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The Effect of Biofuels on Crude Oil Markets

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To quantify the effect of biofuel on global oil markets, we extend the optimal export tax model to the global fuel market (henceforth, denoted as the Cartel-of-Nations model), recognizing that crude oil extraction and production are concentrated in a few countries (namely, the Organization of the Petroleum Exporting Countries), and that there is a wedge between fuel prices in oil-exporting and oil-importing countries. We calibrate the Cartel-of-Nations model to include biofuel using 2007 data. We show that the introduction of biofuel reduces international fuel prices by between 1.07 and 1.10%, as well as reduces the quantity of fossil fuel (i.e., gasoline and diesel) consumed by oil-importing countries by between 0.3% and 0.7%. The global amount of fuel consumed (gasoline, diesel, and biofuels), however, increases by 1.5-1.6%. This outcome suggests that although the introduction of biofuels changes the composition of the fuel consumed (resulting in less carbon emissions per gallon of fuel consumed), it also increases global fuel consumption (resulting in more carbon emissions). The magnitude of these two opposing forces, and therefore the environmental benefits from biofuels, depends on the supply elasticity of fossil fuel and on the pollution intensity of the biofuel feedstock used. Finally, the introduction of biofuels causes welfare in oil-exporting countries to decline by 1.05-1.76%, but it causes welfare in oil-importing countries to increase by 2.92-4.10%.

Key words: biofuel, ethanol, biodiesel, gasoline, diesel, crude oil, export tax, fuel prices, OPEC.

Introduction

The beginning of the 21st Century marks a change in the composition of transportation fuels, where biofuels, in addition to gasoline and diesel, power our cars. Biofuels are a liquid substitute to gasoline and diesel and are produced from biomass using dispersed production units located in oil-importing countries (e.g., the United States, Brazil, and Europe).[1] Gasoline and diesel are liquid fuels produced from crude oil whose extraction capacity is concentrated in the Organization of the Petroleum Exporting Countries (OPEC).[2] One implication from the concentration of oil extraction in a few oil-exporting countries is the observed wedge between fuel prices in oil-exporting and oil-importing countries. For instance, from 1995 to 2006, consumers in OPEC countries paid US $0.28/liter for gasoline at the pump, whereas consumers in oil-importing countries paid US $1.04/liter (Metschies et al., 2007).[3] Such cheap oil policies are akin to cheap food policies, where governments in food-exporting countries subsidize domestic food consumption to achieve political stability and cheap labor (Lewis, 1955; Schultz, 1968; among others).

Recognizing these aforementioned stylized facts, we quantify the effect of introducing biofuels on global fuel markets while utilizing the optimal export tax model. This framework models oil-exporting countries with market power in international markets and is supported empirically (Hochman & Zilberman, 2008). We extend

1. *For a comprehensive survey on biofuels, their economic impacts, as well as their environmental implications, see Rajagopal and Zilberman (2008).*
2. *Recently, in addition to crude oil, unconventional oils such as oil sands have been utilized to produce gasoline. Having said that, and given the relatively small amount of gasoline currently produced from unconventional oils (and since the focus of this article is on biofuels), these alternative gasoline sources are not modeled. Introducing it to the numerical model, however, does not alter qualitatively the results derived in the article.*
3. *The International Energy Agency publishes a quarterly publication that summarizes major international compilations of energy prices at all market levels: import prices, industry prices, and consumer prices. Using this publication, we conclude that current domestic policies in importing countries cannot explain the observed wedge.*

the optimal tax model by introducing biofuel producers as a competitive fringe and denote this model as the Cartel-of-Nations (CON) model. We then calibrate the model to 2007 data and show how the introduction of biofuels affects fuel markets.

We estimate that biofuel production in 2007 increased fuel subsidies in OPEC countries by 1.18-1.65%, while it reduced international fuel prices by 1.07-1.10%. On the other hand, the introduction of biofuels caused the global amount of fossil fuel (i.e., gasoline and diesel) consumed in 2007 to decline by 1.39-1.60 billion gallons a year, i.e., 0.22-0.25% of global consumption. We also compute total reduction in carbon emissions due to the introduction of biofuels by using the average per-unit carbon footprints of different fuels. The potential benefit from carbon savings under the CON model—given plausible scenarios—is large. Finally, we illustrate the importance of market structure and its impact on carbon savings. To this end, we show that if we replace OPEC by a competitive market structure, then the reduction in carbon emissions attributed to the introduction of biofuels would be an order of magnitude smaller.

The next section describes the conceptual framework used to quantify the effect of introducing biofuels to fuel markets. The empirical framework used to quantify the conceptual framework is then described, followed by the results. We conclude the article with a brief discussion on the implications of biofuels on fuel markets.

Global Fuel Markets

We now 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-exporting and in oil-importing countries. We model OPEC as a cartel of nations, thereby extending the optimal export tax model where governments in oil-exporting countries set an export tax to maximize domestic consumer and producer surplus from oil consumption and production by introducing a competitive fringe—i.e., biofuel producers.

Formally, and without loss of generality, we employ a partial equilibrium analysis, focusing on two countries: an oil-exporting country and an oil-importing country. The former has vast oil reserves, whereas the latter has access to biomass and the technology needed to convert it to biofuels. These assumptions capture the structure of the global fuel markets, whereby on 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.[4]

Although crude oil is used to produce several products ranging from gasoline and diesel to asphalt and oil lubricants, in the United States historically (i.e., 1993 to 2008) 65-67% of a barrel of crude oil is allocated to the production of gasoline and diesel.[5] These two products, characterized by relatively high profit margins when compared to other crude products, are an important source of income to downstream refineries. Thus, it creates strong incentives for refineries to maximize the amount of gasoline and diesel produced from crude, an amount that is constrained by technology.[6] This structure seems to suggest that a sufficient statistic for gasoline and diesel consumption is the amount of crude oil a country consumes. To incorporate this structure into the article, we assume a fixed proportion of a barrel of crude oil is allocated to production of gasoline and diesel.

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.[7] Furthermore, although the empirical literature does illustrate that weekly or monthly data on ethanol prices are not perfectly correlated with gasoline prices, looking at annual data does seem to suggest that this assumption is a good approximation. Allowing the difference between biofuel and fossil fuel prices to vary

4. *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 biofuels. Because OPEC countries subsidize gasoline, it makes importing biofuel not profitable. Therefore, we excluded this possibility for simplicity and tractability from the numerical analysis.*
5. *http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm*
6. *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 (1985) and Jones and Pujadó (2006).*
7. *For more on the theoretical relation between ethanol and gasoline prices, in the absence of a mandate, see de Gorter and Just (2009), Tyner and Taheripour (2008), and Hochman, Sexton, & Zilberman. (2010).*

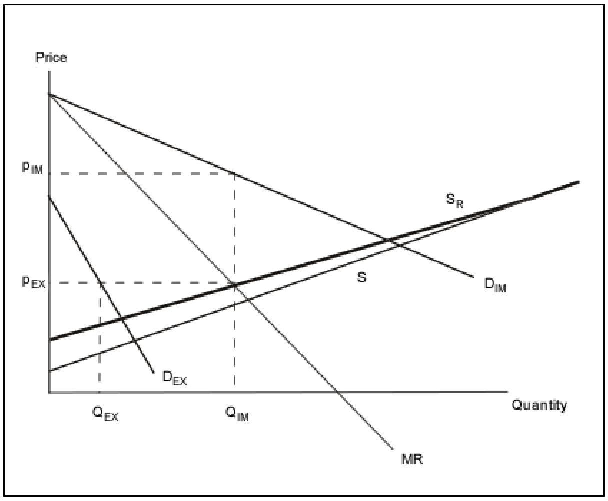

Figure 1. The international fuel market.

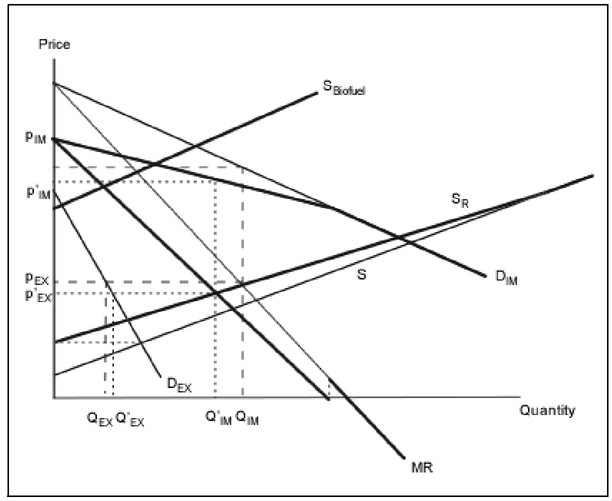

Figure 2. Introducing biofuel to the international fuel market.

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. The larger the difference between biofuel and fossil fuel prices, the bigger the impact of the introduction of biofuels on the fuel markets. Next—and building on the aforementioned assumptions—we depict the conceptual framework.

To allow comparisons between models with and without biofuels, we denote the benchmark case as the case with no biofuels (see Figure 1). The optimal allocation rule is then derived, assuming firms are price takers and the oil-exporting economy has monopoly power in international markets. More specifically, to derive the amount of gasoline consumed, we equate the sum of (i) the marginal revenue (MR) derived from the import demand curve (D_{IM}) (world demand minus demand for fuel in the exporting country)[8] and (ii) the demand for fuel in the exporting country (D_{EX}), with the marginal cost of production (S). Although dynamic facets of fossil fuel can be introduced to the analysis if user costs (incurred over a period of time as a consequence of extracting crude oil that includes the capital, or interest, costs) were incorporated into the analysis and added to the marginal cost, we elected for tractability to focus on marginal costs (MC).[9] Alternatively, denote the excess supply curve, i.e., the marginal cost of extraction and production of crude oil (S) minus domestic demand in oil-exporting country (D_{EX}), as S_R. Then, assuming OPEC countries behave as a leading firm, in equilibrium the excess supply curve (S_R) equals the MR derived from the import demand curve (D_{IM}).

The intersection of D_{EX} + MR curve with the MC curve results in the aggregate quantity of fuel produced (Q_{EX} + Q_{IM}). The price in the oil-exporting country, then, equals the value of the marginal cost in equilibrium (MC = P_{EX}). To find the quantity of fuel consumed in the oil-importing country (Q_{IM}), we use the MR curve. We then plug Q_{IM} into the import demand curve (D_{IM}) to get the international fuel price (P_{IM}) This gives us the amount of fuel produced, consumed, and the price paid in the oil-exporting and oil-importing countries. Needless to say, this solution results in domestic prices in oil-exporting countries being substantially lower than the international price.

Now we introduce a competitive biofuel industry that produces biofuels by many independent biorefineries whose feedstock is produced by competitive farmers. The scale of operation is much smaller than a petroleum refinery. For instance, the average capacity of a biorefinery in the United States is 47 million gasoline energy-equivalent gallons (GEG) per year, and there are about 200 US biorefineries,[10] whereas the capacity of the average oil refinery in the United States is 871 million

8. *The data on demand introduce implicitly domestic policies used by individual countries, such as gasoline taxes. The quantity of fossil fuel demanded is derived given these domestic policies.*

9. *While early papers found support for the Hotelling Valuation Principle (e.g., Miller & Upton, 1985), recent papers did not find such support (e.g., Adelman & Watkins, 1995) and showed using oil and gas transaction data that reserve values are much smaller than the values predicted by the theory.*

Table 1. The parameters.

2007 quantity and price data	Value and units
Quantity of gasoline and diesel in GEG consumed by oil-exporting countries	65.3 billion barrels a year
Quantity of gasoline and diesel in GEG consumed by oil-importing countries	577.4 billion barrels a year
Price of fuel	US $1.7143
Global quantity of biofuel consumed	11.35 billion GEG a year
Parameters used to compute CO_2 emissions	**Value**
Ethanol energy density in megajoule (MJ) per liter	23.5
Biodiesel energy density in MJ per liter (vegetable oil)	35.1
Diesel energy density in MJ per liter	38.6
Gasoline energy density in MJ per liter	33.7
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 [a]	-15
Gram of CO_2 equivalent per MJ of switchgrass [a]	-23

[a] *Source: Notice of Proposed Rule Making for the Renewable Fuel Standard 2*

gasoline gallons, of which there are about 143. 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.

We assume oil-exporting countries behave like a leading firm, treating the biofuel industry as a competitive fringe (Figure 2). The import demand equation now equals the equation D_{IM} minus biofuel supply $S_{Biofuel}$. The marginal revenue derived from the revised import demand equation D_{IM} is then equated to the crude supply equation (S), resulting in lower prices (p_{EX}' and p_{IM}'), both in the exporting and in the importing countries. Thus, the amount of fossil fuel consumed in the oil-importing country declines, the consumption increases in the oil-exporting country, and global fuel consumption increases. The oil-exporting country uses its market power to mitigate the competitive impact of the introduction of biofuels.

Calibrating the Model

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 (OPEC's market share in the fuel market declines with the introduction of biofuels). It suggests that the introduction of biofuels affects the price of fuel, as well as the quantities and composition of fuels consumed. While theory can predict the qualitative effects of biofuel on fuel, quantitative measures are also required to derive policy recommendations. To this end, we conduct numerical analyses to quantify the effects of biofuel on fuel markets.

We develop a system of demand and supply equations, and use it to compute the effect of introducing biofuel to the global fuel markets. The calibration uses data from 2007, where all quantities are adjusted to GEG.

The key parameters in these analyses are price elasticities of supply and demand, which measure the relative change in quantities supplied or demanded that result from a relatively small change in prices. We choose a residual import demand elasticity (the import demand elasticity observed by an exporting country) of -1.05, -1.2, -1.35, and -1.5; demand elasticity in oil-exporting countries of -0.1; and crude oil supply elasticity of 0.10. These values are supported by the empirical literature (Krichene, 2002).

The parameters used to calibrate our model are depicted in Table 1. We assume a gallon of ethanol is equivalent to two-thirds of a gallon of gasoline, whereas a gallon of biodiesel and a gallon of diesel are equivalent to 1.04 and 1.14 gallons of gasoline, respectively.[11] The 2007 data, therefore, imply that global ethanol and biodiesel GEG equal 11.35 billion gallons. To convert crude oil to fossil fuel, we note that a barrel of crude oil equals 42 gallons, of which on average 19.5 gallons are

10. *The data were collected on July 14, 2009, from http://www.ethanolrfa.org/industry/bio-refinery-locations/.*

11. *http://en.wikipedia.org/wiki/Gasoline_gallon_equivalent*

Table 2. The price effect of biofuel in US$.

Demand elasticity	-1.05	-1.20	-1.35	-1.50
Levels: US$				
Exporting country	-0.0381	-0.0426	-0.0400	-0.0370
Importing country	-0.0191	-0.0213	-0.0200	-0.0185
Wedge	0.0191	0.0123	0.0115	0.0107
Percent				
Exporting country	-31.83%	-12.98%	-8.25%	-6.09%
Importing country	-1.10%	-1.23%	-1.15%	-1.07%
Wedge	1.18%	1.51%	1.60%	1.65%

used to produce gasoline and 9.5 gallons are used to produce diesel.[12] We use this ratio to convert barrels of crude oil to GEG. Note that we focus on the international price of fuel (not the price at the pump), because we use global quantities of GEG imported and consumed.

Finally, to compute the contribution of fuel to greenhouse gases, we recognize that every fuel feedstock has its own CO_2 intensity. Therefore, given a biofuel feedstock, to compute total CO_2 emissions, we multiplied for each feedstock the gram of CO_2 equivalent per megajoule (MJ)[13] times the feedstock energy density in MJ times the quantity consumed in equilibrium.

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

The Numerical Analysis

Next, we use the numerical framework to assess the impact of biofuel on fuel markets and the environment. Following that, we illustrate the environmental benefits from OPEC. There we show that with a competitive market structure, in contrast to a CON market structure, the reduction in carbon emissions due to the introduction of biofuels is an order of magnitude smaller.

Table 3. Fossil fuel consumption and the rebound effect (in millions of gallons).

Demand elasticity	-1.05	-1.20	-1.35	-1.50
Millions of gallons				
Exporting country	3,050.3	974.2	587.5	423.4
Importing country	-4,479.4	-2,571.8	-2,086.1	-1,812.0
Total	**-1,429.1**	**-1,597.5**	**-1,498.6**	**-1,388.6**
The rebound effect	9,923.0	9,754.5	9,853.5	9,963.5

The Effect of Biofuel on Fuel Markets and the Environment

Biofuels cause oil prices in importing countries to decline by 1.07-1.10% (Table 2). The wedge, on the other hand, increases by 1.18-1.65% (Table 2). The introduction of biofuels creates pressure to reduce prices. Oil-exporting countries mitigate this cost 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.

On the other hand, introducing 11.35 billion biofuel GEG to fuel markets reduces global fossil fuel consumption by 1.39-1.60 billion gallons (Table 3). At the same time, the rebound effect resulting from lower fuel prices contributes to a net increase of 9.75-9.96 billion GEG. The reduction in fossil fuels consumed increases with the supply elasticity of fossil fuels, resulting in a smaller rebound effect. However, independent of the elasticity, the introduction of biofuels offsets the reduction in fossil fuel consumption and replaces “dirty” fuel with “clean” fuel. The shift in the energy composition toward renewable energy alternatives not only forces oil-exporting countries to reduce prices, but also to reduce production.

With CON, domestic consumption in oil-exporting countries matters. With the introduction of biofuels, domestic consumption increases by more than 400 million GEG. Oil-exporting countries increase consumption of cars, and this effect becomes more significant as GDP per capita in oil-exporting countries increases (e.g., car ownership increases exponentially with GDP per capita once countries pass the US $5,000 mark, as shown in Chamon, Mauro, & Okawa, 2008). Although consumption in the Middle East, Algeria, and Venezuela together currently amounts to 10% of total world consumption of crude oil, consumption grew by 3.5%, 3.4%, and 4.3%, respectively, from 2005 to 2006. In contrast, consump-

12. *http://www.txoga.org/articles/308/1/WHAT-A-BARREL-OF-CRUDE-OIL-MAKES*

13. *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 6-7% 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).*

tion in the rest of the world grew by an insignificant 0.7% (International Energy Agency, 2008).

Our analysis also suggests that the introduction of biofuel reduced the amount paid by consumers in oil-importing countries for oil imported by US $13.36-14.99 billion. Furthermore, whereas welfare in oil-exporting countries declined by 1.05-1.76%, in oil-importing countries it increased by 2.92-4.10%.

Our model predicts that the introduction of biofuels reduces carbon emissions from fossil fuels by 16.55-18.55 million tons of CO_2. These reductions, however, are mitigated by the rebound effect, where lower fuel prices result in more fuel and, hence, biofuel produced and consumed. This mitigation effect depends on the amount of CO_2 a unit of biofuel emits, such that a smaller number results in fewer emissions from total fuel production and consumption. Moreover, if we assume fossil fuel supply elasticity of 0.1, then the introduction of biofuels results in net carbon savings only when biofuels emit less than 20 grams of CO_2 per MJ. This result, however, hinges on the assumptions made on fossil fuel supply. As the supply function becomes more elastic, the reduction in fossil fuels due to the introduction of biofuels becomes larger, and therefore the reduction in carbon emissions larger. To this end, if we assume fossil fuel supply elasticity of 0.5, then the introduction of biofuels results in a net carbon gain, as long as biofuels emit less than 40 grams CO_2 per MJ, an amount that is close to the one suggested by the Environmental Protection Agency's (EPA) *Notice of Proposed Rulemaking for the Renewable Fuel Standard 2* (EPA, 2009) on emissions from cellulosic biofuels (48 grams of CO_2 per MJ). Note also that as demand for fuel increases, the increase in fossil fuel is mitigated by biofuels; in other words, the environmental gains from biofuels increase with demand for fuels.

The Role Played by OPEC

To illustrate the role played by OPEC and how it affects fuel markets, we contrast our findings with those derived under a hypothetical competitive behavior where equilibrium marginal cost equals price. We use supply and demand equations calibrated using the CON model but assume competitive behavior. We also restrict the import demand elasticity to -1.2.

With CON, the introduction of biofuel reduces OPEC's market power and causes OPEC to reduce exports and increase domestic fossil fuel consumption such that global fossil fuel consumption declines by 1.60 billion GEG. These changes result in a smaller markup, i.e., less market power.

On the other hand, with a competitive model, global gasoline consumption declines by only 0.90 billion GEG (44% less than what was suggested with the CON model). OPEC responds to the introduction of biofuels by decreasing gasoline above and beyond what was suggested with the competitive model. It mitigates the decline in prices by reducing total quantity of crude oil produced, and therefore, fossil fuel consumed.

OPEC's response to biofuels translates to lower carbon emissions with the CON model. Whereas with competition the total reduction in CO_2 emissions from fossil fuel equals 10.43 million tons of CO_2, it equals 18.50 million tons of CO_2 with the CON model. The existence of OPEC amplifies the benefits from biofuels above and beyond the benefits attributed to the introduction of biofuel if a hypothetical competitive model is assumed. Reduction in carbon emissions from fossil fuel is 77.34% higher in CON when compared to competition.

Discussion and Concluding Remarks

The introduction of biofuels causes the price of fuel to decline, although it increases total fuel consumption, which then results in a rebound effect. The rebound effect, however, is misleading because we are not interested in reducing fuel consumption per se. We do want to reduce greenhouse gas emissions and, although we can obtain this goal by lowering fuel consumption, we can also introduce (second-generation) biofuels, which are predicted to emit substantially less CO_2 than fossil fuel and therefore may offer an alternative solution to global warming.

Our analysis suggests that although the introduction of biofuels changes the aggregate fuel mix consumed and hence reduces emissions per GEG, it also increases total fuel consumption and ultimately results in more emissions. The magnitude of these two opposing forces, and therefore the environmental benefits from biofuels, depends on the supply elasticity of fossil fuels and the carbon intensity of the biofuel feedstock. The less carbon-intensive is the biofuel feedstock, the larger are the benefits from changing the fuel mix. On the other hand, the larger the elasticity is of fuel supply, the smaller are the environmental costs attributed to the increase in global fuel consumption.

This work also illustrates OPEC's response to the introduction of biofuels. Introducing a substitute to crude oil, and therefore reducing OPEC's market share in the fuel market, creates incentives for OPEC to reduce exports, while increasing its domestic consumption. It achieves this by increasing the wedge between domestic and international prices. Specifically, it increases the magnitude of price discrimination between consumers in oil-exporting and oil-importing countries, and thus it redistributes the benefits of biofuels to its domestic population.

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