The effect of biofuel on the international oil market*

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Abstract

This paper derives a method to quantify the short- to medium-run impact of biofuel on fuel markets, assuming that these markets are dominated by cartel of oil-rich countries, and that prices in these countries are set to maximize the sum of domestic consumer and producer surplus, leading to a wedge between domestic and international fuel prices. We model this behavior by applying the optimal export tax model (henceforth, the cartel-of-nations model) to the fuel markets. Using data from 2007 to calibrate the model, we show that the introduction of biofuels lowered global gasoline and diesel consumption and international fuel prices by about 1% and 2%, respectively. We identify large differences between the effects of introducing biofuels using the cartel-of-nations model, in contrast to the competitive or the standard cartel model (henceforth, the cartel-of-firms model). We illustrate that assessing the effect of biofuels assuming competitive fuel markets overestimates the reduction in fuel price, and underestimates the reduction of gasoline and diesel consumption, and therefore impact of biofuels on greenhouse gas emissions, when compared to the effect under a cartel-of-nations model. Similar conclusions are derived with respect to cartel-of-firms model. Finally, we illustrate that a 20% increase in fuel demand more than doubles the impact of biofuels on fuel markets, compared to 2007.

JEL code: F1, Q4

Key words: Energy, OPEC, biofuel, fuel, carbon savings, optimal export tax model, cheap oil

1 Introduction

Concerns about energy security and high oil prices, as well as greenhouse gases, led to policies that promoted the use of biofuels (e.g., the American Clean Energy and Security Act of 2009[1]; The European Strategy for Sustainable, Competitive and Secure Energy, 2006[2]). Yet, the effects of the introduction of biofuels on fuel markets are not fully understood. Recent studies on the effect of biofuels assume competitive fuel markets (e.g., Rajagopal et al. 2007; de Gorter and Just 2008; Gardner 1987), thus ignoring the Organization of Petroleum Exporting Countries (OPEC). This paper introduces an alternative framework to analyze how OPEC responds to growing biofuel use, which we use to estimate the short- to medium-run effect of biofuel on the fuel markets. Specifically, we discuss the short-run effect of biofuel on fuel prices, quantity consumed, carbon emissions, and the distribution of costs and benefits from biofuel.

The starting point of our analysis is the observation that fuel prices in oil exporting nations are lower than in oil importing nations, and the recognition that OPEC nations cooperate when making oil production decisions. Therefore, we do not model OPEC as a cartel-of-firms (henceforth, COF), which would not allow a wedge between prices among exporting and importing countries, but rather as a cartel-of-nations (henceforth, CON). While building on the traditional optimal export tax model, we model the CON model assuming that oil-exporting countries operate as one unit that maximize the sum of domestic consumer and producer surplus from oil production and fuel consumption, resulting in a wedge between prices in oil-exporting countries and oil-importing countries. This wedge equals the optimal export tax. We also assume biofuel represents a competitive fringe, which affects oil-exporting countries' decision making, and that oil-importing countries behave competitively.[3]

We begin by assuming CON and showing conceptually that OPEC responds to the introduction of biofuels by reducing exports, but increasing domestic consumption, more than suggested by the COM and COF models. Under the CON model, the domestic consumer benefit from fuel consumption, in addition to profits from fuel production, affects OPEC's production decisions. More specifically, we show that the impact of the introduction of biofuels on the amount of gasoline and diesel consumed is largest under the COF model, but smallest under the COM model. On the other hand, although the decline in prices in oil-importing countries due to biofuels is largest under COM, it is smallest under CON not COF.

We then calibrate the model to 2007 data, and estimate that biofuel production in 2007 increased fuel subsidies in OPEC countries by 2%-3%, and it reduced world fuel prices by 2%. On the other

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[1] http://www.govtrack.us/congress/billtext.xpd?bill=h111-2454

[2] http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf

[3] Although theoretically, large oil consuming countries can exercise their monopsony power and impact the international price of crude oil (for example, by levying an import tariffs or quota), the reality is that in the short-run most oil consuming countries have limited scope for adjusting oil supply or demand, particularly as oil demand becomes increasingly concentrated in the transportation sector (IEA 2005) and that the demand for oil in the light duty vehicle sector is becoming increasingly inelastic (Hughes et al. 2008). Having said that, Leiby (2007) calculates that the oil import premium is $13.60 per barrel (in 2004 dollars), with a wide 90% confidence interval ($6.70 - $23.25).

hand, the introduction of biofuels caused the annual consumption of gasoline and diesel to decline by about 1.2 billion gallons a year, i.e., about 1% of total consumption. We also compute total change in carbon emissions due to the introduction of biofuels, using the average per unit carbon footprints of different fuel feedstock. We show that with corn ethanol the CON model results in the smallest increase in greenhouse gas (GHG) emissions, and that the difference between CON and COM are large. We also show that there is a potential for GHG emission savings with the introduction of second-generation of cellulosic biofuels.

Our analysis shows that the model used to characterize the energy market affects the estimates of the effects of biofuels on consumption and production. For example, when compared to the CON model, we show that competition overestimates the price effect, but underestimates both quantity and environmental effects attributed to the introduction of biofuels (the environmental effect is underestimated by about 40%). The impact of biofuel on the oil economy is likely to increase in the future as demand for fuel increases. Assuming fuel demand increases by 20%, we estimate that biofuel consumption as well as its effect on prices will double, and thus the magnitude of the difference between CON and the COM or the COF models becomes even more significant.

Section 2 below describes alternative frameworks used to model oil-exporting countries, and the outcomes under the alternative models are compared in Section 3. The calibration is described in Section 4, whereas the data used is presented in Section 5. The results of the numerical analysis is presented in Section 6. Policy implications and concluding remarks are given in Section 7.

2 OPEC and biofuel: A conceptual framework

Our objective is to introduce biofuels into fuel markets, recognizing that these markets are dominated by a cartel of oil-rich nations, and that there is a wedge between the price in oil-rich countries and in oil-importing countries (Metschies et al., 2007).

The existing literature on biofuels, as well as literature on food versus fuel assumes a competitive fuel market (e.g., Rajagopal et al. 2009; FAO 2008; Abbott et al. 2008). On the other hand, the literature on crude oil usually assumes a COF model employing a static or a dynamic framework (e.g., Adelman 1982; Griffin 1985; Lin 2007).[4] The former literature ignores OPEC, whereas the latter ignores the wedge between domestic and international prices. Unlike the above models, the CON model does capture the wedge we observe in the data and does model OPEC's pricing behavior.[5] With the CON model, the baseline model in this paper, governments in oil-exporting countries set

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[4] A few have also argued that OPEC is a revenue-maximizing entity (e.g., Teece 1982); OPEC is driven mostly by political motives (e.g., Moran 1982); and that OPEC core members behave as a dominant, profit-maximizing firm, while other members respond to a different set of incentives (e.g., Alhajji and Huettner 2000).

[5] Hochman and Zilberman (2010) showed, using data on gasoline prices during the late 1990s to early 2000s, that the CON model explains OPEC's behavior well.

prices to maximize the sum of domestic consumer and producer surplus from fuel consumption and production.

We employ a static partial equilibrium analysis to model the global fuel market, while considering two countries: an oil-rich country (denoted country H, which can be interpreted as OPEC) and an oil-importing country (denoted country F). Country F's variables are denoted with asterisk (*), country H variables with no asterisk.

2.1 The international fuel market

Initially, we assume no biofuels. Country H produces Q units of fuel, with X units sold domestically and M units sold abroad. The price of fuel in country H is p, whereas it is p^* in country F.[6] MC denotes the marginal cost of fuel production. While early papers found support for the Hotelling Valuation Principle (e.g., Miller and Upton, 1985), recent papers did not find such support (e.g., Adelman and Watkins, 1995) and showed using oil and gas transaction data that reserve asset values are much smaller than the values predicted by the Hotelling theory and are considerably below net wellhead prices. We, therefore, remain agnostic to dynamic facets of gasoline and diesel production and do not distinguish between marginal and user costs.[7] Furthermore, our partial equilibrium analysis does not explicitly add the cost of pollution to the oil-exporting country's decision process, a country that produces and consumes fuel extracted and produced from crude but not from biofuels. We do, however, compute the change in GHG emissions due to the introduction of biofuels.

We present and contrast three alternative market structures: the COM, the COF, and the CON models. Whereas the COM market structure suggests demand equals supply and the fuel price equals marginal cost, under the COF model oil firms' maximize their joint profits. Policy in the CON model, in contrast to the other two models, is set to maximize oil-exporting countries' consumer and producer surplus from fuel production and consumption.

More specifically, under a COM model $p = p^* = MC$. Given no-transaction costs and no market power, the fuel price in H equals the price in F. Then, since firms are price takers, the price equals the marginal cost of production. The equilibrium outcome is depicted in Fig. 1, where aggregate demand for fuel is denoted $D + D^*$, such that the oil-exporting and oil-importing countries' demand functions are D and D^*, respectively. Let S denote supply of gasoline and diesel, and the equilibrium point, denoted A in Fig. 1, is obtained at quantity Q_{COM} and price $p_{COM} = p^*_{COM}$.

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[6] For simplicity and without loss of generality we assumed fossil fuel is produced only in country H. Alternatively, we can assume country F imports oil, and derive country F's import demand curve, i.e., aggregate demand in country F minus domestic production.

[7] Having said that, dynamic facets of gasoline and diesel, such as capital or interest costs, can be explicitly introduced to the analysis as user costs, which measure the cost incurred over a period of time as a consequence of extracting crude oil.

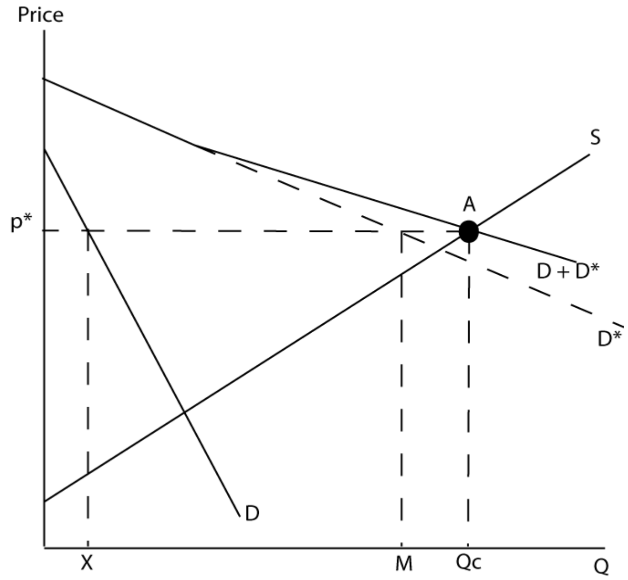

Figure 1: The COM model

The COF model, on the other hand, assumes firms collude and form a cartel (see Fig. 2). Then, in equilibrium $MR = \partial\left(\left(D + D^*\right) \cdot p\right) / \partial Q = MC$. In other words, marginal revenue equals marginal cost and $p_{COF} = p^*_{COF} > MC$. When compared to the COM equilibrium, the COF equilibrium, denoted point B in Fig. 2, yields a higher price to both domestic and foreign consumers. Although this theory explains why fuel prices are higher than marginal cost, the COF model does not explain the observed wedge between oil-exporting and oil-importing countries' fuel prices.

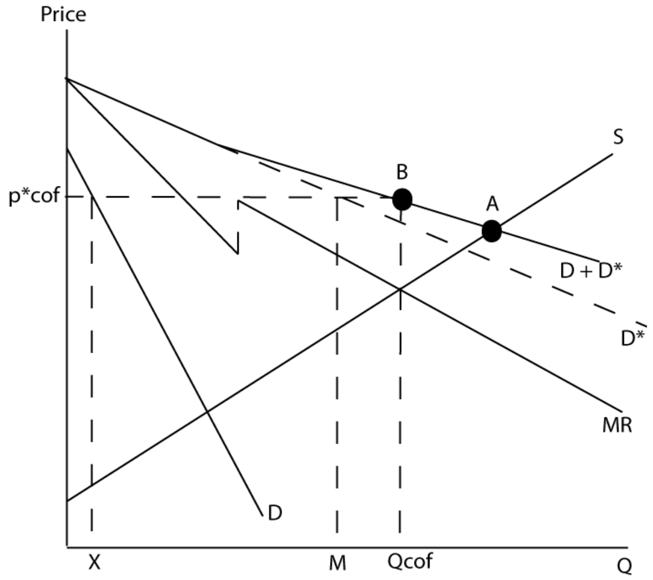

Figure 2: The COF model

Finally, the CON model assumes politicians in the exporting country design the export tax to maximize the sum of its consumers' and producers' net welfare plus export tax revenues. The optimal

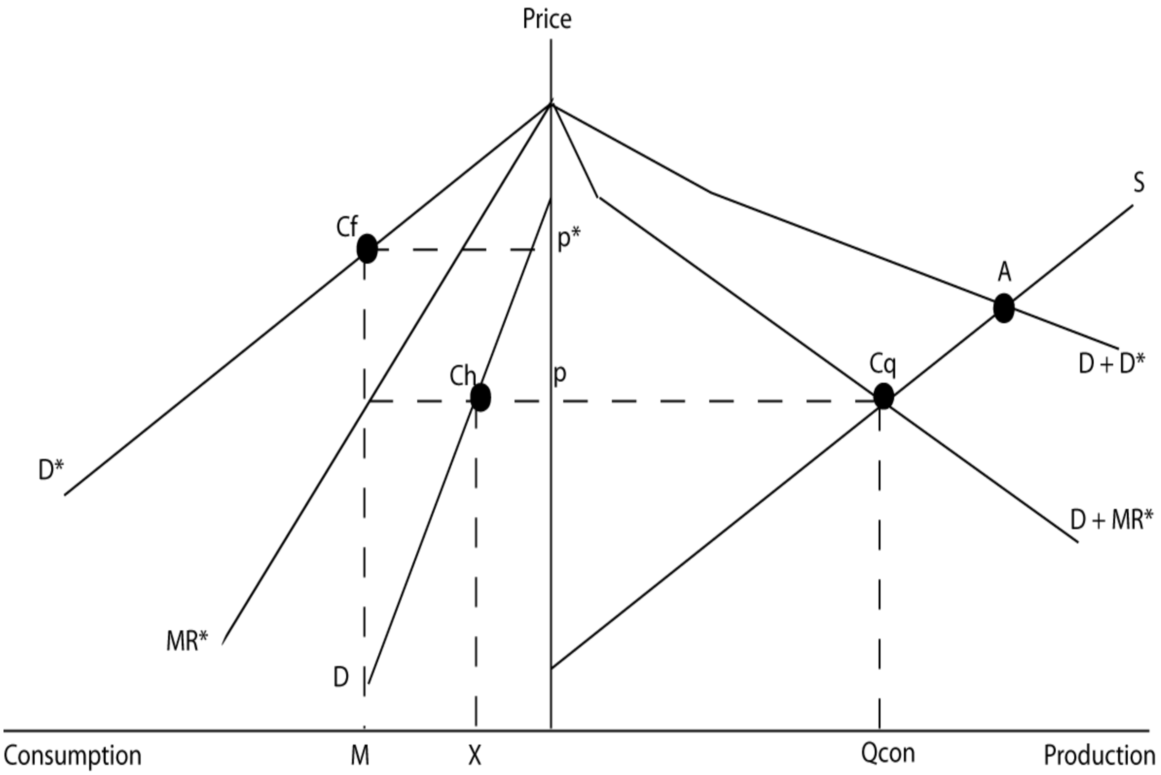

Figure 3: Export tax

allocation rule is then derived, assuming firms are price takers and country H has monopoly power in international markets (captured by points C_Q, C_H, and C_F in Fig. 3). The left-hand part of Fig. 3 depicts consumption, whereas the right-hand side depicts production. The marginal import revenue curve, $MR^* = \partial (p^* \cdot M) / \partial M$, is added to the domestic demand curve, D, to yield the kink curve $D + {MR^*}^{-1}$. The intersection of this curve with the marginal cost curve, S, yields total fuel output, Q_{CON}, which results in export and domestic consumption levels, X_{CON} and M_{CON}, respectively. In this case, p_{CON} denotes domestic price and the import price (world price) $p^*_{CON} > p_{CON}$. To implement this policy, the export tax should equal $p^*_{CON} - p_{CON}$. Such a policy can also be implemented with a quota, Q_{CON}, and a domestic consumption subsidy equal to $p^*_{CON} - p_{CON}$. Henceforth, and for simplicity, we focus on an optimal export tax.

As the CON model suggests, consumers of gasoline and diesel in oil-rich countries pay a significantly lower price at the pump, compared with the price paid by consumers in oil-importing countries (Metschies et al. 2007). Whereas in 2006 super gasoline prices in non-OPEC countries equaled, on average, 1.04 US$ per liter, it equaled only 0.28 US$ per liter in OPEC countries (Metschies et al. 2007). Moreover, nominal subsidies went up in OPEC countries, at times when crude oil prices surged during 2002 to 2006 (Metschies et al. 2007). A similar pattern is observed for diesel prices, such that diesel prices in non-OPEC countries equal 0.9 US$, but they only equal 0.26 US$ in OPEC countries.

2.2 Introducing biofuels into the international fuel market

We now introduce biofuels, denoted B, to fuel markets, such that global fuel consumption equals $Q + B$. Biofuels are liquid substitutes to gasoline and diesel that are derived from grains, sugar, and oil seeds.[8] We assume oil and biofuel feedstock are used to produce fuel, which is measured in terms of gasoline-equivalent energy units. Conceptually, normalizing fuel to a common denominator equalizes fuel prices, independent of the feedstock used. This performs relatively well when we use annual 2007 fuel prices in the United States, in part because biofuel mandates in the United States did not bind for most of 2007 and mandates do not exist in Brazil.[9] Allowing the difference between biofuels and gasoline and diesel prices to vary does not alter the results qualitatively, although it does affect the magnitude of the difference between the price of fuel in oil-importing and oil-exporting countries.

About 50% of biofuel production costs come from the feedstock itself (National Renewable Energy Laboratory website), which is purchased from multiple (farm) locations (for example, 72% of farms in the U. S. plant less than 250 acres of corn per farm). The bio-refinery uses the feedstock to produce a spectrum of products (i.e., food, feed, materials, and chemicals) and energy (fuels, power, and heat), and its scale of operation is much smaller than a petroleum refinery. For instance, the average capacity of a bio-refinery in the United States is 47 million gasoline-equivalent gallons (GEG) per year,[10] whereas the capacity of the average oil refinery in the United States is 871 million gasoline gallons. In Brazil, on the other hand, there were 378 ethanol plants operating by July 2008, 126 dedicated to ethanol production and 252 producing both sugar and ethanol. We, therefore, assumed the biofuel industry behaves competitively, and biofuel is produced by producers located in the country F, i.e., the oil-importing country. OPEC has vast oil reserves, whereas the oil-importing countries have access to biomass and the technology needed to convert it to biofuels. These assumptions capture the structure of the global fuel markets, whereby on the one hand crude oil extraction is concentrated in a region that does not produce biofuels, and on the other hand trade in biofuels is concentrated among oil-importing countries.[11]

For simplicity, we focus on the effect of biofuel on world fuel markets assuming the CON model. Fig. 4 depicts the fuel market, which now includes biofuels (the red curves). The supply of biofuels reduces demand for gasoline and diesel to $D^{*'}$, such that $D^{*'} = D^{*}_{fuel} - B$. The larger the international price of fuel, the larger is the quantity supplied of biofuels and, therefore, the smaller is the quantity of gasoline and diesel imported to country F. The gap between $D^{*'}$ and D^{*} widens as the price increases.

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[8] For a comprehensive survey on biofuels, their economic impacts, as well as their environmental implications, see Rajagopal and Zilberman (2008).

[9] For more on the theoretical relation between ethanol and gasoline prices, in the absence of a mandate, see de Gorter and Just (2008), Wallace and Taheripour (2008) and Hochman et al. (2010).

[10] The data were collected on July 14, 2009, from http://www.ethanolrfa.org/industry/locations/

[11] In reality, there is trade in biofuels, but it is concentrated among non-OPEC countries, which in our simple model are treated as one group. In principle, however, the model may allow OPEC countries to import biofuel. Because OPEC countries subsidize gasoline, it makes importing biofuel not profitable. We, therefore, excluded this possibility for simplicity and tractability from the numerical analysis.

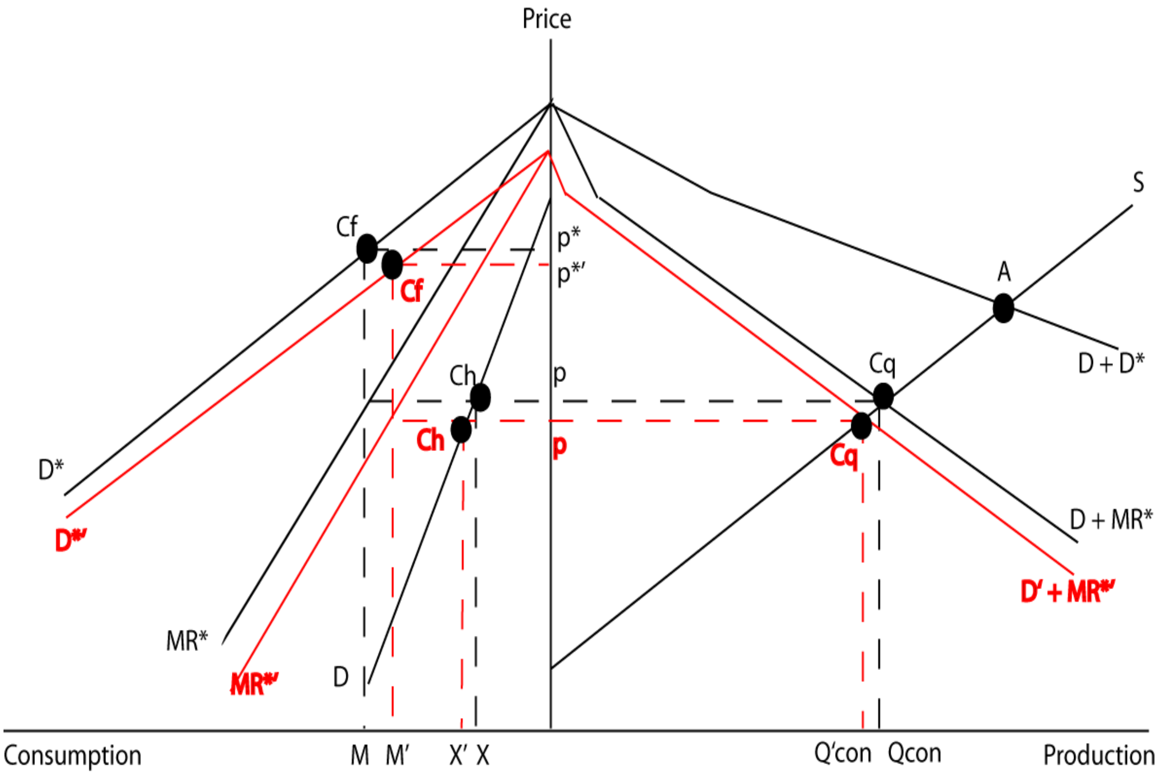

Figure 4: Introducing biofuels to the fuel markets

In equilibrium, the quantity supplied equals the quantity demanded such that $\left(D + MR^{*'^{-1}}\right)^{-1}$ equals MC, where $MR^{*'} = \partial \left(p^{*} \cdot M_{oil}\right) / \partial M_{oil}$. Hence, price in country H declines, as does the price in country F. Note that although fuel prices in country F, gasoline and diesel consumption in country F, and total gasoline and diesel consumption go down, gasoline and diesel consumption in country H goes up. With biofuel, country H, i.e., the oil-exporting country, consumes more gasoline and diesel, as illustrated by the left-hand side of Fig. 4, i.e., $p^{*'} < p^{*}$ and $M' < M$ whereas $X' > X$. The right-hand side of Fig. 4, on the other hand, illustrates that production of gasoline and diesel goes down with biofuel, i.e., $Q' < Q$.

3 Comparing outcomes under the alternative models

3.1 The international fuel markets

We begin by comparing the equilibrium outcomes under the CON, COF, and COM models, assuming fuel can be produced only from crude oil.

Proposition 1 *When demand and marginal costs are well-behaved (that is, when the demand curve is a continuous downward sloping function and marginal cost curve is a continuous upward sloping function),*

1. *Global production is largest under the COM model and smallest under the COF model, i.e.,* $Q_{COF} < Q_{CON} < Q_{COM}$.
2. *Consumption in oil-importing countries is largest under the COM model and smallest under CON model, i.e.,* $M_{CON} < M_{COF} < M_{COM}$ *(i.e.,* $p^*_{CON} > p^*_{COF} > p^*_{COM}$*).*
3. *On the other hand, consumption in oil-exporting countries is largest under the CON model and smallest under the COF model, i.e.,* $X_{COF} < X_{COM} < X_{CON}$ *(i.e.,* $p_{COF} > p_{COM} > p_{CON}$*).*

Furthermore, $p_{COM} = p^*_{COM}$ *and* $p_{COF} = p^*_{COF}$*, whereas the wedge between world and domestic prices in OPEC countries is* $p^*_{CON} - p_{CON}$.

Proof: The proof is relegated to the Appendix.

Under the CON model, less supply is available for export resulting in higher prices and lower quantities in oil-importing countries, compared to outcomes under the COM and COF models. But with the CON model, large quantities are allocated to domestic consumption, and this increase in domestic consumption in oil-exporting countries results in higher overall production compared to the COF model.

3.2 The effect of the introduction of biofuels on the international fuel market

Next, we compare equilibrium outcomes under the CON, COF, and COM models, and show how the introduction of biofuels impacts world fuel markets under the alternative models.

Proposition 2 *Assume demand is downward sloping and marginal cost is upward sloping. Then, the impact of the introduction of biofuels on fuel markets depends on the model used:*

1. *global fuel production increases (fossil fuels plus biofuels), although global fossil fuel production decreases, i.e.,* $0 > \frac{\partial Q_{COM}}{\partial B} > \frac{\partial Q_{CON}}{\partial B} > \frac{\partial Q_{COF}}{\partial B} > -1$,
2. *consumption of fossil fuel in oil-exporting countries increases such that the largest impact is under the CON model, i.e.,* $\frac{\partial D_{CON}}{\partial B} > \frac{\partial D_{COF}}{\partial B} > \frac{\partial D_{COM}}{\partial B} > 0$ *(*$\frac{\partial p_{CON}}{\partial B} < \frac{\partial p_{COF}}{\partial B} < \frac{\partial p_{COM}}{\partial B} < 0$ *)*
3. *consumption of fossil fuel in oil-importing countries decreases such that the smallest impact is under the CON model, i.e.,* $0 > \frac{\partial D^{*'}_{CON}}{\partial B} > \frac{\partial D^{*'}_{COF}}{\partial B} > \frac{\partial D^{*'}_{COM}}{\partial B}$ $(0 > \frac{\partial p^*_{CON}}{\partial B} > \frac{\partial p^*_{COF}}{\partial B} > \frac{\partial p^*_{COM}}{\partial B}$*).*

Proof: The proof is relegated to the Appendix.

The introduction of biofuels causes consumers in oil-importing countries to substitute fossil fuel with biofuels. It also causes oil-exporting countries (firms), with market power in international markets, to restrict fossil fuel production. Specifically, the oil-exporting countries mitigate the decline in prices in oil-importing countries by reducing fossil fuel exports above and beyond what the COM model suggests. Furthermore, under the CON model domestic prices in oil-exporting countries decline the most, because domestic consumer surplus, as well as profits, affect OPEC's production decisions.

The framework presented above, i.e., the CON model, captures an important stylized fact—that there is a positive wedge between prices in oil-exporting and oil-importing countries, and that this wedge increases with the introduction of biofuels. It suggests that the introduction of biofuels affects the price of fuel, and the quantities and composition of fuels consumed, and that the magnitude of its impact is influenced by market structure. While theory can predict the qualitative effects of biofuel on fuel markets, to derive policy recommendations, quantitative measures are also required. To this end, we now resort to numerical analysis to quantify the effects of biofuel on fuel markets.

4 Calibrating the model

To illustrate numerically the welfare implications of the CON model versus the other models, when biofuels are introduced to the fuel market, we develop an example that uses linear demand and marginal cost curves. We denote the quantity of biofuels supplied and consumed in the oil-importing country as $Q_{biofuel}$ and $M_{biofuel}$, respectively, and assume oil-exporting countries behave like a leading firm, treating the biofuel industry as a competitive fringe that takes the international fuel price as given. Subscript {oil} denotes gasoline and diesel consumption, whereas subscript {fuel} denotes fuel consumption (gasoline, diesel, and biofuels), either by OPEC countries (i.e., X) or by the oil-importing country (i.e., M). In other words,

$$\begin{aligned} D &: \quad p = \beta_0 - \beta_1 \cdot X_{oil}, \\ D^* &: \quad p^* = \beta_0^* - \beta_1^* \cdot M_{fuel}, \text{ and} \\ MC &: \quad MC = \alpha_0 + \alpha_1 \cdot Q_{oil}, \end{aligned} \tag{1}$$

and where $X_{oil} + M_{fuel} = Q_{oil} + Q_{biofuel}$. Biofuels are produced and consumed only in the oil-importing country, as observed in 2007. When calibrating the model, all quantities are adjusted to gasoline-equivalent quantities. In addition, assume α_0, α_1, β_0, β_1 ,β_0^*, and $\beta_1^* > 0$.

For the calibration, we assumed short-run biofuel production is capacity constrained, but is upward sloping in the long run. Specifically, the quantity of biofuel supplied is assumed to be fixed in calibrating the model for 2007, but assume biofuel's supply is upward sloping in Section 6.3 when analyzing the effect of biofuel with a 20% increase in demand for fuel.

Authors modeling empirically the demand for fuels use the linear assumption (Dées et al., 2007; Lin 2007; among others), and numerical simulations suggest that the results presented in the paper do not change qualitatively if, instead, we assume constant demand elasticity. Furthermore, an upward-sloping supply function better characterizes the fuel market, in contrast to a constant unit cost function. Whereas the upstream costs for a barrel of oil equivalent in the United States for onshore drilling equals 23.45 US$, it equals 57.20 US$ for offshore drilling. The marginal cost of a barrel of crude oil increases with the quantity supplied – the first barrel comes from onshore drilling, the last from offshore (Energy Information Administration, 2008b).

We used observed data on quantities and prices, given assumptions on equilibrium behavior, to calibrate the model for 2007. The demand elasticity for fuel η_D is used to compute the slope of country F's demand curve:

$$\beta_1^* = \frac{-p^*}{D^* \cdot \eta_D^*}. \tag{2}$$

Equation (2), together with the equilibrium quantity and prices M and p^*, are used to compute the intercept of the demand function:

$$\beta_0^* = p^* + \beta_1^* \cdot M. \tag{3}$$

We use equilibrium behavior to compute the price in country H, given the annual Western Texas Intermediate price of crude oil. To this end, we know that

$$p = MR^* = \beta_0^* - 2 \cdot \beta_1^* \cdot M_{oil} = 2 \cdot p^* - \beta_0^* \tag{4}$$

The first equality in (4) follows from OPEC's equilibrium pricing behavior; the second follows the definition of marginal revenue; the latter uses the fuel demand curve in country H to substitute for X_{fuel}.

Building on demand equations computed above, we compute marginal cost given equilibrium behavior and given assumptions on supply elasticity η_S:

$$\alpha_1 = \frac{S\,(p)}{p} \text{ and } \alpha_0 = Q_{oil} - \alpha_1 \cdot p. \tag{5}$$

Note that each model implies different equilibrium behavior, and therefore different marginal cost curves. Whereas in competition, we equate demand and supply, in the COF model we equate marginal revenue to marginal cost. Unlike the other two models, the CON model equates $\left(D + MR^{*^{-1}}\right)^{-1}$ to marginal cost. The demand curve for country H, but not country F, is also sensitive to the model chosen. This also introduces further differences between the CON model and the COF or the COM models.

5 Data

Building on the assumptions made above, we calibrated the alternative models using data on crude oil and biofuels in 2007 (see Table 1). Crude oil data on prices and quantities is taken from the British Petroleum Statistical Review.[12]

We aim to explain differences in fuel prices among oil-exporting and oil-importing countries, and show how the introduction of biofuels and biodiesel affects these markets. However, we have global data on oil production and consumption but not on gasoline and diesel consumption. We do, however, know that although crude oil is used to produce several products ranging from gasoline and diesel to asphalt and oil lubricants, in the United States from 1993 to 2008 65% to 67% of a barrel of crude oil is allocated annually to the production of gasoline and diesel.[13] These two products, characterized by relatively high profit margins when compared to other crude products, are the main source of income to downstream refineries. This creates strong incentives for refineries to maximize the amount of gasoline and diesel produced from crude, an amount that is constrained by technology.[14] We, therefore, assume a fixed proportion relationship between crude-oil and fossil fuel consumed, i.e., that the quantities of fossil fuel consumed can be derived from the quantities of crude oil and that the optimal quantity of fuel consumed determines the the quantity of crude-oil demanded.

Specifically, a barrel of crude oil, on average, yields 19.5 gallons of gasoline and 8.5 gallons of diesel. This represents 67% of a barrel of crude oil, with the remaining volume used to produce kerosene-type jet fuel, liquefied refinery gases, still gas, coke, asphalt and road oil, and petrochemical feedstock.[15] We use this ratio to convert barrels of crude oil to GEG. This ratio is also used to compute a conservative estimate for the price of a gallon of fuel in oil-importing countries (Table 1). In addition, since we focus on global quantities of GEG imported and consumed (while excluding domestic production in oil-importing countries), the numerical analysis does not include domestic fuel policies in oil-importing countries. Finally, we assume a gallon of ethanol is equivalent to 2/3 a gallon of gasoline, whereas a gallon of biodiesel is equivalent to 1.04 gallons of gasoline.[16] Prices and quantities are combined with demand and supply elasticites to derive the demand and supply of fossil fuels.

To compute fuel's contributions to GHG emissions, we recognize that every fuel feedstock has its own CO_2 intensity. Given a biofuel feedstock, to compute total CO_2 emissions we multiplied for each feedstock the tons of CO_2 equivalent per megajoule (MJ)[17] times the feedstock energy density in MJ times the quantity consumed in equilibrium.

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[12] http://www.bp.com/

[13] http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm

[14] The evolution of the petroleum refinery industry is one where the main objective of technological innovations, dating back to the 1940s, is to maximize the amount of gasoline and diesel produced from a barrel of crude oil. See, for example, Leffler (2008) and Jones and Pujado (2008).

[15] http://www.txoga.org/articles/308/1/WHAT-A-BARREL-OF-CRUDE-OIL-MAKES

[16] http://en.wikipedia.org/wiki/Gasoline_gallon_equivalent

[17] To convert gallons of gasoline, ethanol, or biodiesel to megajoule we use the Lower Heating Value (LHV), which are 32.0, 33.3, and 21.1, respectively. Alternatively, we can use Higher Heating Value, which includes condensation of combustion products, and for biomass is 6% to 7% higher than the LHV. However, because there is no attempt to extract energy from hot exhaust gases, LHV is more appropriate (see http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

Table 1 summarizes the values and parameters used to calibrate the models. Note that the numerical analysis presented below builds on data confined to crude oil, biofuels, and biodiesel, and does not include alternative fuel sources such as heavy oil. Adding alternative fuel sources introduces additional complexity, but does not qualitatively change the results.

6 The numerical analysis

Building on price and quantity data for 2007, we calibrate the COM, the COF, and the CON models, assuming the baseline model is CON.

Key parameters in the numerical analysis are the demand and supply elasticities. The fuel demand elasticities reported in the literature are very low (Kalymon, 1975; Cooper, 2003), where a given change in prices results in a small change in quantities. However, the import demand elasticity observed by OPEC countries is much larger, because more than 50% of global oil consumption is extracted in non-OPEC countries and there are alternative substitutes to crude oil such as oilsands. We, therefore, choose a residual import demand elasticity (the import demand elasticity observed by an exporting country) of -1.25, -1.5, -1.75, and -2.0 and fuel supply elasticity of 0.10.[18] The low supply elasticity captures the fact that global oil production stagnated in the last several years (Hamilton, 2009).

6.1 The baseline model: CON

When the import demand elasticity is -1.25, biofuels cause fuel prices in the importing country to decline by about 1.8% (Table 2).[19] The introduction of biofuels causes the import demand curve to shift down and to the left, leading fuel prices to decline (Proposition 2). The wedge, on the other hand, increases by 2% to 2.5% (Table 2). The introduction of biofuels creates pressure to reduce prices. Oil-exporting countries mitigate this loss in profits due to the introduction of biofuels by redistributing benefits from biofuel to domestic fuel consumers. It reduces exports, but increases domestic consumption. This ability to influence prices, however, declines as demand becomes more elastic, wherever larger levels of biofuel yield more elastic demand functions.

Introducing ethanol and biodiesel to fuel markets reduce gasoline and diesel consumption by 1 to 1.4 billion GEG (Table 3). At the same time, the rebound effect resulting from lower fuel prices contributes to a net increase in fuel consumption of 9.5 to 9.9 billion GEG. The reduction in gasoline and diesel depends on the supply elasticity, such that a larger supply elasticity implies a larger reduction and thus

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[18] Assuming import demand elastic less than 1 in absolute value results in a larger price effect, but it is not applicable for the COF model.

[19] If, instead of focusing on the elastic portion of the import demand curve, we assume an elasticity of -0.75, the decline in prices almost doubles. However, since it is not reasonable that a cartel will locate in this region (the marginal revenue is negative), we elected not to focus on elasticities smaller than 1 in absolute value.

a smaller rebound effect. However, independent of the elasticity, the introduction of biofuels offsets the reduction in gasoline and diesel consumption and replaces dirty fuel with clean fuel (Proposition 2).

Although total quantity of fuel consumed increases with the introduction of biofuel, less gasoline is consumed in equilibrium. Table 4 illustrates that second-generation biofuel feedstock (i.e., switchgrass) yield net carbon savings (consistent with assumptions made in assessments of impact of biofuel mandates by the EPA's Notice of Proposed Rule Making for the Renewable Fuel Standard 2 – RFS2),[20] and assuming the cost of carbon is 30 US$. Otherwise, the rebound effect – where biofuels lower the price of fuel and thus increase fuel consumption – is large and the introduction of biofuels increase GHG emissions (see Table 4, where sugarcane represents an efficient first-generation biofuel feedstock). This rebound effect becomes larger as the elasticity of demand increases (Table 4).

Next, we compare the economic gains from biofuel. In this analysis we assume that corn ethanol is profitable at 1.49 US$ a gallon (consistent with assumptions made in assessments of impact of biofuel mandates by the EPA's Notice of Proposed Rule Making for the RFS2). Assuming import demand elasticity -1.25, the implied marginal cost in equilibrium is 0.34 US$,[21] which should also equal the domestic price in the oil-exporting country. This is consistent with the Energy Information Administration 2008 report[22] that the upstream cost of a barrel of crude oil in the Middle East was 14.85 US$ between 2005 and 2007, which equals 0.35 US$ per gallon of gasoline (14.85/42 = 0.35). Our analysis also suggests that the introduction of biofuels reduced the amount paid by consumers in country F for fuel imported from country H by 23.2 billion US$, for import demand elasticity -1.25.

The marginal revenue off the import demand curve equals marginal cost, which equals domestic price in the oil-exporting countries. Thus, the shift in the energy composition toward biofuels not only reduces total fossil fuel production, but also reduce domestic gasoline prices. To this end, nominal subsidies went up in OPEC countries, at times when crude oil prices surged (2002-2006), investment stagnated, and biofuel supply expanded. During 2006 Saudi Arabia reduced its own fuel prices by 30% officially out of benevolence to its own population (Metschies et al. 2007). Consumer surplus in oil-exporting countries went up by about 2 billion US$. The shift in energy composition, however, costs the oil sector in the oil-exporting countries about 23.2 billion US$ (Table 5), which is approximately 20% of the U.S. current-account deficit in the fourth quarter of 2009 (i.e., $115.6 billion US$).

Biofuels provide the potential for increasing farm income and aiding economic development, because biofuels create additional demand for crop production and because developing countries are thought to have a comparative advantage in energy crop production. During the recent biofuel boom,

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[20] http://www.epa.gov/OMSWWW/renewablefuels/rfs2-nprm-preamble-regs.pdf

[21] Although the empirical literature suggests inelastic global demand for crude oil, the elasticity of the residual demand curve faced by a single exporting country should be higher. Similar elasticities were used in Hamilton (2008), when evaluating Saudi Arabia's pricing behavior.

[22] http://tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm

farm income in the United States is estimated at a record \$89.2 billion in 2008, up slightly from the record setting \$88.7 billion in 2007 and up roughly 50% from its 10-year average. Average farm household income is estimated at \$89,434, nearly 20% above the five-year average from 2001-2006 (U.S. Department of Agriculture, 2008). In parallel to the spike in farm income, biofuel production and profitability spiked in 2007. The introduction of biofuels in oil importing countries increased consumer surplus from fuel consumption by 10.6 billion US\$ and added 2.5 billion US\$ to biofuel producers (Table 5).

Lowering the marginal cost of biofuel production increases the benefits from biofuel to the importing country. We compared the welfare gain from biofuel using the RFS2 estimates with an extreme scenario, where biofuels are costless. For import demand elasticity of -1.25, when biofuel is costless, its introduction increases global welfare by 2%, whereas welfare in the importing country increases by 12%. This simple example illustrates the cost of a mandate, which forces inefficient production of biofuels (1.49 US\$ for corn-ethanol versus about 0.3 US\$ for gasoline and diesel), and complements work done by de Gorter and Just (2008 and 2009) that focused on the implications of the U. S. biofuel policy.

6.2 Comparing outcomes: CON versus COM and COF

We show that the distribution of resources among groups and nations, as well as carbon emitted from energy consumption, are substantially different among various market structures. Selection of the wrong model may lead to (big) measurement errors.

The COM model *overestimates* the price effect of biofuel on prices in country F by 9% to 26%, when compared to the CON model – see Table 2 (and Proposition 2). The COF *overestimates* the price effect by 4% to 17%. On the other hand, the COM model *underestimates* the effect of biofuels on gasoline and diesel consumption by about 40% (Table 3), whereas the COF model *overestimates* the effect by about 10%.

With CON, domestic consumption in oil-exporting countries matters. Whereas with COM or COF, consumption in exporting countries increased by less than 220 million GEGs due to the introduction of biofuel, it increased by more than 500 million gallons with CON. Oil-exporting countries increase consumption of fuels. These considerations are overlooked when COF or COM behavior is assumed, and the bias introduced becomes more significant as GDP per capita in oil-exporting countries increase (e.g., car ownership increases exponentially with GDP per capita once countries pass the 5,000 US\$ mark). Although consumption of crude oil in the Middle East, Algeria, and Venezuela together currently amounts to 10% of total world consumption of crude oil, consumption grew from 2005 to 2006 by 3.5%, 3.4%, and 4.3%, respectively. In contrast, consumption in the rest of the world grew by an insignificant 0.7%.

Next, the impact of biofuels on GHG emissions under the three models is compared. Difference in gasoline and diesel consumption between the three models has implications for carbon emissions (Table 4). The rebound effect is largest under COM, but smallest under COF (Table 3). The COM model *underestimates* by more than 37% the impact of biofuels on carbon emission, because the COM model underestimates the reduction in gasoline and diesel consumption. The largest carbon savings is reported using switchgrass, and employing the COF model (Table 4). The CON model is similar to the COF model, although quantities of gasoline and diesel consumed are marginally larger. The rebound effect increases, under all models, with the import demand elasticity, and decreases with the supply elasticity.

Consumers gain from biofuel. Although the COM model overestimates consumers benefit from biofuel in importing country (country F), it underestimates the benefits to consumers in the exporting country (country H) – see table 5. The COM and COF models underestimate the costs of biofuel to oil-exporting countries due to reduction in domestic fuel prices. The COM model underestimates the cost to oil-exporting countries by 10.5% (Table 5). The COF model underestimates the cost by 1%. The COM model overestimates total monetary benefit from biofuel to the oil-importing country by 20.5%, whereas the COF model overestimates the benefit from biofuel to the oil-importing country by 13%.

6.3 Increasing demand for fuel augments the effect of biofuel on the fuel markets

If history is indicative to the future of fuel markets, then demand for energy, especially fuel, will grow substantially in the coming decades. Total world demand for crude oil increased by more than 18% in the last 10 years (BP statistical review 2008). During September 2008, the EIA baseline scenario (International Energy Outlook 2008) predicted that world marketed energy consumption will grow by 50% between 2005 and 2030. In their report, the EIA concluded that global energy demand would continue to grow, despite sustained high world oil prices. Although high oil prices will probably induce further innovations resulting in more energy efficiency and slower growth in energy demand, all reports we are aware of predict 20% growth in global oil consumption in the coming decades. Furthermore, although during 2008 the credit crisis hampered growth in energy demand, many predict that demand will rebound once the crisis subsides. Weekly export weighted F.O.B. prices for crude oil imported from OPEC countries to the U.S. rebounded in 4 months by more than 55%; on January 2, 2009, the F.O.B. price was 35.48 US$, whereas the price were 55.71 US$ on May 15, 2009. On April 2010, international crude oil prices already hover around 80 US$ (EIA 2010).

We, therefore, considered the case where the importing country's demand for fuel increased by 20%; which is about the growth in global demand for crude oil from 1998 to 2008. We also assumed the oil-exporting country sees an import demand elasticity of -1.25 (for simplicity and tractability, and given the above analysis, we present only one import demand elasticity in this section).

When it comes to the supply of biofuels, we assume short term supply elasticity of 2.5 following Holland et al. (2009), and introduce continuous growth in the productivity of biofuels, in part due to the introduction of second-generation biofuels. Results of variety of studies reported in Alstone et al. (2009) suggest that assuming agricultural productivity growth between 1.5-3% is consistent with historical patterns (although trends in agricultural productivity depend on the period region and crop investigated). The results reported below are for a 2% growth rate in agriculture productivity. We also assumed for the simulation that biofuel is profitable at a price above 1.7143 US$. To mimic the impact of biofuels on the fuel market, while assuming a higher break-even price or lower biofuel supply elasticity, annual productivity growth in biofuel needs to be larger.

Under these assumptions, we show that with an increase in demand for fuels, the effect of biofuels on fuel markets becomes much more substantial in absolute terms. Assuming the increase in fuel consumption comes only from gasoline and diesel implies fuel prices in oil-importing countries increase by 30.5%, whereas gasoline and diesel consumption increases by 2.8% globally, but by 5.7% in oil importing countries.

The introduction of biofuels reduce prices in oil-importing countries by 2%, but reduce prices in oil-exporting countries by 8%. Moreover, biofuel decreases global consumption of gasoline and diesel by 0.4%, but it increases total fuel consumption (gasoline, diesel, and biofuel consumption) by 2.2%—the rebound effect. On the other hand, the sum of surplus to consumers from fuel consumption and profits from biofuel production increases by more than 12%. The impact on GHG emissions is also larger. To this end, the gains from reducing carbon are about 10 billion US$,[23] if (i) biofuels are produced using switchgrass (a second generation feedstock which, according to the RFS2, has negative direct CO_2 emissions—see Table 1), and (ii) the cost of a ton of carbon is 30 US$. The potential benefits from biofuel over time are enormous; the challenge, however, is to produce such large quantities of biofuel in a sustainable, environmental, and economic way.[24]

Finally, if we use a COM model, then the introduction of biofuels reduces gasoline and diesel consumption by only 10.29 billion gallons—44% less than the reduction of gasoline and diesel consumption implied by the CON model. Moreover, the COM model suggests prices decline by 17.12%, in contrast to the 2% suggested above when the CON model was used.

7 Policy implications and concluding remarks

In this paper, we assume oil-rich countries pursue cheap oil policies, which derive a wedge between domestic and foreign prices by restricting the supply of oil in oil-importing countries. We contrast

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[23] See Section 3 and Table 1 for the equation used to compute this value.

[24] For more on sustainability of biofuels, see Khanna et al. (2008).

the findings derived assuming a CON model with those derived when a COM or COF model is used, and we illustrated large quantitative, as well as qualitative, differences among the alternative models. The introduction of biofuels affects fuel prices and quantities, distribution of economic surplus, and climate change. Failure to incorporate OPEC into the analysis will result in poor impact assessment.

In our empirical analysis, we illustrated that COM overestimates the price effect and underestimates the quantity effect due to the introduction of biofuels. Large differences in the amount of gasoline and diesel consumed under the alternative models translate to large differences in GHG emissions. Assuming a ton of carbon is 30 US$, the COM model underestimate the impact of biofuels on carbon emissions by about 40% when compared to CON. Although these differences depend on the elasticity, especially the elasticity of crude-oil supply, the differences remain large under plausible scenarios (recall that introducing biofuels causes gasoline and diesel quantities to decline more under the CON model, when compared to COM). Conceptually, OPEC responds to the introduction of biofuels by reducing exports and increasing domestic consumption, resulting in a decline in total gasoline and diesel consumption above and beyond the decline suggested by the COM model. Then, if the GHG emissions of biofuel are significantly lower than the emissions attributed to gasoline and diesel consumption, the introduction of biofuels results in net GHG savings.

In addition, the effect of biofuel on consumers of gasoline and diesel, and the distribution of benefits across different consumer groups, is different from the benefits derived using the COM or the COF model. In contrast to the COM model, consumers in importing countries gain less because OPEC uses its market power to shift the gains from biofuel to its domestic consumers. Here, we find that fuel consumers benefited from the introduction of biofuel. Choosing the right policy is crucial for developing an economically and environmentally sustainable biofuel industry, and thus picking the right market structure is fundamental for any policy analysis.

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8 Appendix

Proof of Proposition 1

Assume $\frac{\partial D}{\partial p} < 0$, $\frac{\partial D^*}{\partial p} < 0$, and $\frac{\partial MC}{\partial Q} > 0$. Using the equilibrium conditions under COM, COF, and CON, namely

$$
\begin{aligned}
COM &: \left(D + D^*\right)^{-1} = MC\left(Q_{COM}\right) = p_{COM} = p^*_{COM} \\
COF &: \tilde{MR} = MC\left(Q_{COF}\right) < p_{COF} = p^*_{COF} \\
CON &: \tilde{D}^{-1} = MC\left(Q_{CON}\right) = p_{CON} < p^*_{CON},
\end{aligned}
$$

where $\tilde{MR} \equiv \left(MR^{-1} + MR^{*^{-1}}\right)^{-1}$ and $\tilde{D} \equiv D + MR^{*^{-1}}$, we can show that $Q_{COF} < Q_{CON} < Q_{COM}$. The reason is that $D^{-1} = p > MR = p + D \cdot \partial p / \partial D$ because $\partial p / \partial D < 0$. Similarly, we can show that $D^{*^{-1}} > MR^*$. Put differently, given consumption, $D + D^* > D + MR^{*^{-1}} > MR^{-1} + MR^{*^{-1}}$. It then follows that $Q_{COF} < Q_{CON} < Q_{COM}$ because supply is upward sloping, i.e., $\frac{\partial MC}{\partial Q} > 0$. Furthermore, $Q_{CON} < Q_{COM}$ suggests that $p_{CON} < p_{COM}$ (because $\frac{\partial MC}{\partial Q} > 0$), which implies that $X_{CON} > X_{COM}$ and thus $M_{CON} < M_{COM}$ (because $Q = M + X$). Finally, because $MC\left(Q_{CON}\right) = MR^*\left(M_{CON}\right) > MC\left(Q_{COF}\right) = MR^*\left(M_{COF}\right)$ and $\frac{\partial D^*}{\partial p} < 0$, $M_{CON} < M_{COF}$ and $p^*_{CON} > p^*_{COF}$.

Q.E.D

Proof of Proposition 2

Assume $\frac{\partial D}{\partial p} < 0$, $\frac{\partial D^*}{\partial p} < 0$, and $\frac{\partial MC}{\partial Q} > 0$. Also, let superscript {'} denote net fossil fuel, i.e., total fuel consumption minus biofuels. The equilibrium conditions under COM, COF, and CON, are

$$
\begin{aligned}
COM &: \left(D + D^{*'}\right)^{-1} = MC\left(Q_{COM}\right) \\
COF &: \tilde{MR} = MC\left(Q_{COF}\right) \\
CON &: \tilde{D}^{-1} = MC\left(Q_{CON}\right),
\end{aligned}
$$

where

$$
\begin{aligned}
COM &: MC\left(Q_{COM}\right) = p_{COM} = p^*_{COM} \\
COF &: MC\left(Q_{COF}\right) < p_{COF} = p^*_{COF} \\
CON &: MC\left(Q_{CON}\right) = p_{CON} < p^*_{CON},
\end{aligned}
$$

and where $\tilde{MR} \equiv \left(MR^{-1} + MR^{*'^{-1}}\right)^{-1}$ and $\tilde{D} \equiv \left(D + MR^{*'^{-1}}\right)$ (recall that $D^{*'} = D^* - B$, and thus both $D^{*'}$ and $MR^{*'}$ are function of both D^* and B). Then, using the equilibrium conditions while applying the implicit function theorem, assuming the biofuel mandate binds, and that $Q = D + D^{*'}$, we derive the following derivatives:

$$\begin{aligned} COM &: \frac{dQ_{COM}}{dB} = -\frac{\partial p/\partial (D+D^*)}{\partial p/\partial (D+D^*) - \partial MC/\partial Q} \\ COF &: \frac{dQ_{COF}}{dB} = -\frac{\partial \tilde{MR}/\partial (D+D^*)}{\partial \tilde{MR}/\partial (D+D^*) - \partial MC/\partial Q} \\ CON &: \frac{dQ_{CON}}{dB} = -\frac{\partial \tilde{D}^{-1}/\partial (D+D^*)}{\partial \tilde{D}^{-1}/\partial (D+D^*) - \partial MC/\partial Q}, \end{aligned}$$

These derivatives show the impact of the introduction of biofuels on the equilibrium quantity of gasoline and diesel produced and consumed. Then, because,

$$0 > \frac{\partial p}{\partial (D+D^*)} > \frac{\partial \tilde{D}^{-1}}{\partial (D+D^*)} > \frac{\partial \tilde{MR}}{\partial (D+D^*)},$$

we get

$$0 > \frac{dQ_{COM}}{dB} > \frac{dQ_{CON}}{dB} > \frac{dQ_{COF}}{dB}.$$

If, on the other hand, the mandate is not binding and the biofuel supply curve is upward sloping, then the impact of the introduction of biofuels on gasoline and diesel consumption is smaller, although the signs are never reversed. Furthermore, under CON, $p - MC = 0$, and thus total differentiating with respect to Q and D (while holding biofuel constant) results in

$$\frac{\partial p}{\partial D}dD - \frac{\partial MC}{\partial Q}dQ = 0 \Rightarrow \frac{dD}{dQ} = \frac{\partial MC/\partial Q}{\partial p/\partial D} < 0.$$

(recall that $D(p)$ and $MC(Q)$). Put differently, and since $dQ_{CON}/dB < 0$, D increases with the introduction of biofuels. This also implies that $D^{*'}$ decreases with the introduction of biofuels. Although total fuel consumption $D + D^*$ increases with the introduction of biofuels, gasoline and diesel production and consumption, i.e., Q and $D + D^{*'}$, decline. Therefore, because the total increase in fuel consumption in oil-importing country is larger under COM, compared to CON,

$$\frac{dp^*_{COM}}{dB} < \frac{dp^*_{CON}}{dB} < 0.$$

The proposition follows.

Q.E.D

Table 1. The model parameters

	Value
2007 quantity and price data	
Quantity of gasoline consumed by country H	6.2 million barrels a day
Quantity of gasoline consumed by country F	54.8 million barrels a day
Price of a barrel of crude oil	72 US$
Price of gasoline	1.7143 US$
Global quantity of ethanol consumed	13.5 billion GEG a year
Global quantity of biodiesel consumed	6.16 million tones a year
Parameters used to compute CO_2 emissions	
Ethanol energy density in MJ per liter	21.1
Biodiesel energy density in MJ per liter (vegetable oil)	33.3
Gasoline energy density in MJ per liter	32.0
Gram of CO_2 equivalent per MJ of gasoline	95.6
Gram of CO_2 equivalent per MJ of sugarcane	50
Gram of CO_2 equivalent per MJ of corn stover*	-15
Gram of CO_2 equivalent per MJ of switchgrass*	-23

* Source: RFS2

Table 2. The price effect of biofuel in US$

		-1.25	*-1.5*	*-1.75*	*-2*
Levels: US$					
	Competition	-0.0444	-0.0376	-0.0326	-0.0288
	Cartel	-0.0412	-0.0353	-0.0308	-0.0274
	CON				
	Exporting country	-0.0707	-0.0654	-0.0587	-0.0529
	Importing country	-0.0354	-0.0327	-0.0294	-0.0264
	Wedge	0.0354	0.0327	0.0294	0.0264
Percent					
	Competition	-2.52%	-2.15%	-1.87%	-1.65%
	Cartel	-2.35%	-2.02%	-1.77%	-1.57%
	CON				
	Exporting country	-17.10%	-10.27%	-7.40%	-5.81%
	Importing country	-2.02%	-1.87%	-1.68%	-1.52%
	Wedge	2.65%	2.95%	3.09%	3.18%
Percent change relative to CON					
	Competition	25.48%	14.91%	11.00%	8.86%
	Cartel	16.45%	7.83%	5.02%	3.65%

Table 3. Fuel consumption and biofuel (million of gallons)

		Demand elasticity	***-1.25***	***-1.5***	***-1.75***	***-2***
Levels						
	Competition					
		Exporting country	215.23	182.31	158.13	139.61
		Importing country	-1,062.30	-899.80	-780.44	-689.04
		Total	-847.04	-717.49	-622.31	-549.43
	Cartel					
		Exporting country	199.75	171.08	149.61	132.93
		Importing country	-1,772.00	-1,517.60	-1,327.20	-1,179.20
		Total	-1,572.20	-1,346.60	-1,177.60	-1,046.20
	CON					
		Exporting country	1,715.30	951.96	664.80	512.98
		Importing country	-3,065.40	-2,200.80	-1,786.10	-1,522.40
		Total	-1,350.10	-1,248.80	-1,121.30	-1,009.40
	Biofuel		10,927.90	10,927.20	10,927.20	10,927.80
Percent change relative to CON						
	Competition		-37.26%	-42.55%	-44.50%	-45.57%
	Cartel		16.45%	7.83%	5.02%	3.65%
The rebound effect						
	Competition		10,080.86	10,209.71	10,304.89	10,378.37
	Cartel		9,355.70	9,580.60	9,749.60	9,881.60
	CON		9,577.80	9,678.40	9,805.90	9,918.40

Table 4. GHG emissions					
Reduction in the cost of carbon - millions of US$ (assuming 30 US$ per ton of carbon)					
Feedstock		**-1.25**	**-1.5**	**-1.75**	**-2**
Sugarcane					
	Competition	$1,045.80	$1,094.20	$1,129.76	$1,156.99
	Cartel	$774.87	$859.17	$922.32	$971.37
	CON	$857.85	$895.68	$943.35	$985.14
Advance biofuel - low					
	Competition	$422.13	$470.53	$506.09	$533.32
	Cartel	$151.20	$235.50	$298.65	$347.70
	CON	$234.18	$272.01	$319.68	$361.47
Switchgrass					
	Competition	($987.21)	($938.81)	($903.25)	($876.02)
	Cartel	($1,258.14)	($1,173.84)	($1,110.69)	($1,061.64)
	CON	($1,175.16)	($1,137.33)	($1,089.66)	($1,047.87)
Reduction in carbon units -- million of tons					
Sugarcane					
	Competition	34.86	36.47	37.66	38.57
	Cartel	25.83	28.64	30.74	32.38
	CON	28.60	29.86	31.45	32.84
Advance biofuel - low					
	Competition	14.07	15.68	16.87	17.78
	Cartel	5.04	7.85	9.96	11.59
	CON	7.81	9.07	10.66	12.05
Switchgrass					
	Competition	-32.91	-31.29	-30.11	-29.20
	Cartel	-41.94	-39.13	-37.02	-35.39
	CON	-39.17	-37.91	-36.32	-34.93

Table 5. Disaggregating the benefits from biofuel

Changes in economic surplus - millions of USD

Change in:	*Demand elasticity*	***-1.25***
Consumer surplus: Importing country	**Competition**	13,311.00
	Cartel	12,368.00
	CON	10,643.00
Consumer surplus: Exporting country	**Competition**	1,471.10
	Cartel	1,365.60
	CON	2,291.70
Total change in consumer surplus	**Competition**	14,782.00
	Cartel	13,733.00
	CON	12,935.00
PS from biofuel production	**Competition**	2,450.90
	Cartel	2,450.90
	CON	2,450.90
Producer surplus: Exporting country	**Competition**	-14,539.00
	Cartel	-15,816.00
	CON	-23,192.00
Total change in producer surplus	**Competition**	-12,089.00
	Cartel	-13,365.00
	CON	-20,741.00
Export tax revenues		6,300.50
	Producer surplus plus revenues	-16,891.50
Total gain to importing country		
	Competition	15,761.9
	Cartel	14,818.9
	CON	13,093.9
Total gain to exporting country		
	Competition	-13,067.90
	Cartel	-14,450.40
	CON	-14,599.80