D. Zilberman. Challenge of biofuel: filling the tank without emptying the stomach. *Environmental Research Letters*, 2 (9), 2007.

[Rajagopal et al.(2009)] D. Rajagopal, S. Sexton, G. Hochman, and D. Zilberman. Recent Developments in Renewable Technologies: R&D Investment in Advanced Biofuels. *Annual Review of Resource Economics*, 1(1), 2009.

[Sobrino and Monroy(2009)] F.H. Sobrino and C.R. Monroy. Critical analysis of the European Union directive which regulates the use of biofuels: An approach to the Spanish case. *Renewable and Sustainable Energy Reviews*, 2009.

[Timilsina et al.(2005)] GR Timilsina, N. LeBlanc, and T. Walden. Economic impacts of alberta's oil sands. canadian energy research institute, calgary, ab, 2005.

[Tinbergen(1952)] J. Tinbergen. On the theory of economic policy. *Amsterdã: North Holland*, 1952.

## Appendix: Mathematical proofs

**System of equations for a global RFS (fixed market share -$\bar{\alpha}$):** For global policies, we drop the superscripts $h$ and $a$ and rewrite the system of equations (5). Let subscript $ff$ denote the world fossil fuel price and $p$ the world price of transport fuel. The equilibrium under the RFS is defined by the following equations,

$$\frac{q_b}{q_c + q_{os} + q_b} = \bar{\alpha} \tag{7a}$$

$$p = (1 - \bar{\alpha})p_{ff} + \bar{\alpha}p_b \tag{7b}$$

$$p = D^{-1}(q_c + q_{os} + q_b) \tag{7c}$$

$$p_{ff} = S_c^{-1}(q_c) \tag{7d}$$

$$p_{ff} = S_{os}^{-1}(q_{os}) \tag{7e}$$

$$p_b = S_b^{-1}(q_b) \tag{7f}$$

We can solve the 6 equations for the 6 unknowns, namely, $p, p_{ff}, p_b, q_c, q_{os}$, and $q_b$

**System of equations for a global FGIS,** $\bar{z}$: For global policies, we drop the superscripts $h$ and $a$ and rewrite the system of equations (6). The equilibrium under the FGIS is defined by the following equations,

$$\frac{z_c q_c + z_{os} q_{os} + z_b q_b}{q_c + q_{os} + q_b} = \bar{z} \tag{8a}$$

$$p = (1 - \alpha_c)p_c + \alpha_c p_b \tag{8b}$$

$$p = (1 - \alpha_{os})p_{os} + \alpha_{os} p_b \tag{8c}$$

$$p = D^{-1}(q_c + q_{os} + q_b) \tag{8d}$$

$$p_b = S_b^{-1}(q_b) \tag{8e}$$

$$p_c = S_c^{-1}(q_c) \tag{8f}$$

$$p_{os} = S_{os}^{-1}(q_{os}) \tag{8g}$$

We can solve the 7 equations for the 7 unknowns, namely, $p, p_c, p_{os}, p_b, q_c, q_{os}$, and $q_b$. Note that unlike with the a RFS, we now have different prices for fossil fuels that differ in their carbon intensities under a FGIS.

**Proof of proposition 1**: Derivation of proof to show price may increase or decrease under a RFS. For simplicity and without loss of generality assume only one type of fossil, denoted by subscript $f$. The system of equations for the RFS can be written as,

$$\begin{aligned}
\frac{q_b}{q_f + q_b} &= \bar{\alpha} \text{ (RFS)} \\
p &= (1-\bar{\alpha})p_w + \bar{\alpha}p_b \text{ (competitive blending condition)} \\
p &= D^{-1}(q_f + q_b) \text{ (demand equation)}
\end{aligned} \tag{9}$$

Completely differentiating the equations

$$\begin{aligned}
\frac{d\bar{\alpha}}{\bar{\alpha}} &= (1-\bar{\alpha})\frac{dq_b}{q_b} - \bar{\alpha}\frac{dq_f}{q_b} \\
dp &= (1-\bar{\alpha})\frac{\partial S_f^{-1}(q_f)}{\partial q_f}dq_f + \bar{\alpha}\frac{\partial S_b^{-1}(q_b)}{\partial q_b}dq_b + (S_b^{-1}(q_b) - S_f^{-1}(q_f))d\bar{\alpha} \\
dp &= \frac{\partial D^{-1}(q_f + q_b)}{\partial(q_f + q_b)}(dq_f + dq_b)
\end{aligned} \tag{10}$$

Rearranging the equations we can write

$$\begin{aligned}
\frac{dp}{d\bar{\alpha}} &= \frac{[a - b - c(e-f)]\, d}{ae - bf - d(e-f)} \\
\frac{dq_b}{d\bar{\alpha}} &= \frac{a - d + cf}{ae - bf - d(e-f)} \\
\frac{dq_f}{d\bar{\alpha}} &= -\frac{b - d + ce}{ae - bf - d(e-f)} < 0
\end{aligned} \tag{11}$$

where

$$a = (1-\bar{\alpha})\tfrac{\partial S_f^{-1}(q_f)}{\partial q_f} > 0, \quad b = \bar{\alpha}\tfrac{\partial S_b^{-1}(q_b)}{\partial q_b} > 0, \quad c = S_b^{-1}(q_b) - S_f^{-1}(q_f) > 0$$

$$d = \tfrac{\partial D^{-}1(q_f+q_b)}{\partial(q_f+q_b)} < 0, \qquad e = \tfrac{\bar{\alpha}(1-\bar{\alpha})}{q_b} > 0, \qquad f = \tfrac{-\bar{\alpha}^2}{q_b} < 0$$

Since the denominator term in the comparative static expressions in equations (11), $ae - bf - d(e-f) > 0$ and $d < 0$, therefore,

$$\begin{aligned}
sign(\frac{dp}{d\bar{\alpha}}) &= -sign([a - b - c(e-f)]) \\
&= sign\left((1-\bar{\alpha})\frac{\partial S_f^{-1}}{\partial q_f} - \bar{\alpha}\frac{\partial S_b^{-1}}{\partial q_b} - (S_b^{-1} - S_f^{-1})(\frac{\bar{\alpha}(1-\bar{\alpha})}{q_b} - \frac{-\bar{\alpha}^2}{q_b}\right)
\end{aligned}$$

Let $\eta$ denote the supply elasticity. Then $\eta_j = \frac{\partial q_j}{\partial S_j^{-1}(q_j)} \frac{S_j^{-1}(q_j)}{q_j}$, where,$j \in (f, b)$. Substituting for $\eta$,

$$sign(\frac{dp}{d\bar{\alpha}}) \quad = \quad sign\left( \frac{(1-\bar{\alpha})S_f^{-1}(q_f)}{q_f \eta_f} - \frac{\bar{\alpha} S_b^{-1}(q_b)}{q_b \eta_b} - (S_b^{-1}(q_b) - S_f^{-1}(q_f))\frac{\bar{\alpha}}{q_b} \right)$$

Substituting $\frac{\bar{\alpha}}{q_b} = \frac{1-\bar{\alpha}}{q_f}$

$$\begin{aligned} sign(\frac{dp}{d\bar{\alpha}}) &= \frac{\bar{\alpha}}{q_b} sign\left( \frac{S_f^{-1}(q_f)}{\eta_f} - \frac{S_b^{-1}(q_b)}{\eta_b} - \left[ S_b^{-1}(q_b) - S_f^{-1}(q_f) \right] \right) \\ &= sign\left( S_f^{-1}(q_f)\left[\frac{1}{\eta_f} + 1\right] - S_b^{-1}(q_b)\left[\frac{1}{\eta_b} + 1\right] \right) \end{aligned}$$

$$\Rightarrow \frac{dp}{d\bar{\alpha}} > (<)0 \text{ if } S_f^{-1}(q_f)\left[\frac{1}{\eta_f} + 1\right] - S_b^{-1}(q_b)\left[\frac{1}{\eta_b} + 1\right] < (>)0 \tag{12}$$

If $mc$ denotes marginal cost, then $\frac{dp}{d\bar{\alpha}} > (<)0$ if $\frac{mc_f}{mc_b} < (>)\frac{\frac{1}{\eta_b}+1}{\frac{1}{\eta_f}+1}$. When fossil fuel supply is perfectly elastic, i.e, $\eta_f = \infty$ then the right hand side becomes $\frac{1}{\eta_b} + 1$ which is $> 1$ since $\eta_b > 0$. But $\frac{mc_f}{mc_b} < 1$ because of our assumption that policy is binding. This implies $\frac{dp}{d\bar{\alpha}} > 0$. On the other hand, when fuel supply is perfectly inelastic, i.e, $\eta_f = 0$ then the right hand side becomes $\frac{\frac{1}{\eta_b}+1}{\frac{1}{\infty}+1} = 0$. Since $0 < \frac{mc_f}{mc_b} < 1$, this implies $\frac{dp}{d\bar{\alpha}} < 0$. This implies that higher (lower) the elasticity of fossil fuel supply less (more) likely the reduction in fuel price due to clean fuel policies.

A similar proof can be derived under a fuel GHG standard, $\bar{z}$. Under the FGIS, the system of equations (9) become,

$$\begin{aligned} \alpha z_b + (1-\alpha) z_f &= \bar{z} \text{ (FGIS)} \\ p &= (1-\alpha)p_w + \alpha p_b \text{ (competitive blending condition)} \\ p &= D^{-1}(q_f + q_b) \text{ (demand equation)} \\ where, & \\ \alpha &= \frac{q_b}{q_f + q_b} \end{aligned} \tag{13}$$

Completely differentiating the first equation we get, $\frac{d\alpha}{d\bar{z}} = \frac{-1}{z_f - z_b} < 0$. As the FGIS becomes more stringent i.e., $d\bar{z} < 0$, a higher blend ratio is required i.e., it mimics stringent RFS. The remaining three equations in the above system are similar to those for the RFS, except that now the blending ration $\alpha$ is determined by the stringency of the FGIS, $\bar{z}$ and the GHG intensities of the fossil and biofuels.

**Impact of blending subsidy,** $s$ **per unit of biofuel**: With a blending subsidy the system of equations for the RFS(9) now become,

$$\begin{aligned}
\frac{q_b}{q_f + q_b} &= \bar{\alpha} \text{ (RFS)} \\
p &= (1-\bar{\alpha})p_w + \bar{\alpha}(p_b - s) \text{ (competitive blending condition)} \\
p &= D^{-1}(q_f + q_b) \text{ (demand equation)}
\end{aligned} \tag{14}$$

Completely differentiating the equations

$$\begin{aligned}
\frac{d\bar{\alpha}}{\bar{\alpha}} &= (1-\bar{\alpha})\frac{dq_b}{q_b} - \bar{\alpha}\frac{dq_f}{q_b} \\
dp &= (1-\bar{\alpha})\frac{\partial S_f^{-1}(q_f)}{\partial q_f}dq_f + (S_b^{-1}(q_b) - S_f^{-1}(q_f))d\bar{\alpha} + \bar{\alpha}(\frac{\partial S_b^{-1}(q_b)}{\partial q_b}dq_b - ds) \\
dp &= \frac{\partial D^{-1}(q_f + q_b)}{\partial(q_f + q_b)}(dq_f + dq_b)
\end{aligned} \tag{15}$$

Equation (12) now becomes

$$\frac{dp}{d\bar{\alpha}} > (<)0 \text{ if } S_f^{-1}(q_f)\left[\frac{1}{\eta_f} + 1\right] - S_b^{-1}(q_b)\left[\frac{1}{\eta_b} + 1\right] - s < (>)0 \tag{16}$$

To analyze the impact of a change in the level of subsidy, holding the RFS fixed, set $d\bar{\alpha} = 0$. Rearranging the equations we can write

$$\begin{aligned}
\frac{dp}{ds} &= \frac{\bar{\alpha}d(e-f)}{ae - bf - d(e-f)} < 0 \\
\frac{dq_b}{ds} &= \frac{-\bar{\alpha}f}{ae - bf - d(e-f)} > 0 \\
\frac{dq_f}{ds} &= \frac{\bar{\alpha}e}{ae - bf - d(e-f)} > 0
\end{aligned} \tag{17}$$

$$\tag{18}$$

Holding the stringency of the regulation fixed, increasing the subsidy reduces the lowers the fuel price and increases consumption of both biofuel and fossil fuel and thereby increases total emissions $(\frac{dZ}{ds} = z_b\frac{dq_b}{ds} + z_f\frac{dq_f}{ds} > 0)$.

**Proof of proposition 4**: Derivation of proof to show world fossil fuel price decreases under any home policy

Rearranging the equations we can write

$$\begin{aligned}
\frac{dp^w}{d\bar{\alpha}} &= \frac{-\left[ae - f + dg\right]hi}{afh - afi - bfh + bfi + achi + bdgh - bdgi} < 0 \\
\frac{dq_f^h}{d\bar{\alpha}} &= \frac{-\left[fh - fi - aeh + aei - dgh + dgi\right]}{afh - afi - bfh + bfi + achi + bdgh - bdgi} < 0 \\
\frac{dq_f^a}{d\bar{\alpha}} &= \frac{-\left[aeh - fh + dgh\right]}{afh - afi - bfh + bfi + achi + bdgh - bdgi} > 0
\end{aligned}$$

where,

$$\begin{array}{lll}
a = \frac{\bar{\alpha}(1-\bar{\alpha})}{q_b^h} > 0, & b = \frac{-\bar{\alpha}^2}{q_b^h} < 0, & c = (1-\bar{\alpha})\frac{\partial S_f^{-1}}{\partial q_f} > 0 \\
d = \bar{\alpha}\frac{\partial S_b^{-1}(q_b)}{\partial q_b} > 0, & e = S_b^{-1} - S_f^{-1} > 0, & f = \frac{\partial D^-1(q_f^h+q_b^h)}{\partial(q_f^h+q_b^h)} < 0 \\
g = \frac{\partial S_b^{-1}(q_b^h)}{\partial q_b^h} > 0, & h = \frac{\partial S_f^{-1}(q_f^h+q_f^a)}{\partial(q_f^h+q_f^a)} > 0, & i = \frac{\partial D^-1(q_f^a)}{\partial q_f^a} < 0
\end{array}$$

**Proposition 5**: Revised system of equations for FGIS as a result of proposition 5.

$$\frac{z_c q_c^h + z_b q_b^h}{q_c + q_b^h} = \bar{z} \tag{19a}$$

$$p^h = (1-\alpha_c)p^w + \alpha_c p_b \tag{19b}$$

$$p^h = D^{h^{-1}}(q_c^h + q_b^h) \tag{19c}$$

$$p_b = S_b^{-1}(q_b) \tag{19d}$$

$$p^w = D^{a^{-1}}(q_c^a + q_{os}) \tag{19e}$$

$$p^w = S_c^{-1}(q_c^h + q_c^a) \tag{19f}$$

$$p^w = S_{os}^{-1}(q_{os}) \tag{19g}$$

Solve the 7 equations for $p^w, p^h, p_b, q_c^h, q_b^h, q_c^a$, and $q_{os}$