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Modeling for the World Crude Oil and Natural Gas Markets

Tsubasa SHIBATA*

March 2016

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Keywords: Demand–supply, imperfect competition, econometric model
JEL classification: C30, Q41

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Abstract

Crude oil and natural gas have been essential energy sources and play a crucial role in the world economy. Changes in energy prices significantly impact economic growth. This study builds an econometric model to illustrate the substitute relation between crude oil and natural gas markets. Additionally, the determination of the oil and natural gas prices are endogenized, assuming imperfect competition to reflect a real market strategy. In particular, we suppose that different behaviors by oil-producing countries affect the international crude oil market. We set two competing strategies in profit maximization: (i) oil-producing countries who concentrate on ensuring the stability and sustainability of oil price to gain steady profits, and (ii) oil-producing countries who concentrate on individual profit seeking. We estimate the supply functions by these two strategies and target a sample of 22 oil-producing countries of which 12 are OPEC and 10 are non-OPEC. Our empirical results show that the overall performance of this system is acceptable, and the model can be applied to policy analysis for determining monetary or energy policy by introducing this model to the more comprehensive system.

Keywords: Crude oil, Natural gas, Demand–supply, Imperfect competition, Econometric model
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1. Introduction

Crude oil and natural gas have been essential energy sources and plays an important role in the world economy. As changes in energy prices may significantly impact economic growth, the movement of energy prices is of great concern to economists and policy makers.

For the last four decades, oil prices have been controlled by Organization of Arab Petroleum Exporting Countries (OPEC) and major oil-producing countries and industries. In retrospect, between World War II and the 1970s, oil prices were controlled under an international oligopolistic oil market by major western oil companies, the so-called Seven Sisters. Oil producers in Arab countries suffered from this international cartel of production by these major western oil companies. Against these conditions, OPEC was founded in 1960 by Saudi Arabia, Iran, Iraq, Kuwait, and Venezuela with the principal objective of taking back greater control of their own oil production and a gain a right to set pricing. Currently, the organization has twelve members: Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. Subsequently, OPEC took responsibility for virtually 40% of the world's crude oil production and controlled oil prices through its strategy of pricing over volume. Although OPEC had little impact on oil for the first decade, an increase in demand worldwide and the decline of production by major oil companies of the United States caused OPEC to become a significant presence in the international oil market.

Figure 1 represents the interrelation between the movement of oil price and oil production by Saudi Arabia. Saudi Arabia is seen as the swing producer in OPEC. Apparently, Saudi Arabia's crude oil production affected the determination of the West Texas Intermediate's (WTI) crude oil prices until mid-2014. In contrast, since then, the situation has changed. The relation between oil prices and production by Saudi Arabia has been disappearing, and it has become difficult for OPEC to control the oil market.

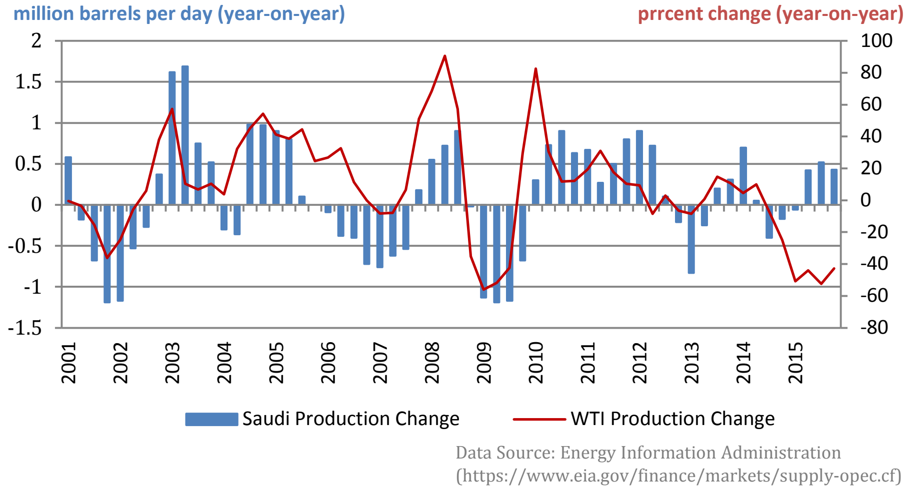

Figure 1. Relation between the production changes by Saudi Arabia and WIT oil price

One of reasons for this is the development of alternative energy sources such as natural gas and nuclear power and an increase in oil production by non-OPEC. According to Figure 2, natural gas production has been increasing worldwide. In particular, this is due to the rising production of natural gas by the United States. The increase of the natural gas supply seems to be loosening the tension between supply and demand, which has resulted in suppressing the rise of crude oil price in the energy market. Crude oil had been the dominant fuel worldwide for a long period of time. However, now, natural gas is a competitive form of energy against crude oil. In the near future, improving the supply of natural gas and using natural gas as an alternative energy source could significantly transform the energy market.

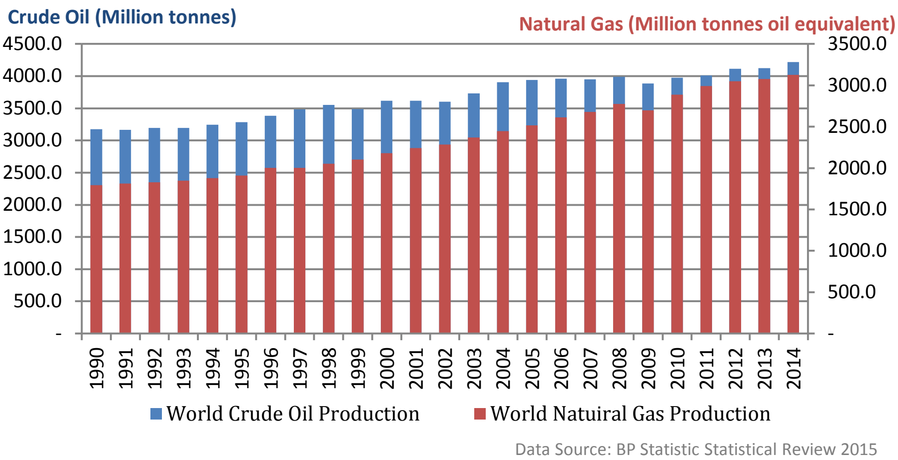

Figure 2. World Crude Oil Production and Natural Gas Production

Based on these considerations, our model is required to describe the demand and supply in substitution of two markets: crude oil and natural gas. In addition, the prices of oil and natural gas are determined on the basis of the economic law of imperfect competition. Many researchers have explored the relation between oil and natural gas prices: Pindyck (2004), Villar and Joutz (2006), Kirichene (2005, 2007), Brown and Yucel (2008), and Hartley et al. (2008). Specifically, Kirichene (2005, 2007) developed the econometric model that describes the correlation between oil and natural gas prices in terms of demand and supply based on the rational expectation framework. The author states that changes in oil prices cause changes in natural gas prices, while natural gas prices do not affect oil prices. It is insufficient that these models describe the market mechanism of pricing based only on supply and demand. Furthermore, some studies developed econometric models that determine oil or natural gas prices based on the supply and demand at the macro level. Dees et al. (2007) and Krichene (2005, 2007) demonstrated the demand–supply approach. Dees (2007) focused only on the oil market, while Krichene (2007) dealt with the correlation between crude oil and natural gas markets. Notably, Dees (2007) distinguished non-OPEC and OPEC behaviors. Kirichene's model (2007) is based on the framework of rational expectation. However, their models do not directly incorporate optimizing of the producers' behavior. In contrast, Kosaka (2015) proposed the framework that oil and natural gas prices are determined under oligopolistic competition. In addition, Kosaka (2015) assumed that the profit maximization behaviors of oil-producing countries are distinguished depending on the strategies of each producing country.

This study builds an empirical model of crude oil and natural gas markets following a theoretical framework by Kosaka (2015). In our model, the substitute relation between crude oil and natural gas prices is incorporated. Under the assumption of imperfect competition, we assume two competing strategies in profit maximization: 1) maximize a country's own profits and 2) maintain stable prices. We estimate the supply functions by these two strategies and target a sample of 22 oil-producing countries of which 12 are OPEC and 10 are non-OPEC.

The rest of the paper is organized as follows. In Section 2, we present the theoretical framework of crude oil and natural gas markets. In Section 3, we explain the data. In Section 4, we explain the empirical analysis and the result of the final test. Finally, the conclusion and remarks are provided in Section 5.

2. Model

In this section, we illustrate the theoretical framework of crude oil and natural gas markets where the prices of crude oil and natural gas are determined from the equilibrium between their demand and supply via the substitution between crude oil and natural gas. We suppose that the producing countries of crude oil or natural gas have market power to some extent. Therefore, we assume that this model is based on an imperfectly competitive market. We basically follow the Kosaka model (2015) as shown below.

2.1. Crude Oil Market

2.1.1. Equilibrium in Crude Oil Market

First, consider the crude oil demand. The aggregate crude oil demand function $X_{oil,t}^{D}$ is defined by

$$X_{oil,t}^{D} = \alpha_0 - \alpha_1 p_{oil,t} + \alpha_2 p_{oil,t-1} + \alpha_3 \sum_{k=1}^{N} D_{oil,t}^{k} \tag{1}$$

where $p_{oil,t}$ and $p_{oil,t-1}$ represent the level of crude oil price at times t and t-1, respectively; $D_{oil,t}^{k}$ shows the k-th country's demand for crude oil; and α_0, α_1, α_2, α_3 are parameters, where $\alpha_0 \geq 0$, $\alpha_1 > 0$, and $\alpha_3 > 0$. The parameter α_3 simply means that the aggregate crude oil depends positively on the level of the aggregated demand for crude oil. Increasing (decreasing) the demand for crude oil leads to an increase (decrease) in aggregate crude oil demand. Then, the second term of (1) shows that the aggregate oil demand and its price at time t have an inverse relation. Moreover, there is no limitation to the effect of oil price at time t-1. If $\alpha_2 > 0$, the oil price at time t responds negatively to that at time t-1. If $\alpha_2 < 0$, $\alpha_2 > 0$ is determined reversely against the oil price at time t-1. If $\alpha_2 = 0$, the oil price at time t is determined independently of the effect of oil price at time t-1.

Next, we see the supply side in the crude oil market. The aggregate world crude oil supply is defined by the summed crude oil production by k's country as follows:

$$X_{oil,t}^{S} = \sum_{k=1}^{M} S_{oil,t}^{k} \tag{2}$$

where $X_{oil,t}^{S}$ denotes the aggregate world supply of crude oil at time t and $S_{oil,t}^{k}$ is the summed crude oil production by k-th country at time t. Namely, the world crude oil supply is defined as the summation of the sample oil-producing countries. The optimal oil production by k's country is determined by k's profit maximization in section 3.1.2.[2]

Then, for crude oil market clearing, we assume that supply and demand balance each other:

[2] see Table 1 for the sample countries in this study.

$$X_{oil,t}^{D} = X_{oil,t}^{S} = X_{oil,t} \tag{3}$$

From (1), (2), and (3), we obtain the following equation:

$$\alpha_0 - \alpha_1 p_{oil,t} + \alpha_2 p_{oil,t-1} + \alpha_3 \sum_{k=1}^{N} D_{oil,t}^{k} = X_{oil,t}^{S} \tag{4}$$

By rearranging (4), the crude oil price is derived as

$$p_{oil,t} = \frac{\alpha_0}{\alpha_1} + \frac{\alpha_2}{\alpha_1} p_{oil,t-1} + \frac{\alpha_3}{\alpha_1} \sum_{k=1}^{N} D_{oil,t}^{k} - \frac{1}{\alpha_1} X_{oil,t}^{S} \tag{5}$$

This implies that the crude oil price at time *t* depends on that at time *t*-1, the summed demand for crude oil and the world crude oil production. This price model might be explainable. However, the determination of oil price should be augmented in two points to develop a model that reflects a more realistic market. First, we must consider the effect of those entering the oil market through a financial attribute such as hedge funds. Investment and speculation often affect the volatility of oil price. Therefore, we set this effect by adding the error term $u_{oil,t}$:

$$p_{oil,t} = \frac{\alpha_0}{\alpha_1} + \frac{\alpha_2}{\alpha_1} p_{oil,t-1} + \frac{\alpha_3}{\alpha_1} \sum_{k=1}^{N} D_{oil,t}^{k} - \frac{1}{\alpha_1} X_{oil,t}^{S} + u_{oil,t} \tag{6}$$

Second, the relation between crude oil and natural gas markets is introduced. The demand for crude oil is likely to be linked to the substitution between crude oil and natural gas. To do so, we include the variable of natural gas price on the demand function (1) as follows:

$$X_{oil,t}^{D} = \alpha_0 - \alpha_1 p_{oil,t} + \alpha_2 p_{oil,t-1} + \alpha_3 \sum_{k=1}^{N} D_{oil,t}^{k} + \alpha_4 p_{gas,t} \tag{1'}$$

where $\alpha_4 \geq 0$. The relation of price between crude oil and natural gas is a substitute. If the natural gas price is relatively high (low) against the crude oil price, crude oil demand increases (decrease) via the substitution effect. Similar to the expansion from (2) to (6), we rearrange the new demand function (1)' and obtain the following oil price model.

$$p_{oil,t} = \frac{\alpha_0}{\alpha_1} + \frac{\alpha_2}{\alpha_1} p_{oil,t-1} + \frac{\alpha_3}{\alpha_1} \sum_{k=1}^{N} D_{oil,t}^{k} + \frac{\alpha_4}{\alpha_1} p_{gas,t} - \frac{1}{\alpha_1} \sum_{k=1}^{M} S_{oil,t}^{k} + u_{oil,t} \tag{7}$$

We employ this model of crude oil price instead of (7).

2.1.2. Determination of Optimal Oil Production

In this section, we show the determination of optimal oil quantity for each oil-producing country based on profit maximization.

In the real market, we suppose that different behaviors by oil-producing countries affect the international crude oil market. For example, Saudi Arabia plays the role of a swing producer by controlling quantity in order to maintain its own desired level profit and keep oil prices stable. Among OPEC, Saudi Arabia, the UAE, Kuwait, and Qatar tend to go along with each other. Conversely, among OPEC, Iran, Iraq and Venezuela tend to act against Saudi Arabia and the western countries, giving priority to their own profits.

We take this into account in our model. Therefore, we set two competing strategies in profit maximization: (i) oil-producing countries who concentrate on ensuring the stability and sustainability of oil price to gain steady profits, and (ii) oil-producing countries who concentrate on individual profit seeking. The first category seeks to not only maximize their profit but also take price stability into consideration. Stabilization of price by controlling the oil-producing volume helps ensure steady profit in the long run. The second category, on the other hand, tends to prioritize individual profit maximization over sustainable market. (ii) corresponds to a general strategy under imperfect competition in microeconomics, while (i) is the extension of the basic strategy such as that used in (ii). The details of each model are as follows.

i) Oil-producing countries who intend to maintain a stable oil price

In this case, some oil-producing countries attempt to maximize their own profit as well as maintain price stability. The following profit function is defined:

$$\pi_{oil,t}^{k} = -\frac{1}{2} w_{oil}^{k} \left(p_{oil,t} - p_{oil,t-1}\right)^{2} + \frac{1}{S_{oil}^{k^*}} \left(p_{oil,t} S_{oil,t}^{k} - C_{oil,t}^{k}\right) \tag{8}$$

where w_{oil}^{k} represents the parameter and $S_{oil}^{k^*}$ is the targeted level of oil production in k's country. The first term formulated by the quadratic loss term indicates the difference between price at times t and t-1. If the difference of price between the two time points increases (decreases), the profit would decrease (increase) by the quadratic loss. The second term also shows the difference between the targeted production level and production at time t. Solving the above for profit maximization, we obtain:

$$\begin{aligned} \frac{\partial \pi_{oil,t}^{k}}{\partial S_{oil,t}^{k}} &= -w_{oil}^{k} \left(p_{oil,t} - p_{oil,t-1}\right) \frac{\partial p_{oil,t}}{\partial S_{oil,t}^{k}} \\ &\quad + \frac{1}{S_{oil}^{k^*}} \left(p_{oil,t} + \frac{\partial p_{oil,t}}{\partial S_{oil,t}^{k}} S_{oil,t}^{k} - \frac{\partial C_{oil,t}^{k}}{\partial S_{oil,t}^{k}}\right) = 0 \end{aligned} \tag{9}$$

where $\partial p_{oil,t}/\partial S_{oil,t}^{k} = -\lambda_{oil,t}^{k}$. Here, we reset $S_{oil,t}^{k^*}$ for $S_{oil,t}^{k}$ and rearrange (9). In this process, we redefine the supply function as $\tilde{S}_{oil,t}^{k}$.

$$\tilde{S}_{oil,t}^{k} = \frac{\left(p_{oil,t} - MC_{oil,t}^{k}\right)}{\left(1 - w_{oil}^{k} p_{oil,t} + w_{oil}^{k} p_{oil,t-1}\right)} \tag{10}$$

where an increase in marginal cost $MC_{oil,t}^{k}$ and oil price imply a decline in production. This is optimal production. However, the oil market is uncertain due to various effects of investment and speculation. Therefore, we set an additional term ρ_{oil}^{k0} to account for effects other than oil price or marginal cost as follows:

$$S_{oil,t}^{k} - S_{oil,t-1}^{k} = \rho_{oil}^{k0} + \rho_{oil}^{k1}\left(\tilde{S}_{oil,t}^{k} - S_{oil,t-1}^{k}\right) \tag{11}$$

By rearranging (11), the optimal supply function of *k*'s country is given by

$$S_{oil,t}^{k} = \rho_{oil}^{k0} + \left(1 - \rho_{oil}^{k1}\right) S_{oil,t-1}^{k} + \frac{\rho_{oil}^{k1}\left(p_{oil,t} - MC_{oil,t}^{k}\right)}{\lambda_{oil,t}^{k}\left[1 - w_{oil}^{k}\left(p_{oil,t} + p_{oil,t-1}\right)\right]} \tag{12}$$

This model is employed into the whole system as the supply function.

ii) Oil-producing countries that intend to simply maximize their own profit

In this case, some oil-producing countries attempt to maximize their own profit. The following profit function is defined:

$$\pi_{oil,t}^{k} = p_{oil,t} S_{oil,t}^{k} - C_{oil,t}^{k} \tag{13}$$

Partially differentiating by $S_{oil,t}^{k}$, the functional form is shown as

$$\frac{\partial \pi_{oil,t}^{k}}{\partial S_{oil,t}^{k}} = p_{oil,t} + \frac{\partial p_{oil,t}}{\partial S_{oil,t}^{k}} S_{oil,t}^{k} - \frac{\partial C_{oil,t}^{k}}{\partial S_{oil,t}^{k}} = 0 \tag{14}$$

where $\partial p_{oil,t}/\partial S_{oil,t}^{k} = -\lambda_{oil,t}^{k}$. Rearranging (14), the following equation is derived as follows:

$$S_{oil,t}^{k} = \frac{\left(p_{oil,t} - MC_{oil,t}^{k}\right)}{\lambda_{oil,t}^{k}} \tag{15}$$

Similarly, we set an additional term ρ_{oil}^{k0} to account for effects other than oil price or marginal cost as follows:

$$S_{oil,t}^{k} = \varphi_{oil}^{k0} + \left(1 - \varphi_{oil}^{k1}\right) S_{oil,t-1}^{k} + \frac{\varphi_{oil}^{k1}}{\lambda_{oil,t}^{k}} \left(p_{oil,t} - MC_{oil,t}^{k}\right) \tag{16}$$

2.2. Natural Gas Market

This section represents the natural gas market. The mechanism of the natural gas market is basically similar to that of the oil market. Therefore, the explanations of some parts are omitted.

2.2.1. Equilibrium in Natural Gas Market

Following (1), the aggregate demand for natural gas is defined as

$$X_{gas,t}^{D} = \beta_0 - \beta_1 p_{gas,t} + \beta_2 p_{gas,t-1} + \beta_3 \sum_{k=1}^{N} D_{gas,t}^{k} + \beta_4 p_{oil,t} \tag{17}$$

where $X_{gas,t}^{D}$ denotes the aggregate natural gas demand, $p_{gas,t}$ represents the natural gas price at time *t*, and $D_{gas,t}^{k}$ is the demand for natural gas by *k*'s country. The parameters β_0, β_1, β_2, β_3, and β_4 are similar to $\alpha_0 \geq 0$, $\alpha_1 > 0$, and $\alpha_3 > 0$ in the crude oil model. The substitute relation between crude oil and natural gas is taken into consideration.

Regarding the supply side, the aggregate world natural gas production is the summation of gas production by *k* country as follows:

$$X_{gas,t}^{S} = \sum_{k=1}^{M} S_{gas,t}^{k} \tag{18}$$

Here, it assumes that the aggregate demand for natural gas balances to the aggregate supply.

$$X_{gas,t}^{D} = X_{gas,t}^{S} = X_{gas,t} \tag{19}$$

Similar to the crude oil market, rearranging (17), (18), and (19) and taking into consideration the error term, the natural gas price is driven as follows:

$$p_{gas,t} = \frac{\beta_0}{\beta_1} + \frac{\beta_2}{\beta_1} p_{gas,t-1} + \frac{\beta_3}{\beta_1} \sum_{k=1}^{N} D_{gas,t}^{k} + \frac{\beta_4}{\beta_1} p_{oil,t} - \frac{1}{\beta_1} \sum_{k=1}^{M} S_{gas,t}^{k} + u_{gas,t} \tag{20}$$

As the specification shows, the natural gas price is affected by the substitutive effect of the crude oil price.

2.2.2. Determination of Optimal Natural Gas Production

For the natural gas market, we assume the profit function as

$$\pi_{gas,t}^{k} = p_{gas,t} S_{gas,t}^{k} - C_{gas,t}^{k} \tag{21}$$

Solving this profit maximization in a manner similar to the oil model, we obtain the following supply function of natural gas for k's country.

$$S_{gas,t}^{k} = \varphi_{gas}^{k0} + \left(1 - \varphi_{gas}^{k1}\right) S_{gas,t-1}^{k} + \frac{\varphi_{gas}^{k1}}{\lambda_{gas,t}^{k}} \left(p_{gas,t} - MC_{gas,t}^{k}\right) \tag{22}$$

3. Data

3.1. Sample Period and Data Source

This study uses annual data from 1990 to 2014.[3] The supply and demand data of crude oil and natural gas are taken from the BP Statistical Review of World Energy. The annual spot prices of crude oil and natural gas are from the Energy Information Administration (EIA) website. The data of marginal cost of the oil or natural gas industry and the marginal cost of each oil-producing country's mining industry are not available. Therefore, the variables of marginal cost are omitted from the model.

Price Data

Regarding price data, the representative crude oil price in our model is the oil price from the WTI benchmark. The global crude oil market has three significant benchmarks: WTI, Brent Blend, and Dubai. These play an important role in crude oil pricing worldwide. Above all, the WTI benchmark is accepted as the most accurate indicator of international crude oil prices because it is the most actively traded in the global oil market due to its excellent liquidity and price transparency. Other crude oil prices worldwide tend to be pegged to the WTI. Then, for the natural gas price, we use the Henry Hub natural gas spot price. Natural gas is susceptible to conditions in local areas. Regardless, Henry Hub is a representative price to use as a benchmark of the world natural gas market.

[3] This study uses annual data due to data availability. If available, it would be more desirable to use quarterly data.

Selected Countries

Our sample of 20 oil-producing countries contains 12 OPEC and 8 non-OPEC. The sample of oil demanding countries also contains 20 different countries. The sample of natural gas producing countries is 18, and the sample of natural gas consuming countries is 20. These sample countries are the major producers and consumers who affect the oil and natural gas markets as well as the world economy. They are summarized in Table 1.

Table 1. Sample Countries in Crude Oil and Natural Gas Markets

	Crude Oil		Natural Gas	
	Supply	Demand	Supply	Demand
1	Algeria* (DZA)	Brazil (BRA)	Canada (CAN)	Argentina (ARG)
2	Angola* (AGO)	Canada (CAN)	China (CHN)	Brazil (BRA)
3	Brazil (BRA)	China (CHN)	Indonesia (IDN)	Canada (CAN)
4	Canada (CAN)	Germany (DEU)	Iran (IRN)	China (CHN)
5	China (CHN)	France (FRA)	Mexico (MEX)	Germany (DEU)
6	Ecuador* (ECU)	India (IND)	Malaysia (MYS)	France (FRA)
7	India (IND)	Indonesia (IDN)	Netherlands (NLD)	India (IND)
8	Indonesia (IDN)	Iran (IRN)	Norway (NOR)	Indonesia (IDN)
9	Iran* (IRN)	Italy (ITA)	Qatar (QAT)	Italy (ITA)
10	Iraq* (IRQ)	Japan (JPN)	Russia (RUS)	Japan (JPN)
11	Kazakhstan (KAZ)	Korea (KOR)	Saudi Arabia (SAU)	Korea (KOR)
12	Kuwait* (KWT)	Mexico (MEX)	Turkmenistan (TKM)	Malaysia (MYS)
13	Libya* (LBY)	Russia (RUS)	United Arab Emirates (ARE)	Mexico (MEX)
14	Mexico (MEX)	Saudi Arabia (SAU)	United States (USA)	Netherlands (NLD)
15	Nigeria* (NGA)	Singapore (SGP)	Uzbekistan (UZB)	Russia (RUS)
16	Norway (NOR)	Spain (ESP)		Spain (ESP)
17	Qatar* (QAT)	United Kingdom (GBR)		Thailand (THA)
18	Russia (RUS)	United Sates (USA)		United Arab Emirates (ARE)
19	Saudi Arabia* (SAU)	-		United Kingdom (GBR)
20	United Arab Emirates* (ARE)	-		United States (USA)
21	United States (USA)	-		
22	Venezuela* (VEN)	-		

Note: * denotes a member of OPEC.

4. Empirical Results

4.1. Estimation Results of Each Model

This study builds a model to illustrate the world markets for crude oil and natural gas. To this end, we estimate each model that is shown in the previous section. We run the ordinal least-squares to estimate prices of crude oil and natural gas, and the supply functions in the sample period from 1990 to 2014. In this section, we show the estimated results.

Price

Tables 2 and 3 represent the estimated results of crude oil and natural gas prices. Statistics shows that prices are well estimated. Both tables clearly show that the natural gas price affects the crude oil price, and vice versa. From the estimated results, we learn that the relation between crude oil and natural gas prices substitute each other. We conclude that the calculations are acceptable.

Table 2. Estimation of Crude Oil Spot Price (WTI)

Explanatory Variables	Coefficient	S.E.
WTI Crude Oil Spot Price (*t*-1)	1.130***	0.147
Henry Hub Natural Gas Spot Price	3.133**	1.090
ln (Aggregated Crude Oil Demand)	40.470	88.275
ln (Aggregated Crude Oil Supply)	-72.415	102.487
Dummy 2000	6.845***	1.938
Dummy 2009	-47.379***	6.417
Constant	532.724	662.242
Observation		25
Adj. R-squared		0.959

Note: Adj. *R*-Squared is adjusted *R*-squared. “S.E.” indicates robust standard errors. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Table 3. Estimation of Natural Gas Spot Price (Henry Hub)

Explanatory Variables	Coefficient	S.E.
Henry Hub Natural Gas Spot Price (*t*-1)	0.627***	0.130
WTI Crude Oil Spot Price	0.047	0.032
Aggregated Natural Gas Demand	0.014**	0.005
Aggregated Natural Gas Supply	-0.015*	0.006
Dummy 2005	2.907***	0.342
Dummy 2009	-3.579***	0.693
Constant	3.070	3.758
Observation		25
Adj. R-squared		0.830

Note: Adj. *R*-Squared is adjusted *R*-squared. “S.E.” indicates robust standard errors. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Supply Functions of Crude Oil

In the previous section, we assume two competing strategies in profit maximization. That is, we propose two types of supply functions of (12) and (16). Therefore, after we estimate the two types of supply functions for each oil-producing country, we select the more favorable model between the two. We explain the detailed process of model selection before showing the estimated results.

First, we estimate two types supply functions, which are (12) and (16), for all oil-producing sample countries by applying ordinal least-squares regression. Second, we perform the sign test and the statistic robust check. If the two types of supply functions of each country have the correct sign and the results of the statistic check are sufficient, we select more a desirable model based on the Akaike information criteria. Otherwise, both models are rejected. If either model shows the correct sign and is well estimated, we accept it. By performing these tests, oil-producing countries are divided into three categories (Table 4): i) the supply function for price stability based on (12), ii) the supply function for simple profit maximization base on (16), and iii) reject. According to Table 4, Saudi Arabia belongs to "Price Stable." Therefore, this result is consistent with a hypothesis that Saudi Arabia is a swing producer. Tables 5 and 6 report the estimated results of the acceptable models. Equation (12) is a highly nonlinear regression model. Repeating much iteration, we calculate parameter w_{oil}^{k}, which shows the magnitude of k-th country's intention for price stability. We conclude that they are basically acceptable.

Table 4. Distinction of Profit Maximization Strategy

	Sample Country	Price Stability	Profit
Non-OPEC	Brazil (BRA)	✓	
	Canada (CAN)	✓	
	China (CHN)		✓
	India (IND)		✓
	Indonesia (IDN)	Reject	
	Kazakhstan (KAZ)	✓	
	Mexico (MEX)	✓	
	Norway (NOR)	Reject	
	Russia (RUS)		✓
	United States (USA)		✓
OPEC	Angola (AGO)	✓	
	Algeria (DZA)	✓	
	Ecuador (ECU)	Reject	
	Iran (IRN)	Reject	
	Iraq (IRQ)		✓
	Kuwait (KWT)		✓
	Libya (LBY)	Reject	
	Nigeria (NGA)	Reject	
	Qatar (QAT)		✓
	Saudi Arabia (SAU)	✓	
	United Arab Emirates (ARE)		✓
	Venezuela (VEZ)	✓	

Table 5. Estimation Results of Crude Oil Supply Function in Equation (12): Price Stability

	BRA	CAN	DZA	KAZ	SAU	VEN	RUS	USA
Crude Oil	1.044***	1.034***	1.002***	1.033***	1.022***	1.004***	0.933***	0.962***
Supply (t-1)	(0.01)	(0.006)	(0.009)	(0.01)	(0.015)	(0.012)	(0.031)	(0.01)
WTI Spot Price	2.894	495.139	2.218	7.002**	90.332	163.643	4239.197**	3359.497**
	(1.981)	(502.348)	(1.421)	(2.947)	(160.19)	(151.676)	(1499.187)	(1113.002)
Regional				48031.51**			-212694.1***	
Dummy 1				(19083.59)			(51281.42)	
Parameter w_{oil}^{k}	4.330	1.878	4.332	4.332	0.276	0.786	0.442	0.627
Observation	25	25	25	25	25	25	25	25
Adj. R-Squared	0.986	0.979	0.904	0.989	0.615	0.694	0.924	0.877

Note: Adj. *R*-Squared is adjusted *R*-squared. "S.E." indicates robust standard errors. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Table 6. Estimation Results of Crude Oil Supply Function in Equation (16): Profit Maximization

	ARE	CHN	IND	IRQ	KWT	QAT	RUS	USA
Crude Oil	0.992***	1.014***	0.981***	0.709***	0.971***	0.919***	0.933***	0.962***
Supply (t-1)	(0.027)	(0.006)	(0.019)	(0.142)	(0.067)	(0.048)	(0.031)	(0.01)
WTI Spot	629.232	82.002	130.934	3907.753*	867.088	1019.133***	4239.197**	3359.497**
Price	(481.93)	(172.64)	(92.258)	(1542.62)	(1007.61)	(313.815)	(1499.187)	(1113.002)
Regional			35267.74**				-212694.1***	
Dummy 1			(12545.53)				(51281.42)	
Observation	25	25	25	25	25	25	25	25
Adj. *R*-Squared	0.807	0.982	0.848	0.971	0.795	0.982	0.924	0.877

Note: Adj. *R*-Squared is adjusted *R*-squared. "S.E." indicates robust standard errors. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Supply functions of Natural Gas

Natural-gas-producing countries are also estimated by applying ordinal least-squares. China, Iran, Mexico, Malaysia, and Norway are basically acceptable, while Canada, Indonesia, Indonesia, United Arab Emirates, and Uzbekistan are rejected based on the sign test and statistic robust check. Table 7 reports the estimated results of the natural gas supply function in (22). Therefore, supply functions of China, Iran, Mexico, Malaysia, and Norway are endogenized in the whole system.

Table 7. Estimation Results of Natural Gas Supply Function

	CHN	IRN	MEX	MYS	NOR
Natural Gas Supply (t-1)	1.059***	1.017***	0.957***	0.968***	0.974***
	(0.011)	(0.021)	(0.034)	(0.03)	(0.051)
Henry Hub Spot Price	0.579***	0.986**	0.681*	0.669*	1.037*
	(0.126)	(0.407)	(0.374)	(0.29)	(0.579)
Regional Dummy 1			-5.913***		
			(1.035)		
Regional Dummy 2			4.695***		
			(0.386)		
Observation	25.000	25	25	25	25
Adj. *R*-Squared	0.998	0.987	0.975	0.971	0.979

(Continued)

	QAT	RUS	SAU	TKM	USA
Natural Gas Supply (t-1)	1.070***	0.988***	1.035***	0.797***	1.018***
	(0.047)	(0.013)	(0.024)	(0.085)	(0.012)
Henry Hub Spot Price	0.796**	1.857	0.252	2.063**	0.013
	(0.282)	(1.124)	(0.229)	(0.707)	(1.479)
Regional Dummy 1		-67.382***			
		(3.531)			
Regional Dummy 2		52.64***			
		(2.597)			
Observation	25	25	25	25	25
Adj. *R*-Squared	0.981	0.987	0.988	0.661	0.987

Note: Adj. *R*-Squared is adjusted *R*-squared. "S.E." indicates robust standard errors. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

4.2. Final Test Results

In total, our crude oil and natural gas model is composed of 28 simultaneous equations: 26 estimated equations (crude oil and natural gas prices and their supply functions), and two definitional identities (the aggregated supply of crude oil and natural gas).The final test of this system is based on data from 1990 to 2014 (annual). Figures 3, 4, and 5 show the results of the final test for the crude oil spot price (WIT), natural gas spot price (Henry Hub), aggregate crude oil supply, aggregate natural gas supply, each country's crude oil supply, and each country's natural gas supply. Although some endogenous variables might be not sufficiently satisfactory, the simulated value can trace the actual values.

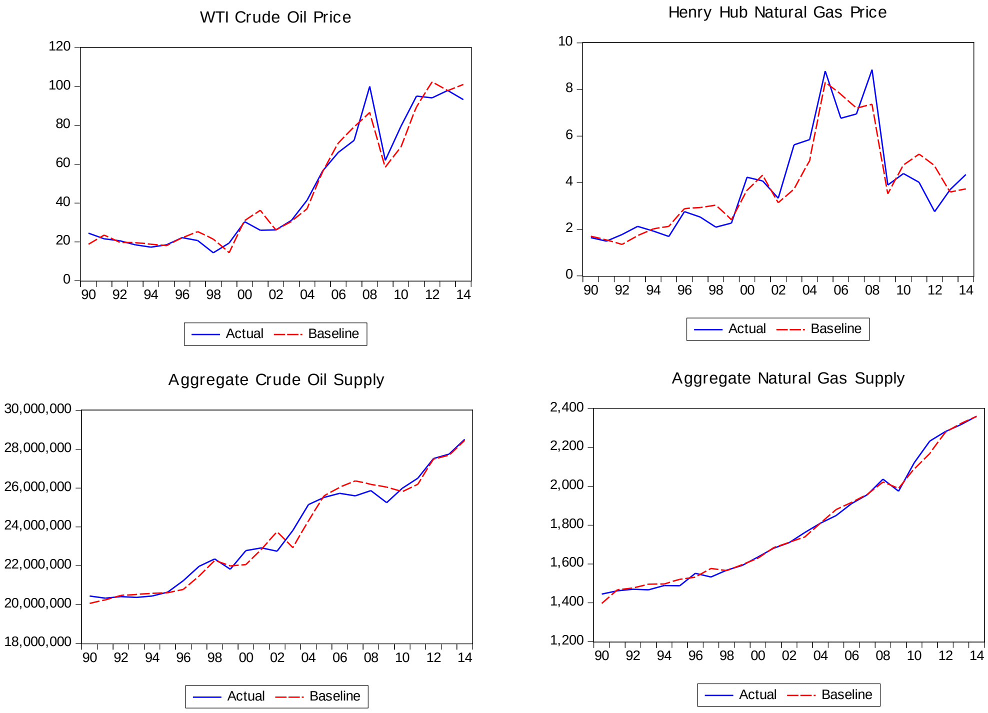

Figure 3. Final Test Results of Prices and Aggregated Supply

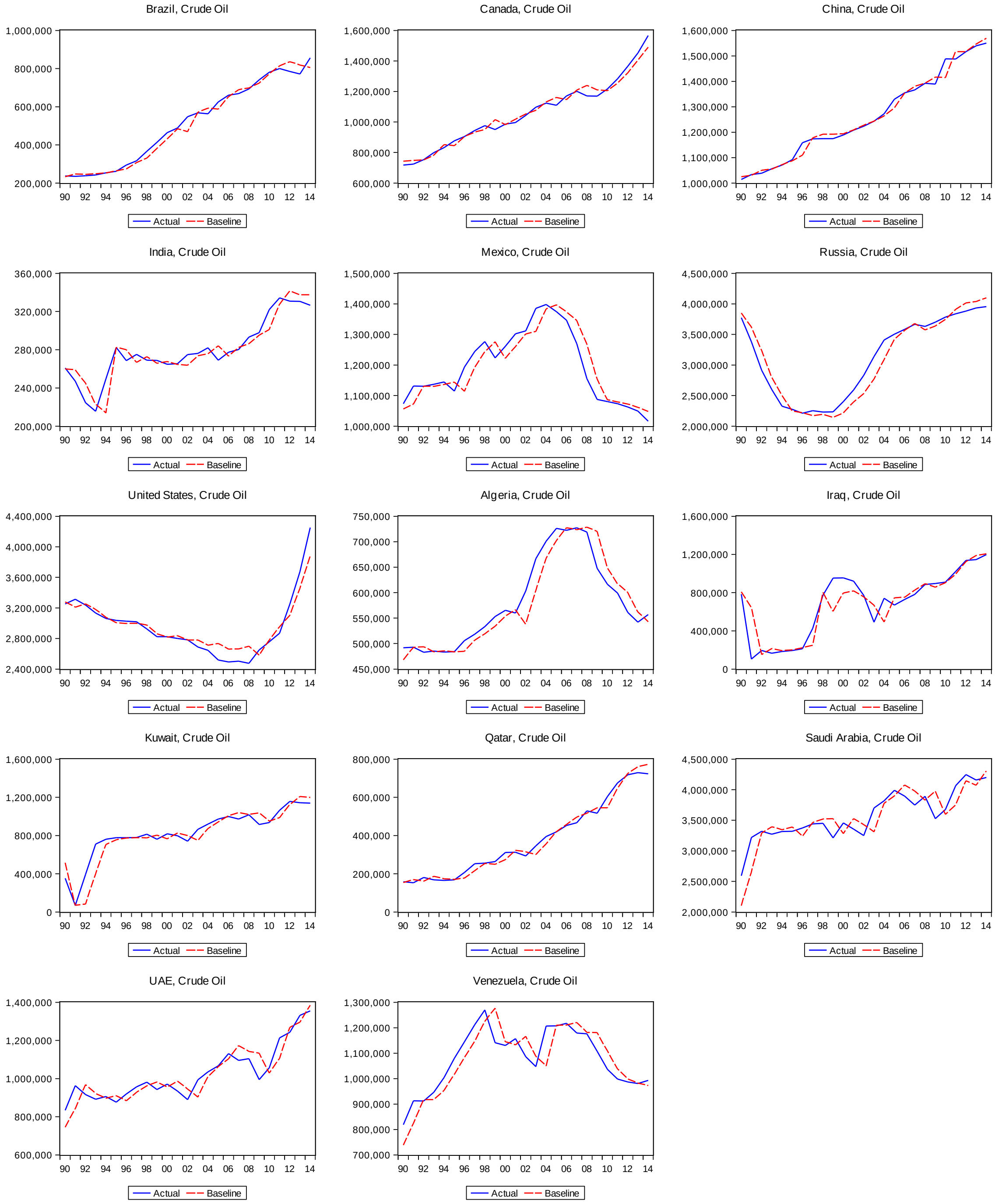

Figure 4. Final Test Results of Prices and Aggregate Supply

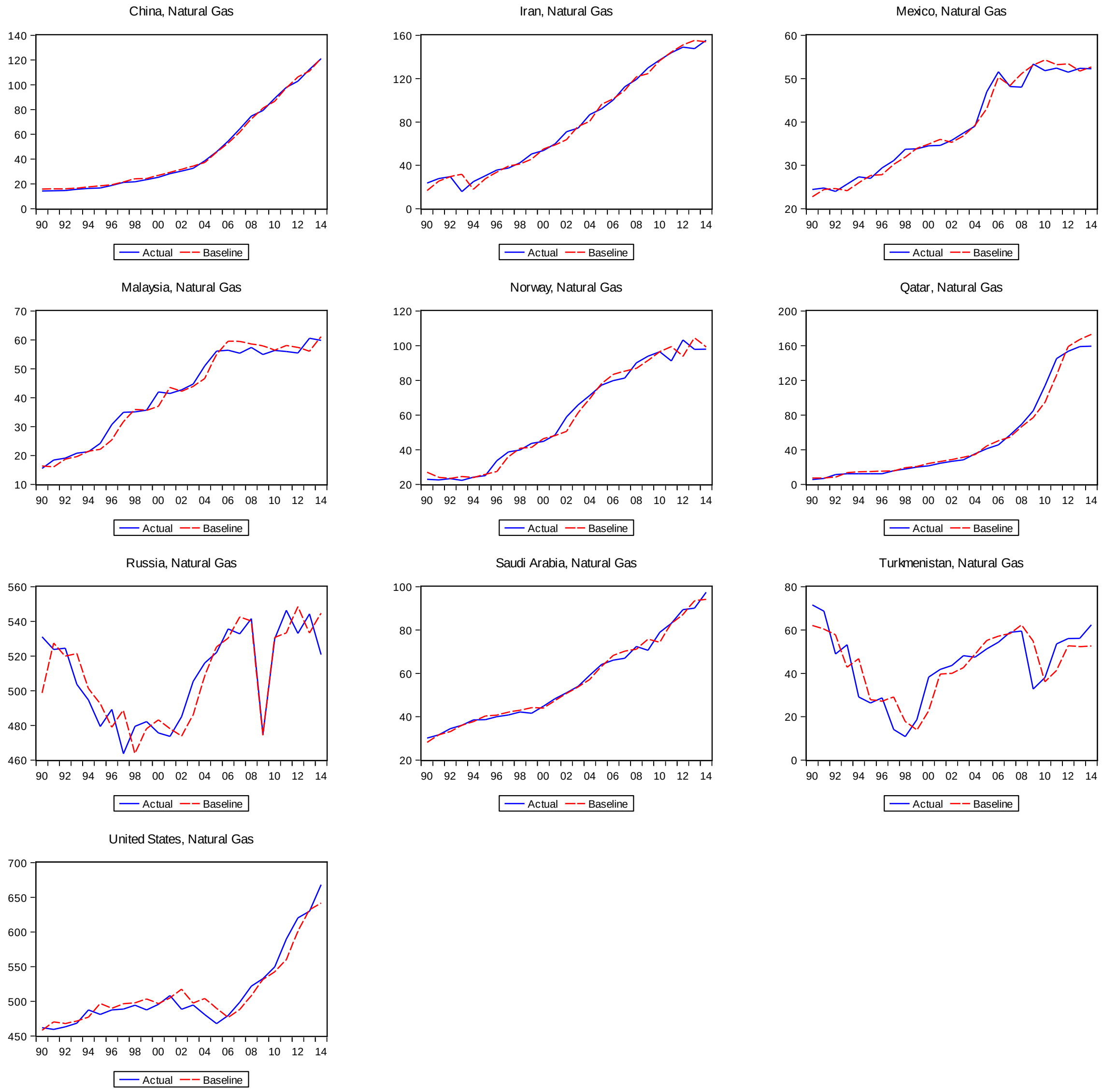

Figure 5. Final Test Results of Crude Oil and Natural Gas Supply

Furthermore, we show the evaluation of model fitness. Several criteria are used to evaluate the accuracy of the estimated value by the final test. In particular, the root mean square error (RMSE), root mean square percentage error (RMSPE), Von Neumann Ratio (V.N.), and mean absolute error (MAE) are often utilized. These are respectively defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\hat{X}_t - X_t\right)^2} \tag{23}$$

$$\mathrm{RMSPE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\frac{\hat{X}_t - X_t}{X_t}\right)^2} \times 100 \tag{24}$$

$$\mathrm{V.N.} = \frac{\frac{1}{T-1}\left[\sum_{t=1}^{T}\{(\hat{X}_t - X_t) - (\hat{X}_{t-1} - X_{t-1})\}^2\right]}{\frac{1}{T}\sum_{t=1}^{T}\left(\hat{X}_t - \frac{1}{T}\sum_{t=1}^{T}\hat{X}_t\right)^2} \tag{25}$$

$$\mathrm{MAE} = \frac{1}{T}\sum_{t=1}^{T}\left|X_t - \hat{X}_t\right| \tag{26}$$

where X_t is the actual observation time series, $\hat{X}$ denotes the estimated time series, and T represents the number of time series data. We test the performance of the simulated value by applying for these criteria samples from 1990 to 2014. The results are shown in Table 8. We infer that this system is acceptable, which describes crude oil and natural gas markets.

Table 8. Evaluation of Model Performance by Four Criteria

	RMSE	RMSPE	V.N.	MAE
_P_GAS_HENRY_HUB	0.79	2.15	0.03	0.57
_P_OIL_WTI	5.51	1.54	1.15	3.93
GAS_S_CHN	1.52	0.41	0.01	1.22
GAS_S_IRN	3.24	0.45	0.09	2.42
GAS_S_MEX	1.39	0.32	0.01	0.97
GAS_S_MYS	2.54	0.61	0.07	1.95
GAS_S_NOR	4.01	0.63	0.37	2.91
GAS_S_QAT	6.82	0.96	0.28	4.36
GAS_S_RUS	11.01	0.22	0.38	8.43
GAS_S_SAU	2.11	0.32	0.05	1.58
GAS_S_TKM	7.46	3.07	4.85	5.05
GAS_S_USA	13.91	0.26	0.25	10.02
OIL_S_ARE	50047.16	0.48	25396568.93	37767.81
OIL_S_BRA	28687.84	0.51	6012623.94	20987.68
OIL_S_CAN	33367.81	0.28	1929629.84	24989.47
OIL_S_CHN	21996.18	0.16	946067.70	13237.86
OIL_S_DZA	28257.54	0.45	1199138.71	20098.07
OIL_S_IND	7632.10	0.26	346347.40	5689.24
OIL_S_IRQ	108440.24	1.57	1057909231.52	64892.55
OIL_S_KWT	50018.21	0.55	30972572.60	37390.31
OIL_S_MEX	44048.26	0.37	2953370.04	33196.10
OIL_S_QAT	26587.57	0.69	6448863.32	20365.86
OIL_S_RUS	140161.67	0.47	4645992.16	97710.06

OIL_S_SAU	179898.86	0.50	416080769.19	136437.25
OIL_S_USA	125579.59	0.41	10244815.12	85793.55
OIL_S_VEN	56953.68	0.50	27121824.23	40204.80
XS_GAS	20.56	0.11	0.21	12.95
XS_OIL	450107.69	0.19	232527497.58	318595.30

5. Conclusions and Future Work

Given the complexity of the international crude oil and natural gas markets, this study proposed an econometric model that shows the prices of crude oil and natural gas are endogenized based on the demand and supply approach. The mechanism of determining prices was taken into account in the substitution between crude oil and natural gas. In particular, profit maximization is assumed to be based on the following two strategies of oil-producing countries: oil-producing countries that intend to preserve market stability and those that intend simply to maximize their own profit. We simulated the final test and evaluated the accuracy of the whole model's performance by the criteria method of RMSE, RMSPE, V.N., and MAE. The results for several variables are not necessarily satisfactory. If quarterly data were available, the performance might be improved. However, the final test shows that, overall, our model could be traceable to the actual value.

However, in future, we should extend this model to improve its applicability to policy analysis. First, the demand for crude oil and natural gas should be endogenized. Since the demand for energy depends on the level of an economy, the macroeconomic economy model can be linked to our crude oil and natural gas model. Furthermore, the volume of CO_2 emissions at the macro level can be calculated by linking the crude oil and natural gas model to a macroeconomic model. Thus, improving this model to a more comprehensive system would support evaluations of monetary or energy policy.

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