A Model for the Global Oil Market: Optimal Oil Production Levels for Saudi Arabia

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Saudi Arabia spends billions to optimize technical efficiencies for producing its five crude grades. However, it is unclear whether this production maximizes economic profits. We build a non linear programming spatial equilibrium model that allows Saudi Arabia to match technical excellence with an economic optimum. We maximize Saudi profits subject to non-Saudi production, crude and refined products supply and demand balances, production and transportation capacities and costs, and refineries yields and capacities. Model flexibility also allows examination of other market structures. By changing the objective function, we model OPEC as a profit-maximizing cartel. By reformulating to a mixed-complementarity model, we also solve for a competitive oil market. Model outputs include market clearing prices and quantities for all crude grades and products for each region. The most interesting result is that both Saudi Arabia and OPEC could have realized higher economic profits in 2004 by producing less and driving up crude prices.

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Opinions or points of view expressed on this dissertation are those of the authors and do not necessarily represent the official position or policies of either Saudi Arabia or Saudi Aramco.

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1. Introduction

Saudi Arabia is the largest crude oil producer and exporter in the world holding almost one quarter of the global proven reserves. Its national oil company, Saudi Aramco, is the world's largest integrated oil company with operations in exploration, production, refining, marketing and international shipping. The company's domestic hydrocarbon system is technically efficient in managing production for its five different crude grades. However, the question remains whether these production levels are economically optimal and guarantee the maximum feasible economic profit.

To answer this question, we turn to economic oil market models. We find such models can be divided into two main streams, papers that (1) include a non-competitive market with Organization of Petroleum Exporting Countries (OPEC) or some OPEC-core countries exercising market power and (2) include a competitive world oil market. However, none of the available world oil market optimization models maximize profits for the Saudi's crude oil sales by five grades, few have regional and sectoral details from wellhead crude to city gate refined products. For models with significant sectoral detail, none use nonlinear functions that allow a more accurate representation of this complex market and all open source oil market optimization models we have found are now decades old.

Market complexity arises from crude oil market geology, structure and behavior, crude and refined products supply and demand balances, product prices elasticities, production and transportation capacities and costs along with refineries yields and capacities. In addition, there are regional differences in all these markets and technologies. Our contribution is to model this complexity and match the technical efficiency of the Saudi oil operations with an economic optimum using non-linear programming (NLP). Because this is a global market and transport costs are non-trivial, our model is spatial and includes 29 regions with transportation costs. Different geological endowments in these regions are represented by six crude types with their non-linear cost functions. Since the demand for crude oil is derived from the demand for oil products, we model seven refined product demands for each region. We link the crude and product markets with the refining sector that incorporates refining technical complexity and global heterogeneity by region using four different refinery configurations.

To complete the optimization, we need to pick a market structure. More often the existing literature on oil market structure and OPEC's behavior has concluded that the oil market is incompetitive. In fact, the literature usually forms conjectures about the degree of competition across crude suppliers. For example, it is common to assume that Saudi (or OPEC) chooses those output quantities that maximize profits conditional on the output decisions of other players. The conjecture determines some element of the data (marginal cost or demand elasticities), which in general conflicts with independent in observation. The conjectures might be flawed whenever market power is not exercised because of political or other considerations. As an alternative, in this thesis, we measure the market conditions (demand and cost schedules) and ask how behavior changes when Saudi decision makers are only concerned with economic profit.

Approaching the world oil market from the perspective that Saudi may not be fully exercising its market power, and may have objectives other than pure profit maximization, allows us to address some interesting questions. At the point of observation how far are the output decisions from those that maximize profits? How much, in profits, is Saudi giving up in order to attain other potential objectives? What is the distribution of market power within OPEC, and how effective is OPEC in maximizing joint profits?

We use four configurations for the oil market. In the first, Saudi Arabia maximizes profits unilaterally given a competitive fringe outside of OPEC and non-Saudi OPEC producers maintaining their existing profit margins. This model run allows us to determine whether Saudi Arabia should be behaving differently within OPEC. In the second, OPEC maximizes its joint profits given a competitive fringe outside of OPEC. Since the market oscillates over time with the market sometimes behaving more and sometimes less competitively, in the third configuration, Saudi Arabia maximizes profits unilaterally given a competitive fringe that includes the rest of OPEC and non OPEC producers. This model run allows us to determine the optimal Saudi behavior when all other producers within OPEC behave more competitively. We even model competitive behavior for everyone in a fourth configuration by reformulating the NLP into a mixed-complementarity problem (MCP). These four configurations conveniently span the possible markets structures and also include those in the literature.

To demonstrate the model's robustness, we examine not only the model's ability to simulate various market structures but also examine the model's outcome sensitivity to changes in supply and demand elasticities, transportation costs and production capacities.

The model's inputs, which took many months to compile, are an additional contribution of this modeling effort. The difficulty of such an effort arises because: (1) no single data source provides the required trading and transportation matrices for either crude by grade or product by type, (2) most of these data are proprietary and therefore had to be obtained through either private contacts or purchased, and (3) even when data is located and purchased, it still needs compiling, validation and balancing. Running the above four configurations using these data yield models outputs including profits from crude production, clearing prices and quantities for both crude and product markets, and refining level in each region.

Our NLP model, in the first configuration, can help Saudi Arabia optimize its production and export operations and evaluate various operational strategies. These strategies may include expanding overall production capacity, targeting specific crude markets, developing fields of certain grades, or even investing or expanding in downstream operations. The second configuration shows OPEC what quotas to assign its members to maximize economic profits. Similar to the first configuration, the third configuration can help Saudis optimize when other producers within OPEC compete and produce at their production capacities. The fourth configuration with a totally competitive market determines the value of OPEC to its members.

In the next section of this paper, we include a brief literature review on both oil market modeling and the behavior of OPEC. In the third section, we mathematically describe and present the proposed NLP model. After presenting our data inputs and validation in the fourth section, we present the model's results for our four cases: (1) Saudi Arabia optimizing given markups for other OPEC countries and supply functions for non-OPEC players, (2) OPEC as a profit-maximizing cartel, (3) Saudi Arabia optimizing unilaterally given a competitive fringe, and (4) a competitive world crude oil market. We also examine the model's sensitivity and robustness by examining the model's output sensitivity to changes in supply and demand elasticities, transportation costs and production capacities. The paper ends with a brief conclusion and suggestions for further future research.

2. Literature Review and Contribution of the Current Work

Our literature review covers two main areas: (1) OPEC's behavior within the oil market, and (2) oil market simulation and optimization modeling. The literature on OPEC behavior (1) can be divided into two major streams. The stream with the most work and the one we think more accurately reflects OPEC behavior in recent decades, concludes that OPEC or some OPEC-core has market power, and usually seeks to maximize profits by controlling production, individually or collusively. In the second stream, a few articles model OPEC as a competitive player, which we think less often represents OPEC behavior (Table 1 in Appendix A).[2]

Out of the forty oil market models we review, only thirteen are optimization models. These models are Ben-Shahar (1976), Bohi and Russel (1975), Cremer and Weitzman (1976), Celta (1998), Deam (1973), Ezzati (1976), Hnyilicza and Pindyck (1976), Kalymon (1975), Kennedy (1974), Manne (1976), Marshalla and Nesbitt (1984), Nordhaus (1973), and Salant (1976). A more detailed literature review is posted online at http:\dahl.mines.edu\LitReviewOPEC.pdf.

Since Saudi Arabia has almost one quarter of global reserves and half of global excess production capacity, has demonstrated a strong willingness to support prices, and is the focus of our interest, as in Kalymon (1975), we model Saudi Arabia maximizing separately, given other OPEC country mark-ups. However, other OPEC countries may also join Saudi Arabia. So, again as in Kalymon, (1975) we model OPEC as a profit-maximizing cartel and determine the effect on profits, prices and quantities of such collusion. In fact, this case can provide Saudis with the information required for their bargaining strategies within OPEC.

We extend Kalymon's simpler approach by using the complexity in Deam (1973) and Kennedy (1974) that contain production, refining, transportation and demand by product for many regions. We improve on Deam's Linear Programming (LP), the model with the most regional and technical detail, with more realistic non-linear functions, more regions, more Saudi crude grades, and with production and demand quantities endogenous. We improve on Kennedy with our extensive level of regional, crude, product, and technical detail. In addition, the above

[2] Appendices A, B, and C can be viewed on line at http://dahl.mines.edu/AQpaper1App.ABC.

articles are now decades old and there have been many technical and market structure changes that our updated model will more closely approximate.

When markets are tight with plenty of money to go around, OPEC members find it easier to abide by their quotas but when the call on OPEC increases dramatically, as seen in recent times, most of the excess production capacity remains within Saudi Arabia. To represent such a tight market scenario, we separately maximize profits for Saudi Arabia given a competitive fringe behavior whereby the fringe includes the rest of OPEC and non-OPEC producers. When markets are weak and prices are falling, cash-strapped OPEC members are more likely to violate quota and compete. To represent cash-strapped weak market scenarios, we take a fourth extreme case of a competitive market with no market power for any region. Thus, our four cases not only span the two streams of literature but also should span the actual market structure.

3. Theoretical Model

The model includes twenty-nine regions (indexed by *s, r*, and *d*) that trade in integrated global crude oil and refined product markets (the model's parameters and variables are summarized in Glossary). Each region produces six crude oil types (indexed by *c*) characterized by different specific gravities and sulfur contents. Once a certain crude type is produced, it gets shipped from producing region *s* to refining region *r* at a transportation cost ρ_{csr}. At the refining region *r*, a barrel of crude type *c* gets refined into seven refined products (indexed by *p*) at fixed refining yields η_{rcp} (%). The refined product *p* is then shipped from refining region *r* to consumption region *d* at a transportation cost ρ_{prd}. For the rest of this section, we will mathematically formulate and describe the four market configurations, conveniently spanning the possible markets structures, revealed by the literature review.

Case-1: Saudi Maximizing Profits Unilaterally

Objective function:

Economic profit is the objective function in all cases. For any producer s (in this case Saudi Arabia), the total profit from all crude types (π_s) equals total production of crude *c* at region *s* (QS_{cs}) times its "markup" (market price of crude *c* at region *s* (PS_{cs}) minus the marginal cost of crude *c* at region *s* (MC_{cs})) summed over all six crude types. Thus for any producing region *s* profits (Saudi Arabia in the first case) are presented as:

$$\pi_s = \sum_c QS_{cs} * (PS_{cs} - MC_{cs}) \qquad s = \text{Saudi Arabia} \qquad (1)$$

Constraints:

A. Crude Supply Constraint:

In maximizing profits for Saudi Arabia, we assume that all non-OPEC producers behave competitively while other producers within OPEC maintain their 2004 markups (τ_{cs}). Starting with the non-OPEC producers, we assume that they supply each crude type *c* at the point where the marginal cost (MC_{cs}) equals the market clearing price (PS_{cs}). The marginal cost function for producing any crude *c* at any region *s* approaches infinity as the production approaches capacity. These two assumptions are included in the model as follows:

$$\frac{A * QS_{cs}^{\psi_{cs}}}{(\overline{QS}_{cs} - QS_{cs})} - PS_{cs} = 0 \qquad (2)$$

where, $MC_{cs} = \frac{A * QS_{cs}^{\psi_{cs}}}{(\overline{QS}_{cs} - QS_{cs})}$ and $\psi_{cs} = \gamma_{cs} - \frac{QS_{cs}}{(\overline{QS}_{cs} - QS_{cs})}$

In these equations, A is a constant, QS_{cs} is the supply of crude *c* by producer *s*, $\overline{QS}_{cs}$ is the production capacity of crude *c* at producer *s*, PS_{cs} is the free on-board (FOB) price of crude *c* at producer *s*, MC_{cs} is the marginal cost of crude *c* at producer *s*, and γ_{cs} is the inverse of the price elasticity of supply of crude c at producer s. For other producers within OPEC, we hold their 2004 crude markups (τ_{cs}) constant as follows:

$$\left[(1+\tau_{cs}) * \frac{A * QS_{cs}^{\psi}}{(\overline{QS}_{cs}-QS_{cs})}\right] - PS_{cs} = 0 \quad \text{where ,} \quad \tau_{cs} = \left(PS0_{cs} \Big/ \left(\frac{A * QS0_{cs}^{\psi}}{(\overline{QS}_{cs}-QS0_{cs})}\right)\right) - 1 \qquad (3)$$

Here, τ_{cs} is the initial markup (%) of crude c at producer s, $PS0_{cs}$ is the initial FOB price of crude c at producer s, and $QS0_{cs}$ is the initial supply of crude c by producer s.

B. Crude Market Clearance Constraint:

Crude type c supplies from region s are exported to refining regions r. The market clears such that:

$$QS_{cs} - \sum_r QD_{csr} = 0 \qquad (4)$$

Since trade theory finds that domestic and imported goods are not perfect substitutes, crude c from different regions are not considered the same products. Instead each c destination region's demand is derived from a technology that aggregates the crude of type c sourced from each region to form a composite type-c crude import available for refining. This is commonly referred to as the Armington (1969) assumption. The composite of imports and domestic M_{cr} is formed via a standard Constant Elasticity of Substitution (CES) technology. The technology is represented by the unit cost C_{cr} which is a function of the FOB prices (PS_{cs}) from each source region plus the bilateral transport margin (ρ_{csr}):

$$C_{cr} = \left[\sum_s \theta_{csr}^{\sigma_{cr}} \ (PS_{cs} + \rho_{csr})^{1-\sigma_{cr}}\right]^{1/1-\sigma_{cr}} \qquad (5)$$

The parameters θ_{csr} and σ_{cr} indicate the distribution across source regions and the elasticity of substitution. Using the cost function, we derive the conditional demands:

$$QD_{csr} = M_{cr} * \left[\frac{\theta_{csr} * C_{cr}}{PS_{cs} + \rho_{csr}}\right]^{\sigma_{cr}} \qquad (6)$$

Substituting equations (5) and (6) back into equation (4) gives the following equation :

$$QS_{cs} - \sum_r \left(M_{cr} \ * \left[\frac{\theta_{csr} * \left(\left[\sum_s \theta_{csr}^{\sigma_{cr}} \ (PS_{cs} + \rho_{csr})^{1-\sigma_{cr}} \right]^{1/1-\sigma_{cr}} \right)}{PS_{cs} + \rho_{csr}} \right]^{\sigma_{cr}} \right) = 0 \qquad (7)$$

C. Refining Activities Constraint:

We assume that all refining regions *r* have fixed technologies that process various crude types at fixed yields (η_{rcp}). Thus, η_{rcp} is the share of product *p* from crude *c* refined at region *r*. These regions operate competitively so crude costs plus value-added input costs are equal to revenues from refined products sales making profits zero at the margin. To satisfy this "zero economic profit" assumption, we have:

$$\left[\left(M_{cr} * C_{cr} \right) + \left(M_{cr} \ * \upsilon_{cr} \ * PI_{cr} \right) \right] - \left[\sum_p \left(\left(M_{cr} * \eta_{rcp} \right) * \ PS_{pr} \right) \right] = 0 \qquad (8)$$

The total crude cost equals the composite of imports and domestic M_{cr} (or crude runs in barrels) times the unit cost of crude delivered C_{cr}. The cost of value-added inputs equals the composite crude M_{cr} times the 2004 value-added inputs υ_{cr} (\$/Barrel) times a price index PI_{cr}. The revenues from the sales of the refined products equal the sum over all refined products of composite of imports and domestic (M_{cr}) times refining yields (η_{rcp}) times refined products prices (PS_{pr}). Substituting equation (5) into (8) yields:

$$\left(M_{cr} * \left[\left[\sum_s \theta_{csr}^{\sigma_{cr}} \ (PS_{cs} + \rho_{csr})^{1-\sigma_{cr}} \right]^{1/1-\sigma_{cr}} \right] \right) + \left(M_{cr} * \upsilon_{cr} \ * PI_{cr} \right) - \left(\sum_p \left(\left(M_{cr} * \eta_{rcp} \right) * PS_{pr} \right) \right) = 0 \qquad (9)$$

D. Product Market Clearance Constraint:

The total refined product *p* supplied by refining region *r* is (QS_{pr}) must equal the consumption of product *p* from region *r* consumed at region *d* (QD_{prd}) summed over all *d*.

$$QS_{pr} - \sum_d QD_{prd} = 0 \qquad (10)$$

The refined product supply of product *p* at region *r* equals to the sum, over all crude types, of the refining region *r* import composite (M_{cr}) times the product refining yield (η_{rcp}). For any refining region *r* and product *p*, which can be presented as follows:

$$QS_{pr} = \sum_c \left(M_{cs} * \eta_{rcp}\right) \tag{11}$$

As with crudes, domestic and imported products are not perfect substitutes. Again, we turn to Armington (1969) and create a unit cost composite of imports and domestic product (M_{pd}) with the following CES unit cost C_{pd} which is a function of the FOB prices (PS_{pr}) from each source region plus the bilateral transport margin (ρ_{prd}):

$$C_{pd} = \left[\sum_r \theta_{prd}^{\sigma_{pd}} \left(PS_{pr} + \rho_{prd}\right)^{1-\sigma_{pd}}\right]^{1/1-\sigma_{pd}} \tag{12}$$

Again, the parameters θ_{prd} and σ_{pd} indicate the distribution across source regions and the elasticity of substitution. Using the cost function, we derive the conditional demands:

$$QD_{prd} = M_{pd} * \left[\frac{\theta_{prd} * C_{pd}}{PS_{pr} + \rho_{prd}}\right]^{\sigma_{pd}} \tag{13}$$

Substituting equations (11), (12) and (13) back into equation (10) gives the following equation:

$$\sum_c \left(M_{cs} * \eta_{rcp}\right) - \sum_d \left[M_{pd} * \left[\frac{\theta_{prd} * \left[\sum_r \theta_{prd}^{\sigma_{pd}} \left(PS_{pr} + \rho_{prd}\right)^{1-\sigma_{pd}}\right]^{1/1-\sigma_{pd}}}{PS_{pr} + \rho_{prd}}\right]^{\sigma_{pd}}\right] \tag{14}$$

E. Products Demand Constraint:

We assume that all consuming regions *d* behave competitively demanding refined products at the point where the marginal benefit equals marginal cost. The marginal benefit of each product *p* at each region *d* equals the inverse demand function (${QD_{pd}}^{-\beta_{pd}}$). The marginal cost equals its delivered composite product cost C_{pd} .

$$C_{pd} - QD_{pd}{}^{-\beta_{pd}} = 0 \quad (15)$$

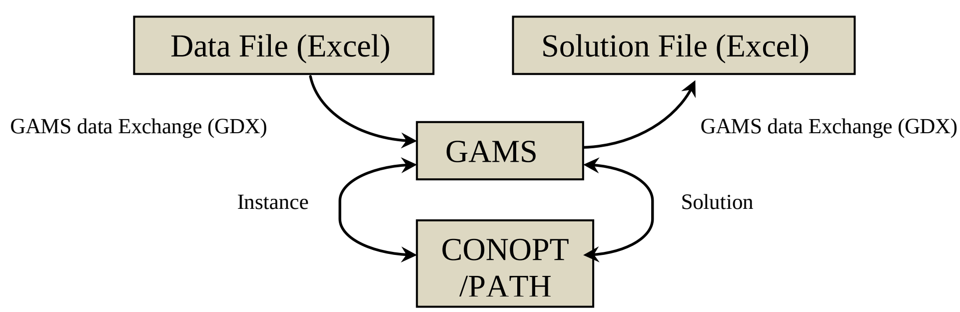
In this equation, β_{pd} is the inverse of the price elasticity of demand. Substituting for the C_{pd} from equation (12) yields:

$$\left[\sum_r \theta_{prd}^{\sigma_{pd}} \left(PS_{pr} + \rho_{prd}\right)^{1-\sigma_{pd}}\right]^{1/1-\sigma_{pd}} - QD_{pd}{}^{-\beta_{pd}} = 0 \quad (16)$$

As this equation shows, the consuming regions' importing preferences are constrained by four factors including: (1) the refined product price, (2) the product transportation costs, (3) the consumer's price elasticity of demand, and (4) the elasticity of substitution between domestic and imported products.

To find the optimal production levels for Saudi Arabia, for case one, we maximize the Saudi profit function, equation (1), subject to the market constraints discussed in equations (2), (3), (7), (9), (14), and (16). We first write the Non-Linear Programming (NLP) formulation in General Algebraic Modeling System (GAMS) and then solve it using the CONOPT solver which is a large scale NLP solver developed by ARKI Consulting and Development (Figure 1 shows the interfaces between GAMS, CONOPT, and Excel). Solving the model yields optimal production levels for the various crude types for Saudi Arabia in addition to all endogenous variables (crude and product markets clearing prices and quantities).

Figure 1: The model interfaces



Case-2: OPEC as a Profit Maximizing Cartel

In the second case, we include all OPEC regions in the profit function and remove constraint (3). OPEC's total profit (π_{OPEC}) from producing all crude types equals total productions of crudes c (QS_{cs}) times their "markup." Again, these markups are equal to the market price of crude c at region s (PS_{cs}) minus the marginal cost of crude c at region s (MC_{cs}) summed over all six crude types and OPEC members . Thus, OPEC's profit function can be presented as follows:

$$\pi_{OPEC} = \sum_s \sum_c QS_{cs} * (PS_{cs} - MC_{cs}) \qquad \forall\, s \in \text{OPEC} \tag{17}$$

We maximize OPEC's profit, equation (17), subject to market constraints (2), (7), (9), (14), and (16). Similar to the previous case, we use GAMS and CONOPT to solve for the optimal production levels for the various crude types for OPEC members in addition to all choice variables (crude and product markets clearing prices and quantities).

Case-3: Saudi Maximizing Profits Unilaterally Given a Competitive Fringe

In this case and similar to the first one, we maximize Saudi Arabia's economic profits given a competitive fringe that includes the rest of OPEC and non-OPEC producers. To find the optimal production levels for Saudi Arabia, we maximize equation (1) subject to the market constraints presented in equations (2), (7), (9), (14), and (16). Again, we write the NLP formulation in GAMS and then solve it using the CONOPT solver. That yields maximum feasible profits and optimal production levels for the various crude types for Saudi Arabia in addition to all other endogenous variables including market clearing prices and quantities for both crude and product markets.

Case-4: Competitive Market

In the fourth case, when all crude producers compete, they operate where prices equal marginal costs. Now equations (2), (7), (9), (14), and (16) are solved using GAMS and the PATH solver. The MCP solution includes the endogenous variables (crude and product markets clearing prices and quantities). In the next section, we describe all input data essential to calibrate and solve these four cases.

4. Model Inputs

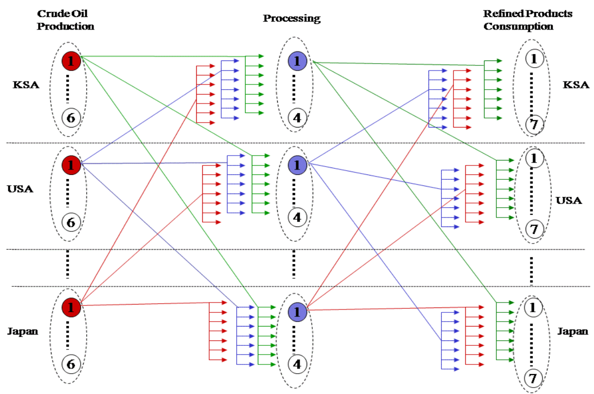
Model parameter inputs include benchmark crude oil and product trade matrices, crude processing configurations and yields, benchmark prices of crudes and products in addition to transportation cost matrices of both crudes and products (all are summarized in the Glossary). Model input functions include crude marginal cost curves by grade and region and refined product demand curves by type and region. All the input data are for the year 2004 because the data were gathered in 2007 when only 2004 numbers were available for all inputs.

Model Aggregation:

In the model description section, we define sets (s), (r), and (d) for crude supplying, crude refining, and for product demanding regions, respectively. Using data from the Energy Information Administration (EIA), we identify twenty-nine regions. We consider a region separately if it produces, refines, or consumes more than 2% of the global market. In the previous section we also define a set (c) of crude types. Despite the fact that several hundred types of crude oil are being produced around the world, we aggregate all these crude types into six crude types, five of which are exported by Saudi Arabia. These crude aggregations include light sweet (LTSW), heavy sweet (HVSW, not produced by Saudi Arabia), light sour (LTSR), medium-1 sour (MD1SR), medium-2 sour (MD2SR), and heavy sour (HVSR). These crudes are defined by their density (API specific gravity) and sulfur content (%), which are major determinants of their value.[3]

In the model, the set (*p*) of refined products includes liquefied petroleum gas (LPG), naphtha (NAPHTH), gasoline (GSLN), jet fuel and kerosene (JTKR), distillates (GSDOIL), residual fuel oil (RFO), and others (OTH). With these three defined sets, a piece of the described model can be presented schematically as in Figure 2.

Figure 2: A schematic representation for the model



In this figure, we assume that each of the twenty-nine regions produces and exports up to six types of crude to either a domestic or a foreign refining market. Once a certain crude type is received by the refining regions, it gets refined at fixed yields into seven refined products and then gets shipped to the consuming regions.

A. Crude Market Inputs

As shown in the Glossary, the parameter $QS0_{csr}$ represents the trade matrices in 2004, which are the crude (*c*) benchmark exports from producer (*s*) to refiner (*r*). Because such trading matrices do not exist for the various crude grades, we have compiled them from various data sources including the International Energy Agency (IEA), Energy Information Administration

[3] Crude grades are defined by API gravity (API) and sulfur content (%). The crude is classified LTSW if API>28 and sulfur content <1%, HVSW if API<28 and sulfur content <1%, LTSR if API>35 and sulfur content >1%, MD1SR if API between 33 and 35 and sulfur content >1%, MD2SR if API is between 30 and 33 and sulfur content >1%, and HVSR if API<30 and sulfur content >1%.

(EIA), Organization of Petroleum Exporting Countries (OPEC), Blackwell Energy Research, Ente Nazionale Idrocarburi (ENI) and Energy Intelligence Research.

We obtained total crude import-exports numbers for the OCED countries from the International Energy Agency (IEA) and OPEC members' imports-exports numbers from *OPEC's Annual Statistical Bulletin*. We filled in data for remaining countries from *World Oil Trade,* published by Blackwell Energy Research. We also used import-export numbers from the Energy Information Agency (EIA) to split the United States data into Eastern and Western regions. The U.S. East includes Petroleum Administration for Defense Districts (PADDs) 1, 2 and 3 while the Western U.S. includes PADDs 4 and 5.[4] The total computed imports for the OECD countries were very comparable and global imports were within 3% of the EIA numbers.

To split the generated trading matrix into six different matrices, one for each crude type, we used two sources: (1) the *Oil and Gas Review 2005* published by ENI and (2) *The International Crude Oil Market Handbook, 2006* published by the Energy Intelligence Research. These two sources were used to calculate production percentages per crude type resulting in six trading matrices, one for each crude type.

To create supply functions for regions *s*, we use equation (2):

$$PS_{cs} = \frac{A * QS_{cs}^{\psi}}{(\overline{QS}_{cs} - QS_{cs})} \qquad \text{where} \qquad \psi = \gamma - \frac{QS_{cs}}{(\overline{QS}_{cs} - QS_{cs})} \tag{18}$$

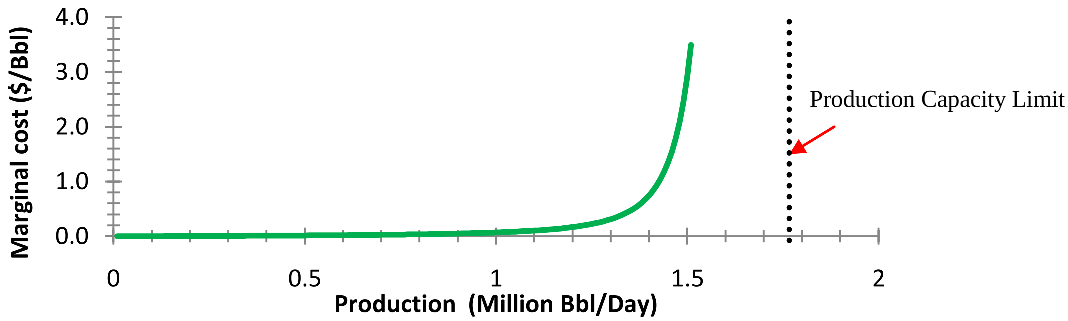
In this equation, the parameter γ is the inverse of the price elasticity of supply. For the model, we assume a long-run price elasticity of supply of 0.5 for regions where oil production has or is peaking (U.S., U.K., North Europe, and others). For regions with larger reserves and lower costs (Saudi, Iran, Iraq, and other Gulf producers), we assumed a larger long-run price elasticity of supply of 0.9 which reflects flatter supply curves. In between, a long-run price

[4] PADDs 4 and 5 include states of Alaska, Washington, Oregon, Nevada, California, Arizona, Montana, Wyoming, Idaho, Utah, and Colorado while PADDs 1, 2 and 3 include remaining states.

elasticity of supply of 0.7 was assumed for regions with larger reserves and higher costs (Canada, Russia, and Venezuela).

We calculate the psi (ψ) and the constant (A), in equation (18), that force the constructed marginal cost curves to go through the observed marginal costs and quantities produced in 2004. Taking the Saudi light sweet crude (LTSW) as an example, we calculate a constant value of 0.0533 and a psi value of 6.8155. Substituting back into equation (17) yields the marginal cost curve presented below in Figure 3. The supply functions for competitive producers outside OPEC are constructed in a similar fashion to those of OPEC with the exception that marginal costs equal market prices.

Figure 3: Supply curve for Saudi Arabian Super Light (LTSW) crude

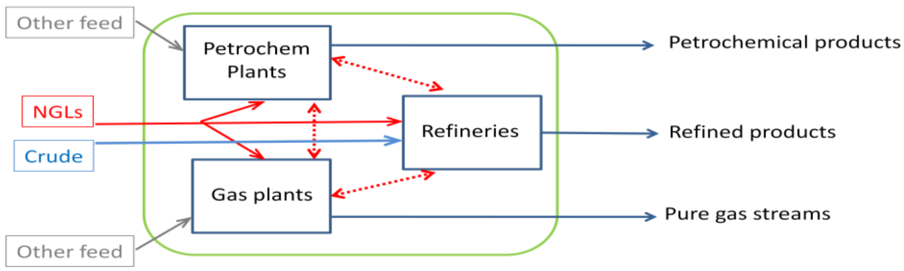


We impose production capacity constraints ($\overline{QS}_{cs}$) on the crude supply side of the model with each region supplying crude as described above until the capacity is reached. Once the marginal cost curve hits capacity, it becomes vertical and approaches infinity. We obtained the data on production capacity from EIA and OPEC.

B. Refining Sector Inputs

In the second component of the model, the refining sector, we link the crude supply sector to the refined product demand sector. The refining sector includes not only refineries but also gas plants and petrochemical plants (Figure 4).

Figure 4: The model's refining sector



The figure shows that NGLs produced from gas production operations get shipped either straight to refineries for blending, or to the petrochemical industry, or sometimes stay within gas plants for further fractionations or direct-market sales. Because we could not find detailed data on NGLs flows between gas plants, refineries and petrochemical industries, we combine these three entities into our "refining" sector. In this sector, we observe crude streams flowing in (crude oil, NGL, refinery feed stocks and other hydrocarbons) with refined product streams flowing out (refinery gas, ethane, LPG, naphtha, gasoline, jet fuel, kerosene, distillate fuel oil, RFO and others).

As there are more than seven hundred refineries around the world, each with a different configuration yielding different refined products cuts for various crude types, we aggregate to simplify the refining activities. We start by aggregating the refining activities in each region into four major refinery types (topping, hydro-skimming, cracking, or coking) and then we choose one refinery type to represent each region. The refinery configuration for region *r* decides the refined product yields by crude type (η_{rcp}). Data on both regional refining activities and refining yields of the various refinery types are obtained from industry sources.

We also need value-added in the refining sector by region so that all processing regions make zero economic profits. This term is calculated as a residual using equation (9) and is positive if the refined products sales from a certain crude type are greater than the cost of that same crude and is negative if the refined products sales from a certain crude type are less than the cost of that same crude.

C. Refined Product Market Inputs

For the required product market's data, we used the same regional aggregation and refined products classification as in the crude supply and processing sectors. As shown in the Glossary, an important input parameter to the model is $QS0_{prd}$ which represents the refined products (*p*) benchmark exports from refining region (*r*) to consuming region (*d*). We obtained data for our refined products trading matrices from Blackwell Energy Research, IEA and EIA.

We used the actual OECD countries' import and export figures obtained from the IEA. For the non-OECD countries, the process is more cumbersome. We started with a trading matrix from Blackwell Energy Research. However, their matrix had two major problems, (1) it showed the aggregate import and export figures for all refined products aggregated, and (2) it showed a total trade figure that was three times that of the EIA's. Nevertheless, since there is no source that provides a better view of refined products flow magnitudes and directions, we used this trading matrix to generate an import percentage matrix and then applied it to the individual countries total import by product obtained from the IEA database.

This resulted in seven different trading matrices, one for each refined product: Liquefied Petroleum Gas (LPG), naphtha, gasoline, kerosene/jet fuel, distillates, residual fuel oil (RFO), and others. Again, we used data from the *International Energy Annual, 2005* published by the EIA to split the United States into two regions, Eastern (including PADDs 1, 2 and 3) and Western (including PADDs 4 and 5). Fortunately, we found the total aggregate trade presented in these seven matrices was within 3% of the IEA figures.

In equation (16), we have β_{pd} in a double log relation between refined products prices and quantities demanded for all consumers. The parameter refers to the inverse of the price elasticity of demand, which we calculate from a database of elasticity studies developed and maintained by Dr. Carol Dahl, Professor of Mineral Economics at Colorado School of Mines.

D. Transportation Costs and Prices Inputs

Since most of the above crude and refined product supply centers are spatially separated from the demand centers, we need transportation costs. In Figure 1, the transportation sector is represented by arcs connecting crude producers to crude refiners and then to end consumers. Also, each of these arcs carries a shipping cost which varies according to the transportation mode, route and distance, crude or product type and tanker size. In the Glossary, parameters ρ_{csr} and ρ_{prd} represent crude transportation costs between crude producing and processing regions and products transportation costs between processing and demand regions, respectively. To find data related to these parameters, we first identify a shipping port for each of the model's twenty-nine regions. We consider only the transportation costs using tankers rather than pipelines for two main reasons: (1) shipping costs on the margin should be similar and were for those we could check, and (2) data on pipelines transportation costs are not readily available, especially on the eastern European block pipelines from Russia.

We obtain the data on transportation costs using tankers between the chosen ports for 2004 primarily from two sources: (1) Worldscale Association (NYC) Inc. which runs a database that covers shipping rates for all tankers' sizes and routes worldwide, and (2) Platts Energy Information, a division of The McGraw-Hill companies. Both sources treat crudes and products as either clean (naphtha, gasoline, jet fuel, and kerosene) or dirty (crude oil, heavy and residual fuel oil, and asphalt). Starting with the dirty products, we filled in the transportation cost matrix using Worldscale numbers. As these Worldscale numbers are reported for a standard vessel at the beginning of the year 2004 and as the shipping rates changed on daily basis throughout the year, the Worldscale number had to be adjusted to reflect the actual shipping rates. The adjustments were done using the Platts numbers which come as a percentage of the Worldscale. We also obtained transportation matrices for the clean products by repeating the exercise.

We use the resulting thirteen transportation matrices, six for crude types and seven for refined products, to create the model's benchmark prices for 2004. To get the crude delivered (CIF) prices at all crude importing regions, we add Ras Tanura's FOB crude prices to the crude transportation costs from Ras Tanura to all the importing destinations. Similarly, to get the refined product CIF prices at all product importing regions, we add Rotterdam's product FOB prices to the transportation costs between Rotterdam and all these importing regions.

5. Model Solutions

Case-1: Saudi Maximizing Profits Unilaterally

Solving the NLP system for the first configuration, maximizing equation (1) subject to (2), (3), (7), (9), (14), and (16), yields the maximum profit for Saudi Arabia along with all the choice variables including clearing prices and the quantities for both oil and refined products. The crude market clearing prices and quantity are then used to calculate economic profits for all other crude oil producers knowing their marginal cost equations. Again, only producers within OPEC make abnormal profits on the margin as they maintain a wedge (mark-up) between market price and their marginal costs.

The model results for this case show that a more optimal crude production allocation grants Saudi Arabia a higher economic profit whereby its crude markups increase by less than \$2 a barrel and its profit increases by about \$5.2 million a day (1.6%) which is equivalent to almost

$1.9 billions a year (Table 1 in Appendix B). Indeed, this demonstrates that Saudi Arabia did a fairly good job in 2004, as actual total production levels were within 3.85% of the optimal.

The rest of OPEC benefited even more from Saudi production decreases by selling more output (23.867 million barrel a day) at higher prices increasing their economic profits by almost $ 3 billion a year (1.02% increase).[5] Producers outside OPEC increase their production by a very small amount at these higher prices reaching 47.091 million barrels a day. They still realize zero economic profits on the margin as they are assumed to produce competitively.

For the refined product market, the quantity demanded by consumers falls by 1 to 3% for all product types in response to the increase in the products prices (1 to 3%). Such an increase in the refined products prices is a natural response to the crude streams price increases as refiners pass their crude costs onto product consumers (Table 2 in Appendix B).

Case-2: OPEC as a Profit Maximizing Cartel

In the second case, OPEC as a whole maximizes its economic profits, equation (1), from its members' six crude grade sales subject to crude and product market constraints presented by equations (2), (7), (9), (14), and (16). Again, only producers within OPEC make economic profits on the margin while non-OPEC producers are assumed to produce competitively at their marginal costs. Looking at Saudi profits, production levels and prices for various crude types, we can see that Saudi Arabia makes more profits when coordinating production with the rest of OPEC because now the rest of OPEC also reduces production (Table 3 in Appendix B). Total world output falls by 1.4 million barrels per day and prices rise in general by less than 7%. At these higher prices, the fringe produces slightly more (36,000 barrels a day).

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[5] The model's output prices are 2004 dollars per barrel and can be converted to 2007 dollars by multiplying by the inflation rate.

In this case, the increase in Saudi profits is over 4 billion dollars a year more, double their profits when they optimize alone. The model suggests that Saudi crude markups increase by less than $4 a barrel and that their benefit of coordinating production with the rest of OPEC is around 4 billion dollars a year or 3.47% of their 2004 profits. Interestingly enough, the benefits to the rest of OPEC members are even higher. When they coordinate production with Saudis, both of their crude mark-ups increase (by less than $4 a barrel) and their profits increase by $28 billion a year which is about 10% of their 2004 profits. In response to the higher oil prices, the model also suggests that producers outside OPEC will increase their production by 36,000 barrels per day reaching 47.116 million barrels per day.

The drop in crude quantity supplied and the increase in crude prices penetrates into the refined product market as refiners pass their crude costs onto the product consumers. The model suggests that the product quantity demanded by consumers would fall by 1 to 5% for all product types and in response the product prices increase by1 to 7% (Table 4 in Appendix B).

Case-3: Saudi Maximizing Profits Unilaterally Given a Competitive Fringe

In the third case Saudi Arabia maximizes its economic profits, equation (1), while all other producers, including the rest of OPEC producers, act competitively (constraints (2), (7), (9), (14), and (16)). Similar to case 1 (Saudi maximizing alone), solving the model yields maximum feasible profits and optimal production levels for the various crude types for Saudi Arabia in addition to all other variables including market clearing prices and quantities for both crude and product markets (Table 5 in Appendix B).

The model output shows that the competitive behavior for the rest of OPEC requires that they increase supplies by 0.94 MBPD (3.94%), mostly light sweet, and collect zero economic profits on the margin. Such a surge in production is met by: (1) a general drop in the oil price of all crude types, and (2) a Saudi attempt to sustain prices at a higher level. Therefore, we notice that prices drop by less than 3% and that Saudi production decreases by about 0.33 MBPD (4.03%). In percentages terms, the Saudi production cuts are 1 to 6% for crude grade streams with the Arabian Light stream (MD1SR), the largest stream, contributing the largest.

Although the new Saudi production levels are optimal, they grant Saudi Arabia a lower economic profit than that of 2004 whereby its profit drops by about $3.09 million per day (around 1%) which is equivalent to almost $1.13 billion a year. The Saudi Arabian crude markups incresae by less than $2 a barrel. Still, the model suggest that Saudi Arabia did a good job in 2004, even if the rest of OPEC acted competitively, as actual production levels were within 4.03% of the optimal. Similar to the previous two cases, the light sweet (LTSW) stream is still the most profitable crude stream as it had the largest differential between its market price and marginal cost. In response to the lower oil prices, the model also suggests that producers outside OPEC will lower their production by a very small amount (less than 10,000 barrels per day) reaching 47.071 million barrels per day.

In general, the quantities of refined products demanded by consuming regions rise by less than 2% for all product types in response to the general decrease in the products prices (1 to 3%). Again, the fall in the refined products prices is a natural response to the crude streams price decrease as refiners pass their crude costs onto product consumers (Table 6 in Appendix B).

Case-4: Competitive Market: OPEC Dissolved!

In case 4, all economic profits for all producers are constrained to be zero on the margin and the model (equations 2, 7, 9, 14 and 16) is solved as an MCP. The former non-competitive players now produce more, driving prices down and economic profits to zero. The former competitive players are now producing less at these competitive prices. Saudi production level increases by 1.16 million barrels a day (11.13%), the rest of OPEC production increasers from all grades by 0.94 million barrels per day (3.9%) and non-OPEC production drops by 0.033 million barrels per day (Table 7 in Appendix B).

We believe that these small changes in the total world crude production (increase of 2.5%) and market clearing prices (fall by 3.8%) are driven mainly by the production capacity limits in the marginal cost curves.[6] We find that relaxing the production capacity limits by 20% results in a Saudi Arabian production level increases of 2.81 million barrels a day (26.93%), the rest of OPEC production increases from all grades by 4.21 million barrels per day (17.63%) and non-OPEC production drops by 0.419 million barrels per day. The model results for this sensitivity run shows a more significant prices drop of 4 to 23%.

This surge in crude quantity supplied and the drop in crude prices stimulated the refined products market encouraging product consumers to demand more at lower product prices. Products prices in some regions dropped as much as 13% and in response, the product quantity demanded by consumers increased by as much as 14% for some product types (Table 8 in Appendix B).

Sensitivity Analysis

As the model's results depend on the choice of parameters in the model, we run some sensitivity analysis to assess the impact of changes in these parameters on the model's outputs of our first model configuration: Saudi maximizing profits unilaterally. The parameters changes include: (1) increasing or decreasing crude and products transportation costs between all regions by 50%, (2) increasing or decreasing the price elasticity of supply by 50% for all regions, (3) increasing or decreasing the price elasticity of demand by 50% for all regions, (4) increasing the

[6] As in equation (2), the capacity limits force the marginal cost curves to shoot to infinity as production approaches capacity.

crude production capacities by 20% for all regions. In Table 2 we present the impact on Saudi Arabia's profit of varying the values of the four parameters mentioned above one at a time.

Table 2: Sensitivity Analysis Effect on the Saudi Profit

Parameter		Parameter Values			Saudi Profits ($Million/Day)			Saudi Profits Changes (%)	
		Low	2004	Up	Low	2004 Optimal	Up	Low	Up
Transport Costs	ρ_{csr} ρ_{prd}	-50%	**Tables 15-27 Appendix B**	+50%	330.511	**330.154**	329.240	**0.11**	**-0.28**
Demand Elasticity	β_{pd}	-50%	**Table 7**	+50%	332.843	**330.154**	329.261	**0.81**	**-0.27**
Supply Elasticity	γ_{cs}	-50%	**Table 6**	+50%	330.747	**330.154**	329.958	**0.18**	**-0.06**
Production Capacity	$\overline{QS}_{cs}$	-	**Table 5**	+20%	-	**330.154**	326.299	**-**	**-1.17**

In general, and as can be seen from the table above, the Saudi profit is more sensitive to the change in production capacities than changes in the other three parameters. When the production capacity constraint is relaxed by 20%, the model results show a surge in the Saudi's production by almost 5% in an attempt to discourage other producers from tapping into their new capacities. This production surge caused prices to fall by 1 to 3%. In response, the rest of OPEC and the rest of the world lowered their production by 0.04% and 0.03% respectively. Although the model suggested that the new Saudi production levels are optimal, we still notice a profit drop of 1.2% for both Saudi Arabia and the rest of OPEC.

In the more competitive market, the fourth case above, we notice that relaxing the capacity constraint has a bigger effect on the model clearing prices (drop of 4 to 23%). This confirms our previous concern that the marginal cost curve structure plays an important role in the model output. The model's detailed outputs and sensitivity cases results are available upon request from the lead author.

6. Conclusion and Extensions

In this thesis we built a unique partial equilibrium model for the global oil market to find optimal production levels for the various Saudi Arabian crude grades that Saudi Arabia produces. The model maximizes Saudi Arabia's profits subject to various oil market constraints including crude oil market structure, crude and product supplies and demands, production and transportation capacities and costs, and refinery yields and capacities. The model includes crude production and transportation, a refining sector, transportation of products, and end use product demand for six crude types, four refinery configurations, and seven refined products for twenty-nine world regions. We believe that such an effort is unique as our literature review reveals that none of the previous models has studied an optimization of Saudi Arabia's production per crude grade at this level of complexity. We also believe that our modeling approach is unique as we measure the actual market conditions (demand and cost schedules) and rather than forming a conjecture about the degree of competition across crude suppliers, we ask how market behavior changes when Saudi or OPEC decision makers are only concerned with economic profit.

We described the model mathematically, explained how various market constraints are modeled, solved the model and then presented the model's output for four cases: (1) Saudi Arabia unilaterally maximizing, (2) OPEC acting as a profit maximizing cartel, (3) Saudi Arabia unilaterally maximizing given a competitive fringe behavior, and (4) a competitive market. We also compared Saudi production profiles, profits and prices by crude grade.

Our direct measurement of the market conditions suggests that Saudi Arabia is not fully exercising its market power, but the deviations for unilateral profit maximization are not great. Profit maximization suggests a 3.85% decrease in Saudi Arabia's output. This translates into $1.9 billion of unrealized profits in 2004. This implies that Saudi Arabia may not fully exercise its market power and may have objectives other than pure profit maximization. We also find that OPEC (both Saudi and rest of OPEC) could increase the joint profits if all regions restrict output. This suggests that OPEC is less than fully effective as a cartel. In addition, our direct measurements suggests that in a competitive market environment, the world's total crude production increases by 2.5%, crude prices fall by about 3.8% on average, total Saudi profit falls by 118 billion dollars a year while the rest of OPEC's total profit falls by 286 billion dollars a year.

As the model results for the first three configurations show, neither Saudi Arabia nor OPEC fully exercises market power. Reasons behind the deviation from the optimal production levels (4-6%) may include an array of social and political objectives. In fact, all OPEC country-members are involved in distributing their oil wealth to their societies in general through fuels subsidies, job programs, and social welfare programs. As oil industries constitute the larger and more sophisticated sector in most of OPEC countries, these industries are always used as a tool in the economic development process introducing new technologies and attracting foreign direct investments. Oil industries and policies are also used by OPEC members to achieve various political objectives including asserting certain political positions, forming political alliances and relationships, or even assuring their major consumers more secured energy supplies.

To test the model's sensitivities to changes in parameters, we assessed the impact of changing transportation costs, crude price elasticities of supply, product price elasticities of demand and production capacities on the Saudi profits in the case when Saudis maximize profits unilaterally. We found the model to be most sensitive to changes in production capacities but not so sensitive to changes in other parameters.

Model expansions for future research include: expanding to four refining configurations in each region, splitting Saudi Arabia to east and west regions, disaggregating gas plants and petrochemicals from the refining sector, including a pipeline transportation sector, including more sophisticated supply and demand functions, making the model dynamic and include reserves, integrating the model backwards to include by field and by well production levels, developing a mechanism to keep the trading and transportation matrices updated, incorporating production subsidies and taxes on refined products, adding crude and refined product stocks, and including product specification limitations on imports for the various regions.

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Model Glossary

Sets:

s	Set of crude producers
r	Set of crude refiners
d	Set of product consumers
c	Set of crude types
p	Set of refined product types

Parameters (exogenous):

$\overline{QS}_{cs}$	Production capacity of crude (*c*) at producing region (*s*) in 10^6Bbl/D
ρ_{csr}	Crude (*c*) transport cost from producer (*s*) to refiner (*r*) in $/Bbl
ρ_{prd}	Product (*p*) transport cost from refiner (*r*) to consumer (*d*) in $/Bbl
η_{rcp}	Refining yields at refiner (*r*), for refined product (*p*) from crude (*c*) in %
γ_{cs}	Inverse of the price elasticity of supply of crude (*c*) for producer (*s*)
ν_{cr}	Initial value added for inputs at refiner (*s*) for crude (*c*) in $
β_{pd}	Inverse of the price elasticity of demand of product (*p*) for consumer (*d*)
τ_{cs}	Initial markup in % (calculated)
m_{csr}	Initial crude (*c*) imports from producer (*s*) to refiner (*r*) in10^6Bbl/D
θ_{csr}	Share of crude (*c*) imported from producer (*s*) to refiner (*r*) in % (calculated)
θ_{prd}	Share of product (*p*) imported from refiner (*r*) to consumer (*d*) in % (calculated)
σ_{cr}	Armington elasticity of substitution between imported and domestic crude (*c*) at refining region (*r*)
σ_{pd}	Armington elasticity of substitution between imported and domestic product (*p*) at consumer (*d*)
$QS0_{cs}$	Initial crude (*c*) supply from producer (*s*) in 10^6Bbl/D
$PS0_{cs}$	Initial crude (*c*) Free On Board (FOB) price at producer (*s*) gate in $/Bbl
$PD0_{cr}$	Initial crude (*c*) Cargo, Insurance and Fright (CIF) price at refiner (*r*) gate in $/Bbl
$QS0_{prd}$	Initial product (*p*) supply/exports from refiner (*r*) to consumer (*d*) in 10^6Bbl/D
$PS0_{pr}$	Initial product (*p*) Free On Board (FOB) price at refiner (*r*) gate in $/Bbl
$PD0_{pd}$	Initial product (*p*) Cargo, Insurance and Fright (CIF) price at consumer (*d*) gate in $/Bbl
C_{cr}	Unit cost function for crude (*c*) at refiner (*r*) (calculated)
C_{pd}	Unit cost function for product (*p*) at consumer (*d*) (calculated)

Variables (Endogenous):

π_s	Profits from crude production operations for any crude producer (s) in $$10^6$
QS_{csr}	Crude (*c*) supply/exports from producer (*s*) to refiner (*r*) in 10^6Bbl/D
QS_{cs}	Crude (*c*) supply/exports from producer (*s*) in 10^6Bbl/D
MC_{cs}	Marginal cost of crude (*c*) at producing region (*s*) in $/Bbl
QD_{csr}	Crude (*c*) imports/demand from producer (*s*) to refiner (*r*) in 10^6Bbl/D
PS_{cs}	Crude (*c*) Free On Board (FOB) price at producer (*s*) gate in $/Bbl
PD_{cr}	Crude (*c*) Cargo, Insurance and Fright (CIF) price at refiner (*r*) gate in $/Bbl
RL_{cr}	Refining level of crude type (*c*) at refiner (*r*) in%
M_{cr}	Composite of imports of crude (c) at refiner (*r*) in10^6Bbl/D
$M0_{cr}$	Initial Composite of imports of crude (c) at refiner (*r*) in10^6Bbl/D
PI_{cr}	Price index on value added inputs of crude (*c*) at refiner (*r*) = (M_{cr}/ $M0_{cr}$)
QS_{pr}	Product (*p*) exports/supply by refiner (*r*) in 10^6Bbl/D
QD_{prd}	Product (*p*) demand by consumer (*d*) from refiner (*r*) in 10^6Bbl/D
QD_{pd}	Product (*p*) demand by consumer (*d*) in 10^6Bbl/D
PS_{pr}	Product (*p*) Free On Board (FOB) price at refiner (*r*) gate in $/Bbl
PD_{pd}	Product (*p*) Cargo, Insurance and Fright (CIF) price at consumer (*d*) gate in $/Bbl
ψ_{cs}	Function of the inverse of the price elasticity of supply of crude (*c*) for producer (*s*)

Appendix-A: Literature Review Summary

Table 1: A summary of the literature review on OPEC behavior

			Model/Study	**Finding**
Market Power Models	A-Cartel Behavior	Indicating Collusive Behavior	Griffin and Teece (1982)	Recognized the presence of economic rent and power over price.
			Geroski, Ulph and Ulph (1987)	Rejected the "constant behavior" hypothesis.
			Dahl and Yucel (1991)	OPEC behavior can be described as a loose coordination or duopoly.
			Polasky (1992)	Pattern of extraction in the oil market is inconsistent with either patterns predicted by competitive theory or dominant firm-competitive fringe theory.
			Danielsen and Kim (1998)	Cooperation among OPEC countries is significant.
			Smith (2005)	OPEC is much more than a non-cooperative oligopoly, but less than a frictionless cartel.
		1-One Cartel Models	Griffin (1985)	Partial market sharing cartel model could not be rejected for OPEC.
			Jones (1990)	Most OPEC members continued to behave like a "partial market sharing" cartel while non-OPEC behaved more competitively.
			Loderer (1985)	Found evidence that OPEC members colluded in years 1980-1983.
			Youhanna (1994)	Partial market sharing cartel model dominates all other models.
			Al-Sultan (1995)	Nash-Cournot non-cooperative model (OPEC as a Nash-Cournot versus a fringe) can potentially explains the oil market more than the competitive.
			Gulen (1996)	Evidence of output coordination and suggested that OPEC acted like a cartel in the 1980's (1982-1993).
			Molchanov (2003)	OPEC behavior is consistent with cartel theory.
			Bockem (2004)	Crude oil market is best describes as a price leader model where OPEC appears to be the leader and all non-OPEC are regarded as price takers.
		2-Two and Three-Part Cartels	Tourk (1977)	Divided OPEC into two blocs as they may have different discount rates.
			Hnyilicza and Pindyck (1976)	The "cartel", OPEC, is composed of two blocks: spenders and savers.
			Aperjis (1982)	Concluded that OPEC behavior could be explained by a two-part cartel including spenders and savers.
			Eckbo (1976), Houthakker (1979), Norenge (1978), and Griffin and Steele (1986)	Three-part cartel including core members, price maximizing members and quantity maximizing members.
	B-Dominant Firm	1-Saudi Arabia as Dominant Firm	Mabro (1975), Erickson (1980)	Saudi Arabia is a dominant producer.
			Plaut (1981)	OPEC behaves more like an oligopoly with Saudi Arabia as a price leader and largest producer.
			Singer (1983)	Saudi Arabia and smaller Arab producers produce the residual demand and determine the worlds' oil price.
			Adelman (1986, 1990, 1993 and 1995)	Identified OPEC as the market power and price increases have nothing to do with scarcity. Saudis have acted as what they are: the leading firm in the world oil market.
			Griffin and Nielson (1994)	Saudi Arabia played a significant role in disciplining and rewarding the cartel members through its tit-for-tat strategy.
			Al-Yousef (1998)	Saudi Arabia acted as a swing producer in the period 1976-1986 and like a market sharing producer for the period 1978-1995.
			Alhajji and Huettner (2000)	OPEC is mainly Saudi Arabia, the dominant producer, and some other sub-groups and Saudi alone acts like a dominant producer.
			Spilimbergo (2001)	Reached the same results as Alhajji and Huettner (2000).
			De Santis (2003)	Short run price fluctuations are due to OPEC quota agreements while in the long run Saudi Arabia acts like a dominant firm.
		2- Core Group as a Dominant Firm	Delay et al (1982)	Grouped OPEC into three groups: Cartel Core (Saudi/Kuwait/UAE/Qatar/Libya), Price Maximizers (Iran, Algeria, Venezuela), and Output Maximizers (rest of OPEC-13).
			Dahl and Yucel (1990)	OPEC, rather than being a weak cartel, consists of a non-competitive core of swing producers.
			Mabro (1991)	The core producers can set either a supply plan or more straightforwardly a price.
			Hansen and Lindholt (2004)	Dominant producer behavior fits core-OPEC very well after 1994.
	C-Target Behavior Models	1-Target Revenue Models	Adelman (1982)	Backward bending supply curve could explain OPEC behavior in the short run.

			Model/Study	Finding
			Teece (1982)	OPEC will shut-in or increase production capacity to meet certain export receipts and foreign earnings.
			Salehi-Isfahani (1987)	Conclusion supported the target revenue model.
			Tussing (1989)	OPEC can control the world oil market via restricting supplies to increase prices and achieve certain revenues.
			Alhajji and Huettner (2000)	African OPEC countries (Algeria, Libya, and Nigeria) were found to be fitting the backward-bending supply curve.
			Ramcharran (2001 and 2002)	Partially supporting the hypothesis of a strict version of the revenue target model.
		2-Target Capacity Models	Suranovic (1993)	Suggested that the Target Capacity Utilization (TCU) model is optimum for OPEC's members when (1) there are no lags in supply and demand or (2) they optimize subject to a minimum revenues constraint.
		3-Target Price Models	Hammoudeh and Medan (1995)	OPEC credibility to intervene is directly related to oil price sensitivity to the change in the output and expectations.
			Hammoudeh (1997)	Suggested that OPEC shifts the target zone when it can not hold in line with previous targets. Also suggested that price fluctuations are caused by market participants who form expectations about OPEC actions.
			Tang and Hammoudeh (2002)	OPEC becomes more explicit in adopting a target price zone model.
Other Models (competitive)	Political Models		MacAvoy (1982)	Oil price increase in 1973-74 and 1979-80 were due to shortages and cut backs from political conditions and accidents.
			Verleger (1987)	Followed the same path as MacAvoy (1982) and explained the oil market behavior using a competitive model.
			Moran (1981)	Saudi behavior can be better explained by "an operational code of advancing Saudi political priorities while minimizing hostile external and internal pressures upon the kingdom .
			Ezzati (1976 and 1978)	Price increase was due to political factors and sustained because OPEC members have limited absorptive capacity.
	Property Right Models		Johany (1979 and 1980)	Argued that the price hike in 1974 was a result of property rights changes (national oil companies have lower effective discount rate than oil companies)
			Mead (1979) and Odel and Rosing (1983)	Believed that the price increased in 1973 was mainly due to the property rights changes.

Appendix-B: Model Results

Case-1: Saudi Arabia Maximizing Profits Unilaterally

Table 1: Crude Market Solution when Saudis Maximizes Profits Unilaterally

Region	Crude*	Model Output When Saudis Maximizes Profits Unilaterally				Changes		
		Price	Quantity	Profits		Price	Quantity	Profits
		$/Bbl	Million Bbl/Day	$Million/ Day	$Billion/ Year	%	%	%
KSA	LTSW	38.28	1.50	52.751	19.254	0.65	-0.65	0.79
	HVSW	-	-	-	-	-	-	-
	LTSR	36.40	1.39	48.130	17.567	1.66	-4.29	1.05
	MD1SR	34.17	4.79	158.621	57.897	1.55	-4.39	2.39
	MD2SR	32.41	1.30	40.192	14.670	2.32	-5.01	0.90
	HVSR	30.64	1.05	30.461	11.118	1.73	-3.76	0.62
			10.02	**330.154**	**120.506**		**-3.85**	**1.59**
R-OPEC (7 regions)	LTSW	39.83	11.44	409.152	149.341	0.93	0.02	1.01
	HVSW	33.73	0.49	12.475	4.553	1.18	0.03	1.26
	LTSR	36.47	2.30	77.586	28.319	0.81	0.02	0.78
	MD1SR	35.00	7.48	232.901	85.009	1.04	0.03	1.07
	MD2SR	33.34	0.75	21.989	8.026	1.46	0.05	1.57
	HVSR	33.28	1.41	38.683	14.119	0.92	0.02	0.89
			23.87	**792.787**	**289.367**		**0.02**	**1.02**
ROW (21 regions)	LTSW	40.94	25.52	0	0	0.91	0.02	0
	HVSW	33.92	2.02	0	0	1.18	0.03	0
	LTSR	38.90	0.11	0	0	1.04	0.02	0
	MD1SR	36.72	11.82	0	0	1.01	0.02	0
	MD2SR	34.58	0.64	0	0	1.51	0.03	0
	HVSR	33.38	6.98	0	0	0.83	0.02	0
			47.091	**0**	**0**		**0.02**	**0**
Total			**80.98**		**409.87**		**-0.47**	**1.18**

Notes: Prices are trade weighted average prices from the model prices output. Quantities are aggregated from model output. Profits for Saudi Arabia are NLP results. Profits for rest of OPEC are calculated using equation (1) and are all zero for non-OPEC regions. Prices are in 2004 US dollars. Light sweet (LTSW), heavy sweet (HVSW), light sour (LTSR), medium-1 sour (MD1SR), medium-2 sour (MD2SR), and heavy sour (HVSR).

Table 2: Products Market Solution when Saudi Maximizes Profits Unilaterally

Region	Product*	Model Output When Saudis Maximizes Profits Unilaterally		Change	
		Price ($/Bbl)	Demand Million Bbl/Day	Price %	Demand %
KSA	LPG	32.689	0.342	1.18	-0.72
	NPHTH	45.860	0.108	1.44	-0.16
	GSLN	51.190	0.279	0.77	-0.41
	JTKR	54.692	0.060	1.09	-0.12
	GSDOIL	51.928	0.427	1.92	-1.51
	RFO	28.261	0.310	1.42	-0.96
	OTH	44.001	0.340	1.96	-1.24
			1.867		**-0.94**
R-OPEC (7 regions)	LPG	31.95	0.413	0.52	-0.35
	NPHTH	44.98	0.150	1.15	-0.10
	GSLN	50.26	1.328	0.32	-0.13
	JTKR	53.94	0.573	1.13	-0.22
	GSDOIL	50.62	1.531	0.97	-0.33
	RFO	27.26	0.943	0.71	-0.12
	OTH	42.77	0.391	0.84	-0.55
			5.329		**-0.24**
ROW (21 regions)	LPG	31.42	7.245	0.43	-0.40
	NPHTH	44.62	4.539	1.30	-0.15
	GSLN	49.89	19.357	0.38	-0.24
	JTKR	53.53	5.792	1.19	-0.34
	GSDOIL	50.08	20.489	0.83	-0.43
	RFO	27.16	8.796	0.72	-0.48
	OTH	42.59	8.805	0.64	-0.41
			75.022		**-0.36**

Notes: Prices are in 2004 US dollars. Liquefied petroleum gas (LPG), naphtha (NPHTH), gasoline (GSLN), jet fuel/kerosene (JTKR), distillate (GSDOIL), residual fuel oil (RFO), and others (OTH)

Case-2: OPEC as a Profit Maximizing Cartel

Table 3: Crude Market Solution when OPEC Maximizes Profits as a Cartel

Region	Crude* Type	Model Output When OPEC Maximizes Profits as a Cartel				Changes		
		Price	**Quantity**	**Profit**		**Price**	**Quantity**	**Profit**
		$/Bbl	**Million Bbl/Day**	**$Million /Day**	**$Billion/ Year**	**%**	**%**	**%**
KSA	LTSW	38.41	1.41	51.925	18.953	0.99	-6.65	-0.79
	LTSR	37.66	1.33	48.495	17.701	5.17	-8.86	1.82
	MD1SR	35.25	4.80	164.023	59.868	4.76	-4.04	5.88
	MD2SR	33.62	1.27	41.157	15.022	6.12	-7.25	3.32
	HVSR	31.63	1.00	30.655	11.189	5.02	-8.06	1.26
			9.81	**336.254**	**122.733**		**-5.93**	**3.47**
R-OPEC (7 regions)	LTSW	41.13	11.01	445.401	162.571	4.24	-3.74	9.96
	HVSW	35.36	0.46	15.576	5.685	6.07	-4.64	26.42
	LTSR	37.40	2.24	81.067	29.589	3.37	-2.67	5.30
	MD1SR	36.26	7.26	251.275	91.715	4.67	-2.92	9.04
	MD2SR	34.57	0.73	23.787	8.682	5.22	-3.81	9.87
	HVSR	34.19	1.35	44.530	16.254	3.69	-4.19	16.14
			23.04	**861.635**	**314.497**		**-3.43**	**9.79**
ROW (21 regions)	LTSW	41.76	25.53	0	0	2.93	0.07	0.00
	HVSW	35.27	2.02	0	0	5.24	0.11	0.00
	LTSR	40.08	0.11	0	0	4.13	0.09	0.00
	MD1SR	37.71	11.83	0	0	3.73	0.08	0.00
	MD2SR	35.63	0.65	0	0	4.59	0.10	0.00
	HVSR	34.01	6.98	0	0	2.74	0.07	0.00
			47.116	**0**	**0**		**0.07**	0.00
Total			**79.97**		**437.23**		**-1.7**	**7.9**

Notes: Prices are trade weighted average prices from the model prices output. Quantities are aggregated from model output. Profits for Saudi Arabia are NLP results. Profits for rest of OPEC are calculated using equation (1) and are all zero for non-OPEC regions. Prices are in 2004 US dollars. Light sweet (LTSW), heavy sweet (HVSW), light sour (LTSR), medium-1 sour (MD1SR), medium-2 sour (MD2SR), and heavy sour (HVSR).

Table 4: Products Market Solution when OPEC Maximizes Profits as a Cartel

Region	Product*	Model Output When OPEC Maximizes Profits as a Cartel		Change	
		Price ($/Bbl)	Demand Million Bbl/Day	Price %	Demand %
KSA	LPG	33.758	0.336	4.49	-2.66
	NPHTH	48.168	0.108	6.55	-0.70
	GSLN	53.315	0.273	4.96	-2.54
	JTKR	56.944	0.060	5.25	-0.56
	GSDOIL	53.649	0.416	5.30	-4.04
	RFO	28.660	0.308	2.86	-1.90
	OTH	45.674	0.332	5.84	-3.58
			1.831		**-2.82**
R-OPEC (7 regions)	LPG	32.37	0.409	1.85	-1.32
	NPHTH	46.87	0.149	5.39	-0.44
	GSLN	51.19	1.317	2.18	-0.91
	JTKR	56.15	0.568	5.27	-1.01
	GSDOIL	51.86	1.517	3.44	-1.26
	RFO	27.57	0.941	1.83	-0.31
	OTH	43.69	0.386	3.01	-1.91
			5.288		**-1.01**
ROW (21 regions)	LPG	31.52	7.184	0.12	-1.24
	NPHTH	46.48	4.516	5.52	-0.67
	GSLN	50.69	19.180	2.00	-1.14
	JTKR	55.44	5.731	4.80	-1.39
	GSDOIL	51.18	20.260	3.04	-1.54
	RFO	27.46	8.743	1.86	-1.08
	OTH	43.25	8.716	2.21	-1.41
			74.329		**-1.28**

Notes: Prices are in 2004 US dollars. Liquefied petroleum gas (LPG), naphtha (NPHTH), gasoline (GSLN), jet fuel/kerosene (JTKR), distillate (GSDOIL), residual fuel oil (RFO), and others (OTH)

Case-3: Saudi Arabia Maximizing Profits Unilaterally Given a Competitive Fringe

Table 5: Crude Market Solution when Saudi Maximizes Profits Unilaterally Given a Competitive Fringe

Region	Crude*	Model Output When Saudis Maximize Profits Given A Competitive Fringe				Changes		
		Price	Quantity	Profit		Price	Quantity	Profit
		$/Bbl	Million Bbl/Day	$Million /Day	$Billion/ Year	%	%	%
KSA	LTSW	37.58	1.49	51.713	18.875	-1.18	-0.86	-1.19
	HVSW	-	-	-	-	-	-	-
	LTSR	35.63	1.39	47.052	17.174	-0.50	-4.32	-1.21
	MD1SR	33.27	4.77	154.078	56.239	-1.14	-4.73	-0.54
	MD2SR	31.61	1.29	39.094	14.269	-0.21	-5.28	-1.86
	HVSR	30.11	1.06	29.971	10.939	-0.04	-3.26	-1.00
			10.01	**321.908**	**117.496**		**-4.03**	**-0.95**
R-OPEC (7 regions)	LTSW	38.67	11.87	0	0	-2.01	3.80	-100
	HVSW	32.50	0.50	0	0	-2.50	2.85	-100
	LTSR	35.80	2.40	0	0	-1.05	4.59	-100
	MD1SR	33.86	7.78	0	0	-2.26	4.04	-100
	MD2SR	32.30	0.79	0	0	-1.69	5.17	-100
	HVSR	32.56	1.45	0	0	-1.23	3.23	-100
			24.80	**0**	**0**		**3.94**	**-100**
ROW (21 regions)	LTSW	40.27	25.51	0	0	-0.76	-0.02	0
	HVSW	32.85	2.02	0	0	-1.99	-0.04	0
	LTSR	37.93	0.11	0	0	-1.47	-0.03	0
	MD1SR	35.74	11.82	0	0	-1.69	-0.04	0
	MD2SR	33.80	0.64	0	0	-0.80	-0.02	0
	HVSR	32.95	6.98	0	0	-0.46	-0.01	0
			47.071	**0**	**0**		**-0.02**	0
Total			**81.88**		**117.50**		**0.63**	**-70.99**

Notes: Prices are trade weighted average prices from the model prices output. Quantities are aggregated from model output. Profits for Saudi Arabia are NLP results. Profits for rest of OPEC are calculated using equation (1) and are all zero for non-OPEC regions. Prices are in 2004 US dollars. Light sweet (LTSW), heavy sweet (HVSW), light sour (LTSR), medium-1 sour (MD1SR), medium-2 sour (MD2SR), and heavy sour (HVSR).

Table 6: Product Market Solution when Saudi Maximizes Profits Given a Competitive Fringe

Region	Product*	Model Output When Saudis Maximize Profits Given A Competitive Fringe		Change	
		Price ($/Bbl)	Demand Million Bbl/Day	Price %	Demand %
KSA	LPG	32.024	0.347	-0.88	0.55
	NPHTH	44.226	0.109	-2.17	0.24
	GSLN	50.807	0.281	0.02	-0.01
	JTKR	53.218	0.060	-1.63	0.18
	GSDOIL	50.057	0.439	-1.75	1.42
	RFO	27.820	0.314	-0.16	0.11
	OTH	42.578	0.347	-1.34	0.87
			1.896		**0.62**
R-OPEC (7 regions)	LPG	31.690	0.417	-0.31	0.50
	NPHTH	43.434	0.150	-2.33	0.20
	GSLN	49.468	1.336	-1.26	0.52
	JTKR	52.008	0.577	-2.50	0.48
	GSDOIL	49.486	1.545	-1.30	0.58
	RFO	27.041	0.944	-0.11	0.02
	OTH	41.814	0.398	-1.41	1.03
			5.367		**0.47**
ROW (21 regions)	LPG	31.382	7.293	-0.33	0.25
	NPHTH	43.156	4.558	-2.02	0.27
	GSLN	49.220	19.505	-0.97	0.53
	JTKR	51.902	5.847	-1.90	0.59
	GSDOIL	49.237	20.697	-0.87	0.59
	RFO	26.977	8.824	0.05	-0.16
	OTH	42.011	8.890	-0.72	0.57
			75.615		**0.43**

Notes: Prices are in 2004 US dollars. Liquefied petroleum gas (LPG), naphtha (NPHTH), gasoline (GSLN), jet fuel/kerosene (JTKR), distillate (GSDOIL), residual fuel oil (RFO), and others (OTH)

Case-4: competitive Market: OPEC Dissolves!!

Table 7: Crude Market Solution in a Competitive Market

Region	Crude*	Model Output for A Competitive Market				Changes		
		Price	Quantity	Profit		Price	Quantity	Profit
		$/Bbl	Million Bbl/Day	$Million /Day	$Billion /Year	%	%	%
KSA	LTSW	38.43	1.716	0	0	1.04	13.88	-100
	LTSR	33.53	1.660	0	0	-6.35	13.99	-100
	MD1SR	31.85	5.357	0	0	-5.34	7.03	-100
	MD2SR	28.96	1.568	0	0	-8.58	14.87	-100
	HVSR	28.41	1.285	0	0	-5.68	17.62	-100
			11.586	**0**	**0**		**11.13**	**-100**
R-OPEC (7 regions)	LTSW	37.76	11.873	0	0	-4.31	3.79	-100
	HVSW	31.36	0.501	0	0	-5.93	2.79	-100
	LTSR	34.82	2.403	0	0	-3.75	4.57	-100
	MD1SR	32.80	7.775	0	0	-5.31	4.01	-100
	MD2SR	30.66	0.792	0	0	-6.70	5.09	-100
	HVSR	32.23	1.451	0	0	-2.25	3.22	-100
			24.796	**0**	**0**		**3.92**	**-100**
ROW (21 regions)	LTSW	39.61	25.498	0	0	-2.38	-0.06	0
	HVSW	31.64	2.017	0	0	-5.62	-0.13	0
	LTSR	36.55	0.107	0	0	-5.04	-0.12	0
	MD1SR	34.87	11.808	0	0	-4.06	-0.11	0
	MD2SR	31.94	0.644	0	0	-6.24	-0.14	0
	HVSR	32.76	6.975	0	0	-1.04	-0.03	0
			47.049	**0**	**0**		**-0.07**	0
Total			**83.43**		**0.00**		**2.5**	**-100**

Notes: Prices are trade weighted average prices from the model prices output. Quantities are aggregated from model output. Profits for Saudi Arabia are NLP results. Profits for rest of OPEC are calculated using equation (1) and are all zero for non-OPEC regions. Prices are in 2004 US dollars. Light sweet (LTSW), heavy sweet (HVSW), light sour (LTSR), medium-1 sour (MD1SR), medium-2 sour (MD2SR), and heavy sour (HVSR).

Table 8: Products Market Solution in a Competitive Market

Region	Product*	Model Output for A Competitive Market		Change	
		Price ($/Bbl)	Demand Million Bbl/Day	Price %	Demand %
KSA	LPG	30.653	0.356	-5.13	3.29
	NPHTH	41.771	0.109	-7.60	0.87
	GSLN	47.388	0.291	-6.71	3.77
	JTKR	50.465	0.060	-6.72	0.77
	GSDOIL	48.093	0.454	-5.61	4.71
	RFO	26.745	0.322	-4.02	2.83
	OTH	40.703	0.357	-5.68	3.83
			1.950		**3.49**
R-OPEC (7 regions)	LPG	31.05	0.421	-2.31	1.45
	NPHTH	41.88	0.150	-5.83	0.51
	GSLN	48.79	1.346	-2.61	1.26
	JTKR	50.68	0.580	-4.99	1.08
	GSDOIL	48.06	1.557	-4.14	1.35
	RFO	26.23	0.950	-3.11	0.59
	OTH	41.14	0.403	-3.01	2.30
			5.407		**1.22**
ROW (21 regions)	LPG	31.14	7.344	-1.09	0.95
	NPHTH	41.42	4.581	-5.95	0.77
	GSLN	48.56	19.653	-2.29	1.29
	JTKR	50.56	5.907	-4.43	1.62
	GSDOIL	47.65	20.981	-4.07	1.97
	RFO	26.08	9.009	-3.29	1.93
	OTH	41.27	8.978	-2.46	1.56
			76.453		**1.54**

Notes: Prices are in 2004 US dollars. Liquefied petroleum gas (LPG), naphtha (NPHTH), gasoline (GSLN), jet fuel/kerosene (JTKR), distillate (GSDOIL), residual fuel oil (RFO), and others (OTH)