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Energy Markets and Economics II

Edited by

Seema Narayan

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Seema Narayan engages in interdisciplinary research. She has authored with over 100 papers published in the subject areas of energy, financial economics, economic development, monetary policy, current account sustainability, exchange rates, international trade competitiveness and determinants, FinTech, emerging markets, portfolio management, time series, and panel econometric analyses. According to Google Scholar, her H-index is 40 and i-10 index is 80.

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Article

Time-Varying Influences of Oil-Producing Countries on Global Oil Price

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Abstract: This paper aims to investigate the time-varying influences of major crude oil-producing countries on Brent oil prices, with seven-panel data over the observation years of 1998 to 2018. We create seven panels with 36 monthly data for each and estimate the contributions of individual producing countries to oil price changes with a multivariate regression technique of ordinary least squares. Most existing researches have focused on identifying relationships among oil price, market fundamental factors, macroeconomic variables, and geopolitical events in broad perspectives. However, this paper undertakes a longitude/panel analysis of nine oil producers' influences, with the Organisation for Economic Co-operation and Development (OECD) consumption and the U.S. Dollar Index (USDX) on oil prices in each panel and intends to identify which producers have statistically significant influencing weights on oil prices. We believe that this research contributes to the body of knowledge in better understanding the relative impacts of major oil-producing countries. Results show empirical evidences that the Organization of the Petroleum Exporting Countries (OPEC) production stayed as the greatest negative influence on the oil price in the periods of Panel 2 (2001–2003) and Panel 7 (2016–2018) only, while the U.S. Dollar Index took over the OPEC's influencing role in most of the other periods, followed by Iran, the U.S., and China.

Keywords: oil producers; oil price; time-varying influence; oil market fundamentals; oil price fluctuation

1. Introduction

Crude oil is a critical source for economic growth and further industrialization, and the industrialized nations import a significant portion of oil from the Persian Gulf [1]. Oil accounts for 33% of global energy consumption and trades in US dollars per barrel of 42 US gallons [2].

Major benchmarks of crude oil include the West Texas Intermediate (WTI) in the U.S., the Brent Blend and the North Sea in Europe, and the Organization of the Petroleum Exporting Countries (OPEC) Reference Basket (ORB) of fourteen blends. While the WTI and Brent benchmark prices are for oil exports to the Atlantic Basin [3], the Brent crude price index is a benchmark to set oil prices for 70% of world oil transactions [4]. Figure 1 presents a map of global crude oils and their positioning by API (American Petroleum Institute) gravity, a measure of liquid petroleum density, and sulfur content. The crude oil with high API gravity has low density and light weight, while the oil with high sulfur content is called a sweet oil [3,5,6]. The WTI oil is very sweet high-quality, and the index is the most famous benchmark in the U.S. and the Western Hemisphere, with its future's products traded on the New York Mercantile Exchange (NYMEX). The Brent oil is not as light as WTI but still a high grade from fifteen oil fields in the North Sea.

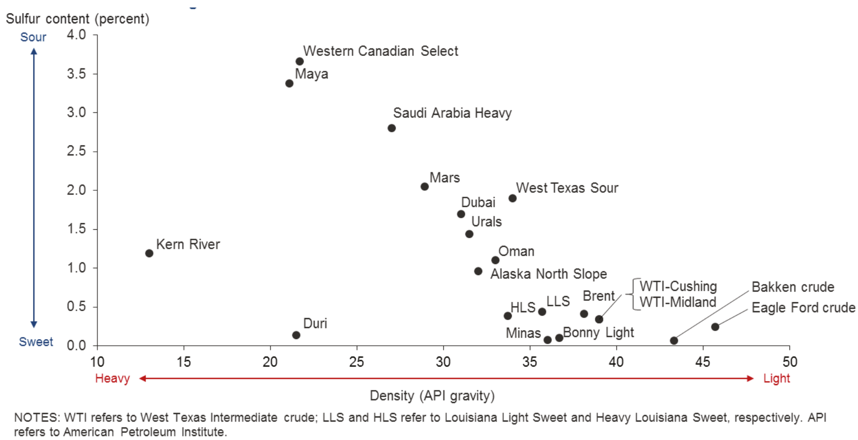

Figure 1. Crude oil is not a homogenous resource. Source: Reprinted with permission from Federal Reserve Bank of Dallas [6].

In 2018, top three crude oil producing countries were the U.S., Russia, and Saudi Arabia, producing over 10 million barrels a day each, followed by Iraq, Canada, Iran, and China, that produce about 4 million barrels a day each (Figure 2). The top three producers accounted for 39% of daily world production, comparable to OPEC's 41%, while the top ten producers had a 69% share with 57 million barrels [7].

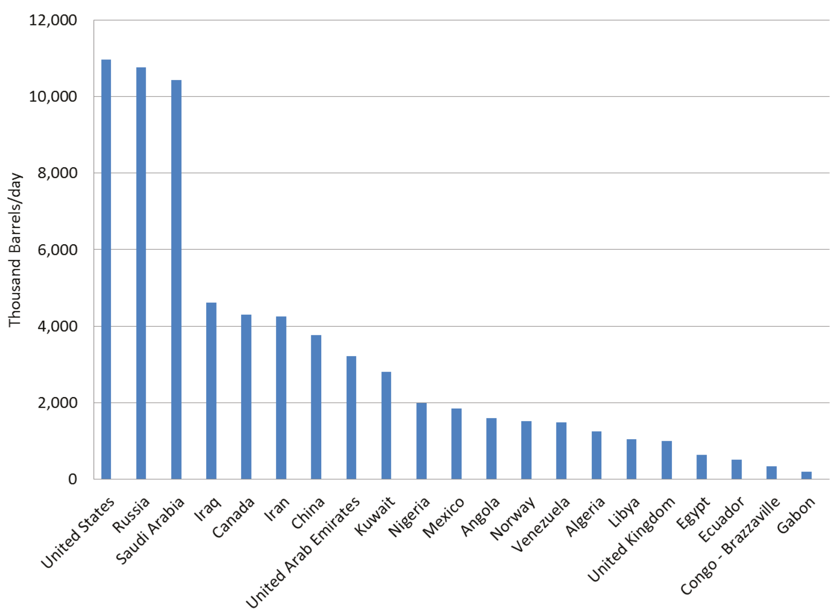

Figure 2. Major crude oil producing countries by production volume in 2018. Data source: U.S. Energy Information Administration [7].

Global oil market has the structure of two major player categories: low-cost public producers and highly competitive private producers [8]. Public producers include national oil companies (NOCs), including OPEC and non-OPEC-producers (Russia and Mexico), and account for 60% of global oil production. As such, global oil markets are heavily political, far away from a competitive market [9], and 94% of world proven reserves are controlled by governments [2]. There are some questions how long OPEC, the most influencing oil producing organization, would last as an international cartel given the historical examples of other commodity cartels, International Tin Association (1954 to 1985), and International Coffee Association (1962 to 1989) [10].

The global oil market has invisible hands of suppliers and consumers affecting oil prices. Oil price behavior, in a social system, may follow one of several fundamental modes, exponential growth, goal seeking, and oscillation, affected by a simple feedback structure of the components as suggested by a systems theory [11]. Other modes of nonlinear behavior include S-shaped growth, S-shaped growth with overshoot and oscillation, and overshoot and collapse.

In both academia and industry, it has been the subject of debate, what intrinsically drives crude oil prices. Figure 3 is a behavior over time (BOT) chart of annual prices of Brent spot and WTI spot from 1997 to 2018. The price level of U$20 per barrel in 1997 increased to U$100 in 2008 and settled down at U$65 to U$70 in 2018. Three explanations are postulated for the causes of the price declines: those associated with oversupply, those associated with under-consumption even with under-supply, and the future oil markets' bearish views of future market fundamentals and sell-now executions [8].

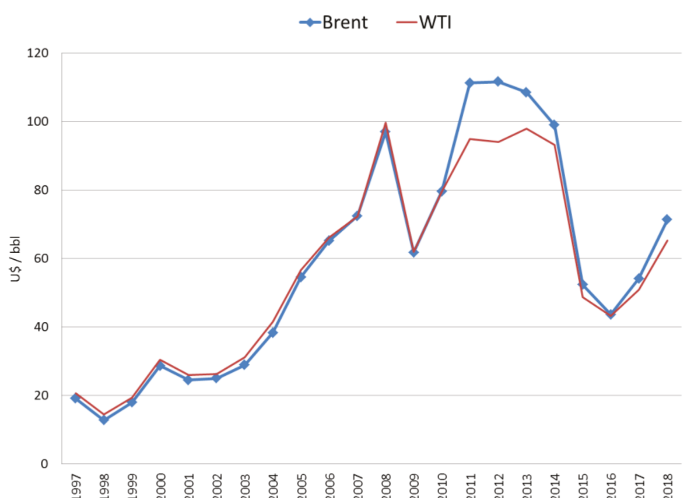

Figure 3. Crude oil benchmark annual prices (Brent and West Texas Intermediate (WTI) spot, nominal)—1997 to 2018. Data source: U.S. Energy Information Administration [12].

The period of 1973–1996 was quoted as "the age of OPEC" and the years of 1997 to present as a new industrial age outside OPEC [13], which describes the dominant power of OPEC through the mid-1990s and then emerging new forces in the late 1990s. Previous studies focused on identifying relationships between oil price and macro variables: relationship with supply factors [2,8,10,14], demand factors [15,16], macroeconomic variables [2,17], event-driven factors [9], and the consequences of high/low oil prices [18].

Oil discovery and technical improvement takes time to keep a market at an equilibrium state, and multiple time scales, short-term, mid-term, and long-term are more appropriate for analysis [19]. In a similar context, this paper takes the approach of multiple time panels, away from a traditional single time horizon.

This paper aims to investigate the influencing weights of major crude oil-producing countries on the Brent oil price in seven individual panels with 36 monthly data each. Nonproduction-related variables are petroleum consumption and the U.S. Dollar Index (USDX). This paper takes longitude/panel study approaches, from 1998, a year after 1997, a starting year of "the new industrial era" to 2018, and intends to provide empirical evidence which oil-producing countries were relatively more influential to the Brent oil price in each of the time-varying panels. As this is the first paper with a unique approach in oil market analysis, we believe that it provides better understanding of dynamic roles of major oil-producing countries in each defined period. This paper is organized as follows: Section 2: review of the current state of the art, Section 3: data and methodology, Section 4: results and discussion, and Section 5: conclusions and policy implications.

2. Review of the Current State of the Art

A review of literatures resulted in a number of studies that attempted to explain the fluctuations of crude oil prices, in terms of historical overviews, supply side (OPEC and non-OPEC), demand side, macroeconomic factors, price decline factors, oil future's market and speculation, event-driven factors, impact of oil prices on producers and consumers economies, and consequences of oil price shocks.

2.1. Historical Overview

When the first oil crisis took place in 1973, the imported crude oil price to the U.S. quadrupled in 1973/1974, and the West Texas Intermediate (WTI) rose from U$4.31 in September 1973 to U$10.11 per barrel in January 1974. Prior to 1973, oil price fluctuations were the results of shift in demand or global economic expansion [20], but since the early 1980s, the fluctuation has reflected the disruption of the flow, exogenous political events, war, revolution, and OPEC coalition [13]. Figure 4 presents a historical overview of oil prices, with geopolitical and economic events in a chronological order, from 1970 to 2015 [2].

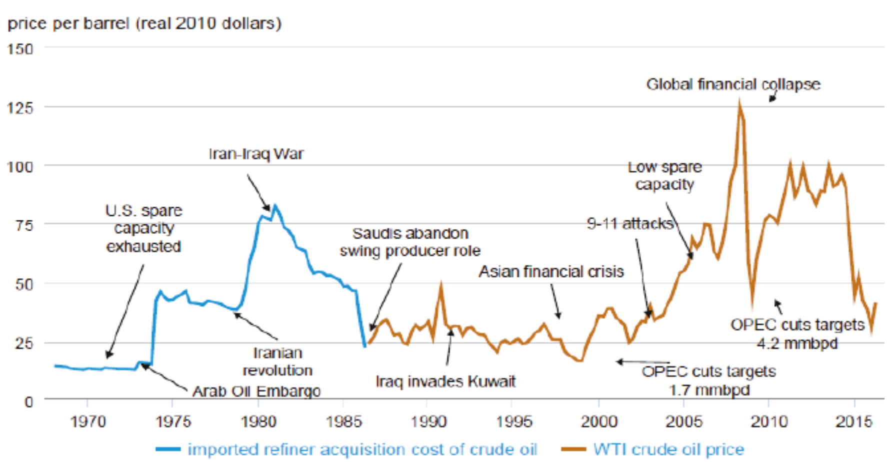

Figure 4. Geopolitical and economic effects on crude price. Source: Reprinted with permission from Solomon Adjei Marfo [2].

Baumeister & Kilian (2016) [20] describes four main episodes in the past four decades: the periods of the 1973/1974 oil crisis, the 1979/1980 crisis with Iran revolution, 1980s/1990s with Iran-Iraq war, and 2003/2008 with global financial crisis. The first episode was the Arab oil embargo where OPEC cut production by 5% and then an additional 25%. The second episode was the Iranian Revolution, resulting in oil price skyrocketing to U$40 per barrel in April 1980, from U$15 in September 1978.

The third episode period 1980s/1990s was a result of a large exogenous supply disruption, and subsequently, non-OPEC countries, Mexico, Norway, and the U.K., responded by transforming themselves to oil producers. In the aftermath, OPEC's market share of 53% in 1973 dropped to 43% in 1980 and then 28% in 1985. Approximately 10 years later, the WTI price plummeted to U$25 per barrel in 1996 due to the Asian financial crisis and then down to U$11 per barrel in 1998. The global financial crisis occurred and ran in parallel during the fourth episode in 2003–2008, when the WTI oil traded in the wide range of U$28 to 134 per barrel. Demand growth in India and China contributed to the rising prices throughout the mid-2008, but the global financial crisis led to a sharp drop in demand, pushing down the price to U$39 per barrel in February 2009.

2.2. Supply Side—OPEC

OPEC, founded in 1960 by five oil-producing nations, and with fourteen members as of August 2019 [21], accounts for an estimated 42% of global oil production and 73% of world oil proven reserves. OPEC started setting a target production in 1980 for each of its members to maintain stable oil prices [2].

Major producers prior to 1970 were seven western companies called "Seven Sisters": Anglo-Persian Oil Co, Gulf Oil, Standard Oil of California, Texaco, Royal Dutch Shell (RDS), Standard Oil of New Jersey, and Standard Oil of New York [22], and these producers now account for 5% of global oil reserves [2].

Oil spare production capacity could be a factor to affect oil price volatility. OPEC uses its spare production capacity to stabilize the oil market. Four core producers, Saudi Arabia, Kuwait, Qatar, and U.A.E., successfully balanced oil market and reduced price volatility to one-half of the normal level by adjusting production to offset supply and demand shocks and by maintaining the volume of spare capacity at 85% as swing producers [14].

In the "age of OPEC" prior to 1997, OPEC production quantity was accompanied by non-OPEC production quantity; for example, in 1982–1985, OPEC reacted to lower real oil prices [23]. In the "new industrial age" when OPEC's market power was getting weakened [13], OPEC production quantity just sustained the global production/consumption for GDP growth.

2.3. Supply Side—Non-OPEC

Small producing countries, each with a less than 5% share of world oil output, increased their combined share from 59.4% to 65.1% between 1995 and 2010 [24]. The small producers include Angola and Algeria in Africa, Indonesia, and Malaysia in Asia, and Mexico and Venezuela in South America, and Norway in Europe. They responded to the changes in the world oil market, and their decisions indicated that there was a strong relationship between their production levels and changes in oil consumption but with a lower relationship between the production level and change in prices.

Growth of the U.S. shale oil production is notable. The shale production was close to zero in 2008 but grew to 4.25 million barrels a day in 2016, standing with a 48% share of the U.S. oil production and 5% of the global production [10]. At the end of 2018, the U.S. shale production stood at 6 million barrels a day, accounting for 57% of the nation's total production. The shale production also contributed to an increase of the U.S.'s global market share to 13% in 2018, up from 8% in 2000, potentially influencing the oil price collapses in the recent decade [25].

Shale oil production can respond to changes in oil prices much quicker than a traditional oil technology, with the competitive edges of improvement in fracking technology and its lower extraction costs. The U.S. shale oil development may be analogous to a structural change in systemic processes. Kuhn (2012) describes three ways for a paradigm to respond to crises: one, proving to solve the crisis, two, giving up with no solution and leaving for next generations, and three, ending up with a new accepted paradigm after the battle [26]; the shale oil case belongs to the third way.

2.4. Demand Side

On the oil consumption side, the most influential driver is demand for refined oil products, and OECD accounts for 50% of world petroleum demand [2]. When the refining capacity is lost, it would affect the oil demand side. Notably, the Arab embargo in 1973 disrupted the oil supply and pushed up the market price, resulting in depressing the U.S. and OECD demand by 2–4% per year in 1974 and 1975 [12].

Oil price rise in 2004–2008 is also the subject of debate. While a price rise is viewed in association with increased demand, another view is that oil price is more sensitive to supply as production approaches its capacity [15]. Thus, refining utilization rates, OPEC capacity utilization, and oil future's markets affect oil price. Oil price movements may exert negative impacts on gross domestic product (GDP), consumer price index (CPI), and unemployment in oil consuming countries, in particular, based on economic data collected from 26 OECD countries [16].

2.5. Macroeconomic Factors

Economic growth and energy investments lead to more available oil supply, as well as oil demand. As crude oil trades in US dollars in global markets, the depreciation of US dollars leads to more demand for oil, and vice versa [2], indicating negative correlations between oil demand and the US dollar strength. Other macroeconomic factors may include future oil markets, speculators, hedgers, brokers, and exchanges available to the global players.

There are meaningful relationships between oil price and more extensive macroeconomic variables, such as global industrial production, prices, and interest rate [17]. Among five countries in the study, the global macro factors were main drivers for the U.S., Europe, and China but minor ones for Japan and India. Other studies also examined relationships between oil price and macroeconomic variables [27–29].

2.6. Price Decline Factors

Price decline in 2007–2008 was a good example of formation and collapse of an oil price bubble, going through combined effects of stagnant oil supply, unexpected economic growth in India and China, low interest rate, a weak U.S. dollar, and a consequent sharp spike in oil prices [30]. This behavior is similar to a mode of overshoot and collapse in a social system [11].

The World Bank lists causal factors to sharp drops in oil prices: supply and demand, changes in OPEC objective, geopolitics, the U.S. dollar appreciation, speculative demand and investment management, relative contribution of supply and demand, and oil price outlook [10]. Fundamental oil supply and demand set the conditions for a long-term trend in price, but in the short-term, market sentiment and expectation led to price fluctuations.

The World Bank reported that the oil price drop in June 2014 was significant but not an unprecedented event, as a 30% price decline were observed in five cases over a seven-month period in history [10]. Those five periods are 1985–1986 with strong production from non-OPEC, 1990–1991 with the U.S. economic recession, 1997–1998 with Asian financial crisis, 2008–2009 with global financial crisis, and the latest, June 2014–January 2015 with a supply glut from unconventional sources since mid-2014. In November 2014, OPEC changed its policy and abandoned an objective to set a target price.

2.7. Oil Future's Market and Speculation

Crude oil future's market usually reflects the expectation of market fundamentals. Unexpected disruption in the oil market comes with large regression residuals, and the derivative paper markets contain information on the magnitude and duration of major market disruption [31]. Empirical results are derived from investigating price volatility of Brent oil (2000–2014) in relationship with the term structure of option-based implied volatilities and global macro-economy; physical market fundamentals (OPEC surplus output, capacity, and storage); and equity volatility index (VIX).

On a short run, if oil market is not price-sensitive, or relatively inelastic, then oil investment would be slow to take place [32]. Oil prices spiked in the period of 2000 to 2010, and one of the explanations was that speculative pressure exerted influence on the prices of the storable commodities.

2.8. Event-Driven Factors

When political instability is prevailing in any of the oil-producing countries, oil production capacity may be disrupted and reduce available supply [2]. Roles of political economic news in oil pricing are also important [9].

The Arab embargo in the early 1970s led to technology advancements among non-OPEC nations to secure oil resources, resulting in active developments of unconventional and offshore oil sources, with the North Sea in the 1970s and the Gulf of Mexico in the 1980s. The shale oil, a tight rock formation, has a shorter life cycle of 2.5 to 3 years from shale development to full extraction and contributes to the global supply with low capital costs [10].

Wars or political tensions may disrupt oil supply to the markets, but, by their models, show no direct effect [33]. As demand is inelastic to price change, economic activity is the most significant factor to affect demand. Major wars/political events in oil markets include Arab-Israeli War (1973), Persian Gulf War (1991), Operation Desert Fox (1998), Iraq War (2003–2011), Arab Spring (2011), global financial crisis (2008), and European debt crisis (2010).

2.9. Impact of Oil Prices on Producers' and Consumers' Economies

Impacts of oil price shocks vary with on oil producers and oil-consuming economies [29]. Among twelve economies analyzed for a period of 1995 to 2006, oil producers, Russia and Canada, benefited from oil price shocks, while oil importers found their economic activities suffer a slowdown in their GDP. The largest negative effects from the shocks were present in Japan, China, the U.S., Finland, and the Switzerland.

When oil price shocks take place at the markets, their consequences include shocks to key supply chains, global economic activities, national accounts, inflation, and searches for non-oil sources [10,34]. The price also shocks inflation in low oil-dependency and high oil-dependency countries [18].

There is a strong relationship between oil price shocks and the U.S. recessions [35], and Canada is affected by U.S. domestic monetary policies. Foreign disturbances, such as innovations and the U.S. interest rate, leads to significant inflation in the Canadian economy [36]. Due to the oil price volatility, even oil producers find it hard to meet their government expenditure. Bahrain implemented a policy in the late 1970s to diversify their economy by attracting finance investment in the state [37]. Oil price fluctuations also affected economic activities of small oil-producing countries, Trinidad and Tobago [38], and fiscal policies in oil-exporting countries [39].

3. Data and Methodology

3.1. Data

Oil price is the response (dependent) variable or a simple average monthly spot price of Brent crude oil (denoted here as BRENT), published by the U.S. Energy Information Administration (EIA). The Brent crude oil price is selected as a global oil proxy price, because it represents a benchmark price for about 70% of the global oil transactions [4]. The period for analysis is 21 years, or 252 months, from 1998 to 2018, with 1997 being the start of "the new industrial age" in the global oil market, according to Hamilton (2013) [13]. The base unit is U$ per barrel.

Explanatory (independent) variables are monthly crude oil production data by country collected from EIA, and data for analysis covers the same period of 1998 to 2018. Producing countries for analysis are nine major countries, including five OPEC and four non-OPEC countries, based on their production ranks in 2018. They are United States (US), Russia, Saudi Arabia, Iraq, Canada, Iran, China, UAE, and Kuwait. OPEC is also included for analysis, due to its heavy share (41%) of the global production in

2018. In this paper, the capitalized names of explanatory variables represent the individual production quantity of the country or organization. The base unit for oil production is one thousand barrels per day.

Two non-production related variables are selected besides the explanatory variables. Monthly petroleum consumption data for OECD is collected from EIA and used as a proxy of world petroleum consumption, since the Old World consumption data is not available on a monthly level. The OECD's share of the world consumption accounts for an average of 56% in the years 1998–2018. OECDCON represents monthly petroleum consumption of its 36 members. Its unit is also one-thousand barrels per day. Another non-production-related variable is the monthly Trade Weighted U.S. Dollar Index (USDX), a macroeconomic variable, with January 1997 as a base month. This index represents the strength of the U.S. dollar. As oil price trades in U.S. dollars, this index influences oil demand and oil price. For example, when the U.S. Dollar Index is strong (high), then consumers tend to consume oil less. The data source is the Federal Reserve Bank of St. Louis (https://alfred.stlouisfed.org). The unit is dimensionless.

Each panel covers a 36-month period, with seven panel data over the 21-year period, with an assumption that additional production may be possible to react to a need for additional supply with a 3-year period. Conventional oil development takes 5–10 years [40], but the shale oil development requires a shorter cycle [41].

The response variable and explanatory variables are all transformed to a natural logarithm format, or LN, so a percentage change in the response variable may be estimated with respect to a percentage change in one exploratory variable, if they are statically significant at the 0.1 (10%) level.

3.2. Methodology

In the whole period and each of seven panel period data, coefficients of variation (CV) are first calculated to understand a degree of fluctuations of each variable. Coefficient of variation (CV) is defined as a ratio of the standard deviation to the mean of a variable, indicating a common measure of the magnitude of variability for comparison among the variables. This measure helps identify potential variables that may influence more on the response variable, Brent oil price.

In each of seven panel data, a multivariate regression technique with ordinary least squares is used as a main tool to measure the coefficient estimates of explanatory variables, and the coefficient estimates will be compared to determine influencing weights among the variables. If p-value of the regression parameter estimates of any explanatory variables is greater than 10%, the variables will be excluded from comparisons of the coefficient estimates, because they are not statistically significant at the level.

There are a total of eight runs of regression models in this analysis; that is, one for the whole period and seven for seven panels. Each of the eight runs has individual summaries of parameter estimates, and then the coefficient estimates of statistically significant explanatory variables are compared to measure influencing weights.

Equation for multivariate regression parameter estimation in each of panels is:

$$\begin{aligned} LN\_BRENTt = \alpha_t + LN\_OPEC_t + \beta_1 \times LN\_US_t + \beta_2 \times LN\_RUSSIA_t + \beta_3 \times LN\_SAUDI_t \\ + \beta_4 \times LN\_IRAQ_t + \beta_5 \times LN\_CANADA_t + \beta_6 \times LN\_IRAN_t + \beta_7 \times LN\_CHINA_t + \beta_8 \times \\ LN\_UAE_t + \beta_9 \times LN\_KUWAIT_t + \beta_{10} \times LN\_OECDCON_t + \beta_{11} \times LN\_USDX_t + \varepsilon_t \end{aligned} \quad (1)$$

where

Response variable:

LN_BRENT_t: natural log of monthly Brent oil price (BRENT) at a month t;

Explanatory variables:

LN_CANADA_t: natural log of monthly Canada production (CANADA) at a month t;

LN_CHINA_t: natural log of monthly China production (CHINA) at a month t;

LN_IRAN_t: natural log of monthly Iran production (IRAN) at a month t;
LN_IRAQ_t: natural log of monthly Iraq production (IRAQ) at a month t;
LN_KUWAIT_t: natural log of monthly Kuwait production (KUWAIT) at a month t;
$LN\_OECDCON_t$: natural log of monthly OECD petroleum consumption (OECDCON) at a month t;
LN_OPEC_t: natural log of monthly OPEC production (OPEC) at a month t;
LN_RUSSIA_t: natural log of monthly Russia production (RUSSIA) at a month t;
LN_SAUDI_t: natural log of monthly Saudi Arabia production (SAUDI) at a month t;
LN_UAE_t: natural log of monthly UAE production (UAE) at a month t;
LN_US_t: natural log of monthly U.S. production (US) at a month t;
LN_USDX_t: natural log of monthly U.S. Dollar Index (USDX) at a month t.

4. Results and Discussion

Starting with a summary for the whole period of 1998 to 2018, all the variables, responses, and explanations are summarized in the tables of descriptive summary statistics in each panel, followed by a summary table of parameter estimations. Units of each variables are also displayed on Table 1, and the units stay the same in all tables and figures of this paper, unless otherwise specified.

Table 1. The whole period (1998–2018): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT (U$/bbl)	252	59.87	56.36	32.66	54.54	9.82	132.72	122.90
CANADA (1000 bbl)	252	2800	2601	711	25.41	1832	4520	2688
CHINA (1000 bbl)	252	3727	3754	346	9.29	3134	4408	1274
IRAN (1000 bbl)	252	3810	3900	385	10.10	3018	4624	1606
IRAQ (1000 bbl)	252	2746	2515	963	35.05	53	4815	4762
KUWAIT (1000 bbl)	252	2425	2500	307	12.66	1785	2951	1166
OECDCON (1000 bbl)	252	47,816	47,562	1835	3.84	44,239	52,782	8543
OPEC (1000 bbl)	252	30,940	31,438	2299	7.43	25,256	34,976	9720
RUSSIA (1000 bbl)	252	8949	9423	1503	16.80	5707	11,051	5344
SAUDI (1000 bbl)	252	9138	9220	875	9.58	7210	11,045	3835
UAE (1000 bbl)	252	2680	2602	363	13.55	2050	3451	1401
US (1000 bbl)	252	6605	5804	1752	26.52	3974	11,961	7987
USDX (base = 1997)	252	112	114	10	8.70	95	130	35

4.1. The Whole Period: 1998–2018

Average Brent oil spot price was U$59.87 per barrel during the whole observation period of 21 years, with its coefficient of variation (CV) the highest (54.54) among all variables (Table 1). Producing countries with high CVs for the 21-year period are Iraq (35.05), the U.S. (26.52), Canada (25.41), and Russia (16.80). These high-CV countries could be notable contributors to such a volatile Brent oil price. Summary statistics of all the variables for each of the panels will be discussed separately.

For the whole period of 1998 to 2018, parameter estimates by the multivariate regression to explain the response variable LN_BRENT are summarized on Table 2. Major explanatory variables with a statistical significance level of 0.1% or 10% are LN_USDX, LN_RUSSIA, LN_SAUDI, LN_CHINA, LN_KUWAIT, LN_IRAN, and LN_IRAQ. Among the significant variables, USDX (the U.S. Dollar Index), the only macroeconomic variable in this analysis, is the greatest influencing factor in the whole period, with one percent change in USDX resulting in a 3.68% decline in the Brent price, while one percent change in production from Kuwait, China, and Iran negatively affected the price by 1.56%, 1.5%, and 0.63%, respectively.

Meanwhile, production of other significant producers, Russia, Saudi Arabia, and Iraq, co-moved with the price, or one percent change in production leading to 2.96%, 2.46%, and 0.12%, respectively. These co-move coefficient estimates are in contradiction with the basic economic theory; a price negatively correlates with supply quantity [10]. Some of the interpretations for this co-moving supply-price relationship are that an information asymmetry may exist due to a production location being remote from a market place that the Brent oil index is based on, or the producer's change in supply did not simply change oil price direction.

Table 2. The whole period (1998–2018): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	13.0011	8.4379	1.54	0.1247
LN_CANADA	0.0778	0.2710	0.29	0.7744
LN_CHINA	−1.4954	0.4886	−3.06	0.0025 *
LN_IRAN	−0.6239	0.2122	−2.94	0.0036 *
LN_IRAQ	0.1207	0.0527	2.29	0.023 *
LN_KUWAIT	−1.5579	0.5193	−3.00	0.003 *
LN_OECDCON	−0.5698	0.5152	−1.11	0.2698
LN_OPEC	0.1627	0.8836	0.18	0.8541
LN_RUSSIA	2.9632	0.3117	9.51	<0.0001 *
LN_SAUDI	1.4614	0.4328	3.38	0.0009 *
LN_UAE	0.3710	0.4805	0.77	0.4409
LN_US	−0.2759	0.1981	−1.39	0.165
LN_USDX	−3.6848	0.2900	−12.71	<0.0001 *
RSquare	0.90			

Note: * represents statistical significance at a level of 0.1. t Ratio is defined as Estimate divided by Std Error to calculate p-value, while RSquare represents the explained portion of variance by an independent variable.

In the analysis of the whole period, it is also worthwhile to note that the U.S. production, OECD consumption, or OPEC production have not influenced the BRENT price in a statistically significant way (10%).

4.2. Variability of Variables

One of the ways to understand a system begins with knowledge of its variation, besides a system itself [42]. Coefficients of variations would represent how the variables experienced fluctuations over a specified period. Table 3 and Figure 5 present the coefficients of variations for each variable during each of the 36-month periods. BRENT price tops in the CV ranking in six periods of the total seven, except in Panel 2 (2001–2003) when Brent's CV of 13.1 is second to the IRAQ production variable with a CV of 40.5. BRENT price range over the 21 years is U$123 per barrel, with a low of U$10. IRAQ production has shown the most fluctuations among all the producers in all the past seven panels, as well as over the whole period. Over the whole period, IRAQ production tops with a CV of 35.0, followed by US (26.5), CANADA (25.4), and RUSSIA (16.8).

Table 3. Coefficients of variations for each of variables by panel.

Variable	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Whole
	(1998–2000)	(2001–2003)	(2004–2006)	(2007–2009)	(2010–2012)	(2013–2015)	(2016–2018)	(1998–2018)
BRENT	38.09	13.07	23.90	31.69	16.49	30.96	23.17	54.54
CANADA	3.09	6.13	4.96	3.36	7.51	6.41	9.24	25.41
CHINA	1.36	1.83	2.54	1.47	2.51	1.86	3.08	9.29
IRAN	3.90	4.67	1.86	1.90	9.57	2.75	7.11	10.10
IRAQ	19.09	40.48	9.19	7.88	10.48	13.92	3.11	35.05
KUWAIT	5.92	6.56	3.48	4.25	6.20	2.93	2.87	12.66
OECDCON	3.31	2.35	2.40	3.81	2.10	1.72	1.76	3.84
OPEC	3.70	3.90	2.53	2.80	2.34	2.47	1.15	7.43
RUSSIA	4.74	7.43	2.73	0.98	1.24	1.10	1.79	16.80
SAUDI	4.93	7.18	4.08	5.42	5.49	3.49	2.43	9.58
UAE	4.86	6.08	4.43	5.20	6.59	3.33	3.07	13.55
US	3.91	2.43	5.93	5.07	8.63	10.33	10.54	26.52
USDX	2.21	3.30	2.37	4.67	2.59	6.95	2.66	8.70

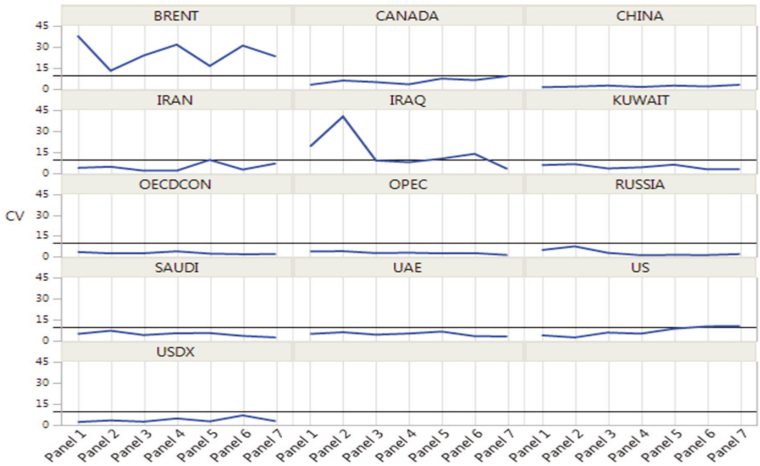

Figure 5. Coefficients of variations for each variable by panel. CV: coefficient of variable.

Table 4 is a summary of the top four crude oil-producing countries with high CVs in each panel period. Over the whole period (1998–2018), IRAQ production experienced the highest CV (IRAQ production and ranked first for most of the panels, except for a recent Panel 7 Period (2016–2018) when U.S. production takes the top position. U.S. production recorded the CVs over 10 in the past two panel periods, indicating a swing volume of ten percent or more in recent years. One observation is that CHINA, the world's top seventh oil producer, has maintained a low CV in each of the panels, implying the country is not an oil exporter but, rather, a domestic producer-consumer.

Table 4. Top four countries with the highest coefficients of variations for by panel.

Panel	Period	Rank 1	Rank 2	Rank 3	Rank 4
Panel 1	(1998–2000)	IRAQ (19.1)	KUWAIT (5.9)	SAUDI (4.9)	UAE (4.9)
Panel 2	(2001–2003)	IRAQ (40.5)	RUSSIA (7.4)	SAUDI (7.2)	KUWAIT (6.6)
Panel 3	(2004–2006)	IRAQ (9.2)	US (5.9)	CANADA (5)	UAE (4.4)
Panel 4	(2007–2009)	IRAQ (7.9)	SAUDI (5.4)	UAE (5.2)	US (5.1)
Panel 5	(2010–2012)	IRAQ (10.5)	IRAN (9.6)	US (8.6)	CANADA (7.5)
Panel 6	(2013–2015)	IRAQ (13.9)	US (10.3)	USDX (6.9)	CANADA (6.4)
Panel 7	(2016–2018)	US (10.5)	CANADA (9.2)	IRAN (7.1)	IRAQ (3.1)
Whole	(1998–2018)	IRAQ (35)	US (26.5)	CANADA (25.4)	RUSSIA (16.8)

4.3. Panel 1: 1998 to 2000

Panel 1 Period covers 36 months in 1998 to 2000, with an average BRENT price of U$19.72 per barrel. BRENT shows the highest CV (38.09), and the producers with high CVs are IRAQ (19.09), KUWAIT (5.92), SAUDI (4.93), and UAE (4.86) (Table 5). Among the producers, IRAQ production is the most fluctuating in this period, while the US and OPEC look stable in their production volume. BRENT price range is U$23 per barrel, with a low of U$10.

A summary of parameter estimates in Table 6 shows that RUSSIA is the only statistically significant variable at a level of 10%, with none of the producers significant. RUSSIA production exerted influence on BRENT prices in a co-move or 1% change in RUSSIA production leading to 10.31% in BRENT prices. This could be counter-intuitive in the economic sense because of the usual negative relationship between supply volume and a market price. One interpretation is RUSSIA took a good timing of the oil market, and their additional significant volume did not push down the market price or vice versa.

This panel period corresponds to the events of the Asian financial crisis (1997–1998) and Operation Desert Fox, a 4-day bombing campaign on Iraq targets.

Table 5. Panel 1 period (1998–2000): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	19.72	17.47	7.51	38.09	9.82	33.14	23.32
CANADA	36	1955	1960	60	3.09	1832	2064	232
CHINA	36	3214	3213	44	1.36	3134	3300	166
IRAN	36	3630	3635	141	3.90	3415	3925	510
IRAQ	36	2410	2540	460	19.09	1261	3055	1794
KUWAIT	36	2021	2020	120	5.92	1785	2215	430
OECDCON	36	48,101	47,831	1593	3.31	44,411	52,101	7690
OPEC	36	28,188	28,120	1043	3.70	25,956	30,282	4326
RUSSIA	36	6137	6088	291	4.74	5707	6771	1064
SAUDI	36	8210	8187	405	4.93	7610	8975	1365
UAE	36	2295	2300	111	4.86	2105	2480	375
US	36	5985	5885	234	3.91	5739	6541	802
USDX	36	117	117	3	2.21	114	124	10

Table 6. Panel 1 period (1998–2000): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	−75.3176	55.9357	−1.35	0.1913
LN_CANADA	1.0698	1.3973	0.77	0.4517
LN_CHINA	2.3875	2.9872	0.8	0.4323
LN_IRAN	−1.4313	1.7139	−0.84	0.4122
LN_IRAQ	0.0774	0.6667	0.12	0.9086
LN_KUWAIT	0.4467	2.6488	0.17	0.8676
LN_OECDCON	−1.7855	1.2473	−1.43	0.1657
LN_OPEC	0.2553	9.6455	0.03	0.9791
LN_RUSSIA	10.3123	1.8497	5.58	<0.0001 *
LN_SAUDI	−0.0967	3.5770	−0.03	0.9787
LN_UAE	−1.3004	2.2682	−0.57	0.572
LN_US	1.7922	2.4417	0.73	0.4704
LN_USDX	−4.0685	2.5809	−1.58	0.1286
RSquare	0.87			

Note: * represents statistical significance at a level of 0.1.

4.4. Panel 2: in 2001 to 2003

Panel 2 period has an average BRENT price of U$26.10 per barrel, up about U$6 from the Panel 1 period. BRENT has the second-highest CV (13.07) to IRAQ production (40.48), followed by producers RUSSIA (7.43), SAUDI (7.18), and KUWAIT (6.56) (Table 7). Among the producers, IRAQ production is still the most fluctuating in this period, and the US and OPEC still look stable in their production volume, with CVs of the 2.40–3.90 range. BRENT price range is U$14 per barrel, with a low of U$19.

A summary of parameter estimates in Table 8 presents that five producers/organizations are influencers to BRENT prices in this period at a significance level of 10%: IRAQ, OPEC, CHINA, SAUDI, and the U.S. Negative price influencers are OPEC and the U.S., with the effects of 3.15% and 1.84%, respectively, by one percent change in their production. Co-move price influencers with their production are CHINA, SAUDI, and IRAQ, with the effects of 2.98%, 1.86%, and 0.16%, respectively, by one percent change in production. This period includes the U.S. recovery time from March 2001.

Table 7. Panel 2 period (2001–2003): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	26.10	25.80	3.41	13.07	18.71	32.77	14.06
CANADA	36	2168	2166	133	6.13	1953	2480	527
CHINA	36	3366	3371	62	1.83	3220	3490	270
IRAN	36	3637	3692	170	4.67	3365	3935	570
IRAQ	36	1909	1969	773	40.48	53	2879	2826
KUWAIT	36	2009	1976	132	6.56	1803	2354	551
OECDCON	36	48,729	48,792	1144	2.35	46,491	51,589	5098
OPEC	36	27,479	27,631	1071	3.90	25,256	29,433	4177
RUSSIA	36	7485	7434	556	7.43	6680	8448	1768
SAUDI	36	8146	8060	585	7.18	7210	9521	2311
UAE	36	2212	2195	135	6.08	2050	2450	400
US	36	5732	5753	140	2.43	5358	5905	547
USDX	36	124	126	4	3.30	114	130	15

Table 8. Panel 2 period (2001–2003): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	10.1815	26.0803	0.39	0.6998
LN_CANADA	0.6510	0.9991	0.65	0.5211
LN_CHINA	2.9807	1.4067	2.12	0.0451 *
LN_IRAN	1.5051	1.0922	1.38	0.1815
LN_IRAQ	0.1644	0.0420	3.91	0.0007 *
LN_KUWAIT	0.4455	0.9480	0.47	0.6429
LN_OECDCON	−1.4286	0.8767	−1.63	0.1168
LN_OPEC	−3.1486	0.9435	−3.34	0.0029 *
LN_RUSSIA	−0.8248	1.0001	−0.82	0.418
LN_SAUDI	1.8548	0.8840	2.1	0.0471 *
LN_UAE	0.1352	1.3897	0.1	0.9233
LN_US	−1.8395	0.9814	−1.87	0.0736 *
LN_USDX	0.0125	1.4004	0.01	0.993
RSquare	0.76			

Note: * represents statistical significance at a level of 0.1.

4.5. Panel 3: 2004 to 2006

Panel 3 period sees a 50% spike in an average BRENT price of U$52.60 per barrel, up about U$25 from the Panel 2 period. This period corresponds to the period when China and India were booming as emerging economies. BRENT regained the highest CV (23.90), followed again by IRAQ production (9.19) and U.S. (5.93), CANADA (4.96), and UAE (4.43) (Table 9). Among the producers, IRAQ production is still the most fluctuating in this period, and the U.S. came to play with a relatively volatile volume. BRENT price range is U$43 per barrel, with a low of U$31.

A summary of parameter estimates in Table 10 shows that CHINA is the only producer statistically significant at a level of 10%. However, CHINA is a co-move price influencer with the effect of 3.55% by one percent change in its production. However, OPEC and RUSSIA follow CHINA as potential price influencers, though the significance level is a little away at 11%. This period is characterized by a growth theme in China and India.

Table 9. Panel 3 period (2004–2006): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	52.60	54.80	12.57	23.90	30.86	73.67	42.81
CANADA	36	2431	2411	121	4.96	2172	2669	497
CHINA	36	3589	3603	91	2.54	3393	3716	323
IRAN	36	4056	4035	76	1.86	3950	4230	280
IRAQ	36	1961	1903	180	9.19	1603	2303	700
KUWAIT	36	2480	2500	86	3.48	2300	2600	300
OECDCON	36	50,205	50,106	1207	2.40	47,433	52,782	5349
OPEC	36	31,217	31,448	791	2.53	29,368	32,382	3014
RUSSIA	36	9031	9028	247	2.73	8457	9450	993
SAUDI	36	9268	9500	378	4.08	8400	9600	1200
UAE	36	2550	2602	113	4.43	2220	2702	482
US	36	5237	5192	310	5.93	4214	5617	1403
USDX	36	111	111	3	2.37	107	117	10

Table 10. Panel 3 period (2004–2006): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	−76.7298	23.1602	−3.31	0.003 *
LN_CANADA	−0.4416	0.5312	−0.83	0.4144
LN_CHINA	3.5469	1.2921	2.75	0.0115 *
LN_IRAN	−3.3315	2.1477	−1.55	0.1345
LN_IRAQ	−0.5150	0.4697	−1.1	0.2842
LN_KUWAIT	−0.6316	2.1740	−0.29	0.774
LN_OECDCON	−0.8209	0.6835	−1.2	0.2419
LN_OPEC	11.1122	6.7097	1.66	0.1113
LN_RUSSIA	1.9980	1.2326	1.62	0.1187
LN_SAUDI	−3.5561	2.3156	−1.54	0.1383
LN_UAE	−0.3896	0.7672	−0.51	0.6164
LN_US	0.0905	0.3718	0.24	0.8099
LN_USDX	0.4339	1.4334	0.3	0.7648
RSquare	0.94			

Note: * represents statistical significance at a level of 0.1.

4.6. Panel 4: 2007 to 2009

Panel 4 period sees a 30% lift in an average BRENT price of U$76.93 per barrel, about U$24 from the Panel 3 period. This period corresponds to the period when China and India continued growing. BRENT is still fluctuating with the highest CV (31.69), followed by again IRAQ production (7.88) and SAUDI (5.42), UAE (5.2), and U.S. (5.07) (Table 11). Among the producers, the U.S. comes to play with a relatively volatile volume, with IRAQ, SAUDI, and UAE. BRENT price range is U$93 per barrel, with a low of U$40.

A summary of parameter estimates in Table 12 displays that two macro-variables (USDX and OECDCON) and two producers are BRENT influencers in this period, at a significance level of 10%. Negative price influencers are USDX, IRAN, and OECDCON, with the effects of 4.79%, 3.76%, and 1.72%, respectively, by one percent change in their production or index. Co-move price influencers include SAUDI, with the effects of 3.89%, by one percent change in production. This period is still characterized by a growth theme in China and India, which caused the WTI future's price to spike to an unprecedented U$150 per barrel in August 2008.

Table 11. Panel 4 period (2007–2009): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	76.93	72.05	24.38	31.69	39.95	132.72	92.77
CANADA	36	2596	2593	87	3.36	2436	2809	373
CHINA	36	3774	3775	56	1.47	3643	3884	241
IRAN	36	3999	4000	76	1.90	3900	4100	200
IRAQ	36	2284	2353	180	7.88	1753	2505	752
KUWAIT	36	2467	2448	105	4.25	2350	2629	279
OECDCON	36	48,206	48,275	1838	3.81	44,239	51,491	7252
OPEC	36	31,496	31,105	880	2.80	30,335	33,191	2856
RUSSIA	36	9430	9415	93	0.98	9296	9654	358
SAUDI	36	8743	8600	474	5.42	8068	9700	1632
UAE	36	2661	2612	138	5.20	2242	2850	608
US	36	5140	5141	261	5.07	3974	5555	1581
USDX	36	103	103	5	4.67	95	112	17

Table 12. Panel 4 period (2007–2009): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	43.3000	23.1744	1.87	0.0745 *
LN_CANADA	−0.2797	0.3697	−0.76	0.457
LN_CHINA	0.7812	1.2245	0.64	0.5298
LN_IRAN	−3.7626	1.1971	−3.14	0.0046 *
LN_IRAQ	0.2652	0.3597	0.74	0.4684
LN_KUWAIT	−0.1553	1.6641	−0.09	0.9265
LN_OECDCON	−1.7258	0.7941	−2.17	0.0403 *
LN_OPEC	−3.2596	3.4539	−0.94	0.3551
LN_RUSSIA	2.8192	1.9612	1.44	0.164
LN_SAUDI	3.8902	1.0800	3.6	0.0015 *
LN_UAE	0.2585	0.3869	0.67	0.5107
LN_US	−0.1685	0.3369	−0.5	0.6218
LN_USDX	−4.7920	0.4936	−9.71	<0.0001 *
RSquare	0.97			

Note: * represents statistical significance at a level of 0.1.

4.7. Panel 5: 2010 to 2012

Panel 5 period also experiences a 25% spike to an average BRENT price of U$100.81 per barrel, up about U$24 from Panel 4 period. This period corresponds to the one with major events, such as Arab Spring and European Debt Crisis, in Portugal, Italy, Iceland, and Greece. BRENT still tops the CV (16.49) but lower from the CV of the previous period (31.69), followed by again IRAQ production (7.88) and IRAN (10.48), U.S. (8.63), and CANADA (7.51) (Table 13). U.S., IRAN, and CANADA were actively participating in the additions of oil supply with the prices moving higher. The U.S. shale oil and Canada oil sands play significant roles. BRENT price range is U$52 per barrel, with a low of U$74.

Table 13. Panel 5 period (2010–2012): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	100.81	109.28	16.62	16.49	73.75	125.45	51.70
CANADA	36	2926	2968	220	7.51	2484	3427	943
CHINA	36	4068	4055	102	2.51	3891	4281	390
IRAN	36	3841	4049	368	9.57	3018	4127	1109
IRAQ	36	2669	2600	280	10.48	2325	3275	950
KUWAIT	36	2488	2550	154	6.20	2250	2650	400
OECDCON	36	46,323	46,354	971	2.10	44,486	48,361	3875
OPEC	36	32,000	31,967	750	2.34	30,585	33,409	2824
RUSSIA	36	9796	9806	121	1.24	9557	10048	491
SAUDI	36	9396	9440	515	5.49	8240	10040	1800
UAE	36	2804	2890	185	6.59	2570	3010	440
US	36	5877	5613	507	8.63	5299	7088	1789
USDX	36	100	99	3	2.59	95	105	10

A summary of parameter estimates in Table 14 displays that there are four significant factors: one macro-variable (USDX) and three producers: UAE, CANADA, and IRAN. Under the average price of U$100 per barrel this period, the only negative price influencer is USDX, with an effect of 2.29% by one percent change in the index strength, while UAE, CANADA, and IRAN exert, as co-move influencers, the effects of 3.27%, 0.47%, and 0.5%, respectively, by one percent change in their production. This period is characterized by continued price spikes. The co-move influencers may not able to lower the prices by adding supplies, failing to turn the economic theory to work.

Table 14. Panel 5 period (2010–2012): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	−24.2252	19.1291	−1.27	0.218
LN_CANADA	0.4716	0.2284	2.07	0.0504 *
LN_CHINA	0.6489	0.4588	1.41	0.1707
LN_IRAN	0.5004	0.2903	1.72	0.0982 *
LN_IRAQ	−0.1679	0.3016	−0.56	0.5831
LN_KUWAIT	−0.5369	0.7518	−0.71	0.4824
LN_OECDCON	0.4828	0.5913	0.82	0.4226
LN_OPEC	1.3692	0.9356	1.46	0.1569
LN_RUSSIA	−0.6539	1.2249	−0.53	0.5986
LN_SAUDI	−0.7222	0.5973	−1.21	0.2389
LN_UAE	3.2733	0.7638	4.29	0.0003 *
LN_US	−0.1340	0.4333	−0.31	0.7599
LN_USDX	−2.2889	0.6903	−3.32	0.003 *
RSquare	0.96			

Note: * represents statistical significance at a level of 0.1.

4.8. Panel 6: 2013 to 2015

Panel 6 period underwent a price decline mode with an average BRENT price of U$86.67 per barrel, now down about U$13 from the Panel 5 period. This period corresponds to the one when oil supply glut and slow growth in the Chinese economy were observed. BRENT still tops the CV (30.96) but back up from the CV of the previous period (16.49), followed by again IRAQ production (13.92) and U.S. (10.33), CANADA (6.41), and SAUDI (3.49) (Table 15). The U.S. and CANADA continue to be active producers in the global oil market. The U.S. shale oil and Canada oil sands play significant roles. BRENT price range is U$78 per barrel, with a low of U$38.

Table 15. Panel 6 period (2013–2015): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	86.67	102.41	26.83	30.96	38.01	116.05	78.04
CANADA	36	3538	3548	227	6.41	3026	3922	896
CHINA	36	4217	4225	78	1.86	4040	4408	368
IRAN	36	3215	3230	88	2.75	3064	3389	325
IRAQ	36	3488	3325	486	13.92	2825	4416	1591
KUWAIT	36	2692	2650	79	2.93	2550	2880	330
OECDCON	36	45,960	45,933	789	1.72	44,250	47,862	3612
OPEC	36	32,206	32,083	794	2.47	30,980	33,616	2636
RUSSIA	36	10,137	10,110	111	1.10	9955	10,407	452
SAUDI	36	9864	9840	344	3.49	9140	10,490	1350
UAE	36	3032	3026	101	3.33	2836	3190	354
US	36	8551	8750	884	10.33	7025	9650	2625
USDX	36	107	103	7	6.95	99	122	23

A summary of parameter estimates in Table 16 displays that there are two significant factors: one macro-variable (USDX) and the only producer SAUDI. Under the average price of U$87 per barrel this period, the only negative price influencer is USDX, with an effect of 6.03% by one percent change in the index strength, while SAUDI exerts, as a co-move influencer, an effect of 1.83%, by one percent change in their production. This period is characterized by a downward price trend, with the U.S. and Canada increasing the production.

Table 16. Panel 6 period (2013–2015): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	38.1038	29.3481	1.3	0.207
LN_CANADA	−0.1507	0.3298	−0.46	0.652
LN_CHINA	−0.3178	0.8719	−0.36	0.7188
LN_IRAN	1.1216	0.9468	1.18	0.2482
LN_IRAQ	0.4410	0.3328	1.33	0.1981
LN_KUWAIT	−0.5086	1.3276	−0.38	0.7052
LN_OECDCON	0.2343	0.8602	0.27	0.7877
LN_OPEC	−1.5576	1.8365	−0.85	0.4051
LN_RUSSIA	−1.8185	2.5350	−0.72	0.4804
LN_SAUDI	1.8321	0.5320	3.44	0.0022 *
LN_UAE	0.4340	0.8341	0.52	0.6078
LN_US	−0.0180	0.3033	−0.06	0.9532
LN_USDX	−6.0316	0.7167	−8.42	<0.0001 *
RSquare	0.98			

Note: * represents statistical significance at a level of 0.1.

4.9. Panel 7: 2016 to 2018

Panel 7 period continued a downward trend, with an average BRENT price of U$56.29 per barrel, now collapsing about U$30 from the Panel 6 period. This period corresponds to the one when oil supply glut and slow growth in the Chinese economy were seriously observed. The U.S. shale oil growth was remarkable in contributing to the growth of the oil supply. The shale production was close to zero in 2008 but grew to 4.25 million barrels per in 2016, standing with a 48% share of the U.S. oil production and 5% of the global production [10]. BRENT still tops the CV (23.27), followed by U.S. production (10.54) and CANADA (9.24), IRAN (7.11), and IRAQ (3.11) (Table 17). IRAQ showed the highest CV-producer position to the U.S., and the U.S. and CANADA continue to be active producers in the global oil market, with the U.S. shale oil and Canada oil sands.

Table 17. Panel 7 period (2016–2018): summary statistics.

Variable	N	Mean	Median	Std Dev	CV	Min	Max	Range
BRENT	36	56.29	53.95	13.04	23.17	30.70	81.03	50.33
CANADA	36	3985	3993	368	9.24	2811	4520	1709
CHINA	36	3859	3827	119	3.08	3694	4166	472
IRAN	36	4291	4417	305	7.11	3351	4624	1273
IRAQ	36	4503	4475	140	3.11	4217	4815	598
KUWAIT	36	2821	2792	81	2.87	2681	2951	270
OECDCON	36	47,188	47,160	831	1.76	45,356	48,714	3358
OPEC	36	33,998	34,017	391	1.15	33,227	34,976	1749
RUSSIA	36	10,630	10,558	190	1.79	10,254	11,051	797
SAUDI	36	10,339	10,240	251	2.43	9992	11,045	1053
UAE	36	3211	3185	99	3.07	3025	3451	426
US	36	9713	9214	1023	10.54	8519	11,961	3442
USDX	36	122	122	3	2.66	117	129	11

A summary of parameter estimates in Table 18 displays that there are six significant influencing producers/organizations: IRAN, U.S., SAUDI, OPEC, CHINA, and UAE. Under the declining average price of U$56 per barrel this period, there are two negative price influencers and four co-move price influencers. Negative influencers are OPEC and CHINA, with the effects of 3.98% and 1.48%, respectively, by one percent change in their production volume, while the co-move influencers are SAUDI, IRAN, US, and UAE, with the effects of 2.65%, 2.31%, 1.82%, and 1.37%, respectively, by one percent change in their production. This period is characterized by a downward price trend, with a low of U$31 per barrel and BRENT price range of U$50.

Table 18. Panel 7 period (2016–2018): LN_BRENT prediction-parameter estimation.

Variable	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	0.1928	17.4762	0.01	0.9913
LN_CANADA	−0.1381	0.2158	−0.64	0.5283
LN_CHINA	−1.4797	0.8041	−1.84	0.0787 *
LN_IRAN	2.3120	0.3141	7.36	<0.0001 *
LN_IRAQ	−0.2414	0.8582	−0.28	0.781
LN_KUWAIT	−0.3288	0.6797	−0.48	0.6332
LN_OECDCON	−1.4119	0.8919	−1.58	0.1271
LN_OPEC	−3.9778	1.6584	−2.4	0.025 *
LN_RUSSIA	0.6585	1.2600	0.52	0.6062
LN_SAUDI	2.6515	1.0254	2.59	0.0165 *
LN_UAE	1.3743	0.7865	1.75	0.0939 *
LN_US	1.8205	0.2571	7.08	<0.0001 *
LN_USDX	0.1597	0.7861	0.2	0.8408
RSquare	0.96			

Note: * represents statistical significance at a level of 0.1.

4.10. Summary of Results from Seven Panel Periods

In the CV approach to measure a level of fluctuations, the Brent oil price recorded the highest CV of 54.4 over the whole period of 21 years, among all the variables, and maintained a top position during most of the seven-panel periods. Among explanatory variables, Iraq (35) topped in the variability of the production volume, followed by the U.S. (26.5), Canada (25.4), and Russia (16.8), over the whole period and has held the position for all panel periods, except for the Panel 7 period, or 2016–2018, when the U.S. takes the top spot. Only the four countries that recorded a CV of 9.0 or above in each of the periods are Iraq, Iran, the U.S., and Canada, implying their capability to expand the production capacity, for the U.S. and Canada, or unstable production levels, for Iraq and Iran.

The multivariate regression approach was used to estimate a percentage change in the Brent oil price with respect to a percentage change in explanatory variables. Figure 6 displays a behavior over time (BOT) chart of coefficient estimates of each variable for each panel period. The coefficient estimates are present only when a variable is statistically significant at the 10% level; otherwise, the estimates are treated as zero in the chart. The U.S. Dollar Index (USDX) has been shown as the most influencing variable on the Brent oil price, with a coefficient estimate of −3.68, followed by Kuwait (−1.56), China (−1.5), and Iran (−0.62), in its magnitude.

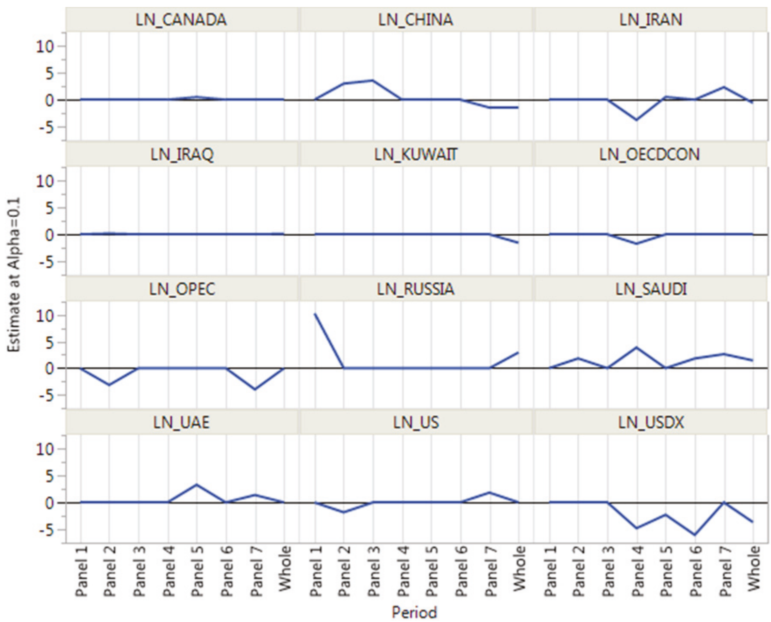

Figure 6. Coefficient estimates of variables by producer and panel at a significance level of 0.1.

In line with the economic theory that a negative relationship exists between production quantity and a market price, Table 19 presents a summary of negative impact ranks based on significant coefficients at the 10% level. From the analysis, OPEC was not the first influencer in all the seven panels but just in two panels, Panel 2 (2001–2003) and Panel 7 (2016–2018).

Table 19. Negative impact rank, based on significant coefficient estimates at the 10% level.

Panel	Period	Rank 1	Rank 2	Rank 3	Rank 4
Panel 1	(1998–2000)	none significant			
Panel 2	(2001–2003)	OPEC (−3.15)	US (−1.84)		
Panel 3	(2004–2006)	none significant			
Panel 4	(2007–2009)	USDX (−4.79)	IRAN (−3.76)	OECDCON (−1.73)	
Panel 5	(2010–2012)	USDX (−2.29)			
Panel 6	(2013–2015)	USDX (−6.03)			
Panel 7	(2016–2018)	OPEC (−3.98)	CHINA (−1.48)		
Whole	(1998–2018)	USDX (−3.68)	KUWAIT (−1.56)	CHINA (−1.5)	IRAN (−0.62)

While there were no significant influencing countries in Panel 1 (1998–2000) and Panel 3 (2004–2006), Panel 2 (2001–2003) has two influencers of OPEC (−3.15) and the U.S. (−1.84). In the other panels, USDX has appeared as the strongest influencer starting in Panel 4 (2007–2009), with −4.79, and then in

Panel 5 (2010–2012), with −2.29, and, in Panel 6 (2013–2015), with −6.03. Panel 7 (2016–2018) records both OPEC and China as two most influencing producers, with −3.98 and −1.48, respectively.

Contrary to the economic theory of production quantity and price, some oil producers' production quantities have shown a co-move relationship with the Brent oil price in some panel periods, indicating their increased production co-moved with higher prices or decreased production with lower prices. These producers include Russia, China, Saudi Arabia, UAE, Iran, and the U.S., with a coefficient estimate of positive 1.0 or greater, as shown in Table 20. China appeared with positive coefficients in Panel 2 (2001–2003) and Panel 3 (2007–2009) when there was a growing demand for energy due to their economic growth, and both Iran and the U.S. joined the co-move impact group in Panel 7 (2016–2018). Table 20 presents the co-move impact rank.

Table 20. Co-move impact rank, based on significant coefficient estimates at the 10% level.

Panel	Period	Rank 1	Rank 2	Rank 3	Rank 4
Panel 1	(1998–2000)	RUSSIA (10.31)			
Panel 2	(2001–2003)	CHINA (2.98)	SAUDI (1.85)	IRAQ (0.16)	
Panel 3	(2004–2006)	CHINA (3.55)			
Panel 4	(2007–2009)	SAUDI (3.89)			
Panel 5	(2010–2012)	UAE (3.247)	IRAN (0.5)	CANADA (0.47)	
Panel 6	(2013–2015)	SAUDI (1.83)			
Panel 7	(2016–2018)	SAUDI (2.65)	IRAN (2.31)	US (1.82)	UAE (1.37)
Whole	(1998–2018)	RUSSIA (2.96)	SAUDI (1.46)	IRAQ (0.12)	

5. Conclusions and Policy Implications

We investigated the relationships between Brent oil price and major producers' volumes to identify influencing weights of major crude oil producers in the world oil market, as well as those of petroleum consumption of OECD countries and the U.S. Dollar Index (USDX), with seven panels of 36 monthly data each across the years of 1998 to 2018. This paper is the first attempt to investigate the relationship between global oil price and major individual producing countries at three-year intervals for analysis over 21 years. The results will help energy policymakers understand the variability of oil market drivers in the specific time horizons and, in particular, the influences of the producing countries on world oil prices in the ever-evolving energy environment.

In the volatility measure of the CV (coefficient of variation), the CV of Brent oil price has been greater than any of the explanatory variables in all of the seven panel periods, while Iraq production, on the production side, has shown the highest CV among all the producers in the past six periods, but the U.S. later took the top position in Panel 7 (2016–2018). Iraq, the U.S., Iran, and Canada, with high CVs of 9.0 or greater, may have potentials to continue exerting significant influences on the global oil price. Surprisingly, the OPEC production volume was not as volatile as in the individual producers in the 21-year seven-panel history.

Parameter estimates from multivariate regression models for the seven panels showed that there had been various influencing producers in each of the seven panels, at the statistical significance level of 10%, that have depressed the global oil price. OPEC appeared only twice in Panels 2 (2001–2003) and 7 (2016–2018), while the U.S., Iran, and China did once each. On the petroleum consumption side, OECD consumption also appeared once as a negative influencer in Panel 4 (2007–2009) when the crude oil price spiked to a $140/bbl level in 2008. Notably, the U.S. Dollar Index (USDX), a macroeconomic variable, was the most prevalent influencer—three times in Panels 4, 5, and 6, or for 2007–2015. This result may be due to the fact that global oil is quoted and traded in U.S. dollars. Recent influencers in Panel 7 (2016–2018) were OPEC, the biggest producer in aggregate, and China.

We admit that there is a room for further researches to understand the dynamics of the global oil market. This paper focused on a panel of 36 months each, based on the assumption that a period of three years may be sufficient to bring a change to improve supply and demand situations in the oil markets, but with the advancement of technology, the panel period could be set shorter or longer for analysis, depending on the purpose of further research. Besides, as the OECD consumption in this paper is at the aggregate level of its member nations, further research may use individual nation's consumption data to investigate the influences of major/emerging economies in Europe, North America, and Asia.

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The Oil Market Reactions to OPEC's Announcements

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Abstract: Because of the crucial implications of the market power of OPEC, the aim of this paper was to investigate the oil asymmetric market reactions, such as the price and risk reactions, to OPEC's announcements. Specifically, this paper first explored the oil price reactions to OPEC's announcements and their heterogeneity to depict the directional role of OPEC based on event study methodology. Furthermore, this paper analyzed the oil risk reactions in the framework of a linear model. Our findings reveal several key results. The oil price reactions to OPEC production decisions behave quite heterogeneously in three kinds of decisions. Specifically, the reaction to announcements of a production increase shows an invert "U" shape, whereas there is a linear effect of cut announcements. Otherwise, when a maintain decision is announced, the oil prices have no obvious change over the sample period. Additionally, the oil risk reactions to OPEC's announcements are heavily related to the interaction item between OPEC decisions and its production over full sample periods. Furthermore, OPEC's role in promoting stability in crude oil markets by changing its production shows a heterogeneous condition after global financial crisis.

Keywords: market reactions; OPEC; oil price reactions; oil risk reactions; production decision

1. Introduction

The geopolitical instability of the world supply sheds light on the dominant role of the Organization of the Petroleum Exporting Countries (OPEC) in the crude oil market [1,2]. On the one hand, the oil price reactions could be regarded as direct market reactions. Indeed, OPEC, as a cartel, influences the oil price through coordinating its members' production quotas. However, this impact is a conflicting issue among different stakeholders [3]. For one thing, the correlation between OPEC and oil price varies over a time horizon, because of the changing market share of non-OPEC oil production [4]. For another, the role of OPEC changes over time due to the market fundamentals. On the other hand, the risk reactions indirectly depict market responses to OPEC's announcements. As stated by Balcilar and Ozdemir [5], the higher oil price volatility is, the greater uncertainty and risk are for market participants. Moreover, the primary aim of OPEC is to assure the balance between producers and investors, in turn promoting market stability. In this vein, this paper explored the question of how oil price and risk react to OPEC's announcements. The logical relations among these three sides are shown in Figure 1.

Figure 1. The logical relations among oil price reactions and oil risk reactions to OPEC's announcement.

The oil price reactions could depict the market power of OPEC. As we all know, future oil production for OPEC members is announced by OPEC conferences, based on the outlook of the balance between oil supply and demand. Obviously, OPEC's exercise of market power restrains its production level to maintain higher oil prices and decrease its markets share of oil production related to competitors [1]. Because of the benchmark role on pricing oil and other related oil derivatives, Figure 2 presents the Brent spot price reactions to OPEC conferences from 2002 to 2018. Among them, OPEC announcements, especially those agreeing to cutting or increasing production, have diverse impacts on oil prices. Moreover, OPEC is better off making a maintain decision, for the most part, when taking the change in oil demand into account. This is due to the fact that OPEC exercises its market power to control the oil price [6]. In this sense, instead of precisely estimating OPEC's behavior, this paper investigated the oil price reactions to OPEC's announcements.

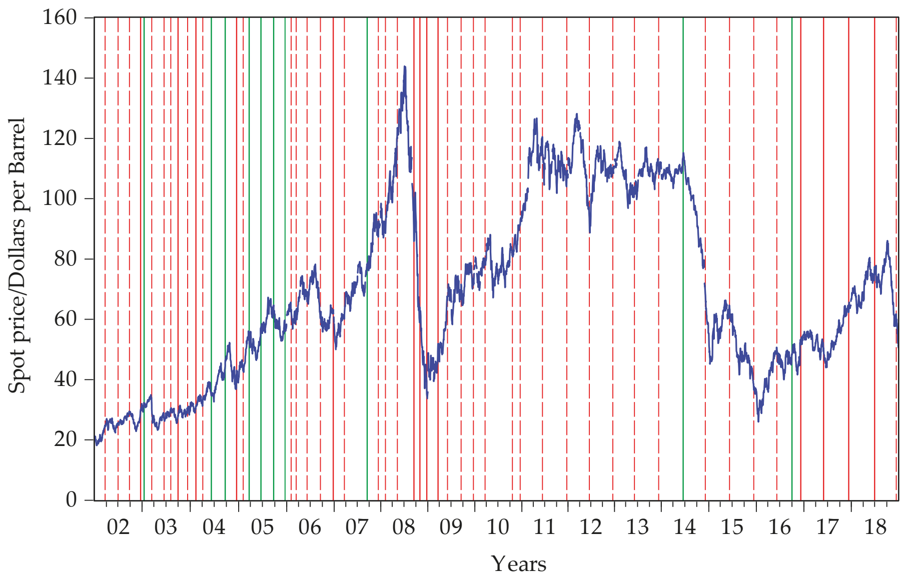

Figure 2. Brent spot prices and OPEC's announcements. The solid, red line represents the "cut decision", the green line shows the "increase decision", and the dotted, red line depicts the "maintain decision".

Since the seminal work by Draper [7], abundant papers have explored how announcements or major events are impounded into financial asset prices [8–12]. However, little literature deals with the price reactions to the different types of OPEC's announcements based on the event study methodology. Indeed, Draper [7] first attempted to explore the oil future price reactions between fall 1978 and 1980 and found that OPEC's announcements were impacted by investors' expectations. Recently, Ji and Guo [13] investigated that there are inconsistent reactions to OPEC's announcements. Loutia et al. [3] analyzed the crude oil prices as well as two benchmark indices over two sub-periods, distinguishing that oil price uniformly increased and were turbulent. They found that the oil price reactions to OPEC's announcements evolve over time and among decisions, and these reactions are more significant for production cut and maintaining. In addition, OPEC's announcements are also sensitive to the benchmark index. However, studies that model oil price reaction to OPEC's announcements during pre- and post-crisis periods are scarce.

Additionally, high return risks create increased uncertainty in crude oil markets. Indeed, the oil return risks could inhibit current investment for crude oil [5]. Changes in market stability have considerable impacts on economy [14–18]. First, changes in crude oil return risks essentially impact decisions made by market participants, such as oil producers, consumers, and policy makers. Otherwise, changes in oil return risks also determine investors' decisions for pursuing maximum profits. In this sense, this paper further explored the oil risk reactions to OPEC's announcements. Theoretically, there are asymmetric risk reactions to OPEC's announcements over time horizons. The announcement of OPEC's decision generally exerts a simultaneous impact on oil return risks, that could be regarded as a source of participants' attention [19]. Because of the nature of OPEC's announcements, its role is perceived differently by the global crude oil market fundamentals.

Not surprisingly, an increasing number of studies have been exploring the consequences of OPEC's power to promote market stability. For example, models are often constructed to conduct theoretical and empirical analyses on OPEC announcements' role on oil prices, using production quotas, market competition, and spare capacity [20–24]. Besides, a common belief is that the market role of OPEC changes between an oil producer and a cartel, which in turn makes oil markets deviate largely from competition [25]. Another view is related to economic, market, and geopolitical conditions, indicating that OPEC's behavior is time-varying and this effect cannot be described by a single model [21]. Moreover, the linkage between oil price volatility and OPEC's announcements has been analyzed in the literature. For instance, Schmidbauer and Rösch [26] provided evidence that there is a strong effect on oil volatility as there is an asymmetric post-announcements effect on volatility. Mensi et al. [27] argued that the "cut" or "maintain" decisions play a dominant role on the oil price volatility. Furthermore, the potential ability in OPEC members to stabilize the oil price could be related to the spare capacity [28]. However, sparse attention has been paid to the analysis of oil risks.

The main contributions, which were the primary objectives of this paper, were to explore the oil asymmetric market reactions to OPEC's announcements. First, based on an event study methodology, this paper contributes to research on the oil price reactions to OPEC's announcements during distinct periods (pre- and post-financial crisis). More precisely, this objective aims to depict the direct market reactions to OPEC's announcements as mentioned above. Our second contribution is to explore the indirect market reactions to OPEC production decision, as well as investigating the heterogeneity during two distinct periods. To achieve this goal, we investigated the asymmetric risk reactions to OPEC's announcements in a framework of a linear model. Unlike existing studies focused on the influence of OPEC announcements to oil price volatility, we explored the asymmetric impacts on oil return risks. Additionally, Lin and Tamvakis [29] did not find a significant difference between oil qualities. Thus, the potential reactions to OPEC's announcements as the regressors are explicitly specified in a linear regression framework. Moreover, we divided the sample periods into two sub-periods because of the potential shock of global financial crisis in crude oil markets [30]. Importantly, this allows us to assess the heterogeneous role of OPEC in oil markets after global financial crisis.

The remainder of this paper is organized as follows. Section 2 briefly introduces the research hypothesis supported in this paper. Section 3 presents and discusses the oil price reactions to OPEC's announcements. In Section 4, we proceed to model the oil risk reactions to OPEC's announcements. Finally, the conclusions and policy implications are described in Section 5.

2. Research Hypothesis

The oil price reactions to OPEC's announcements are heterogeneous, during both pre- and post-crisis periods. It is well known that the oil price reactions can be foreseen by market participants. In other words, the oil price reactions to these decisions are asymmetric. Specifically, an increase decision in oil supply can drive price up. In terms of oil producers, the optimistic attitude held by OPEC members for an increase in production plays a dominant role in crude oil markets. For other investors, they cannot change the investment decision to an increase production because of their expectations. In this sense, the expectations of market participants promote them to pursue higher profits, which in turn lead to the oil price increase. Additionally, the oil price reaction to increase announcements is heterogeneous during pre- and post-crisis periods. This is not surprising due to the market fundamentals. For one thing, OPEC can be regarded as a marginal producer in order to partially control the imbalance between global oil demand and oil supply for non-OPEC producers through its members' quota. For another, non-OPEC oil producers can be regarded as price takers, meaning that there are few price reactions during pre-crisis periods. Thus, the oil price reactions to increase announcements vary during the post-crisis periods. Taking all these considerations together, it is obvious that the reactions of oil price to an increase announcement could be interpreted by market participants.

The picture changes a little for quota reduction. Following a cut decision, oil prices should go up. Indeed, oil prices heavily depend on the expectations of market participants. When a cut production decision is announced, it means that the production quota incudes the crude oil market's anticipation and the information on evolution of oil price. At this time, the imbalance between oil supply and demand could be expanded by quota reduction, thus driving oil price up. However, a different story may emerge. Despite the quota reduction, the oil prices could continue to decrease. This picture is more pronounced during post-crisis periods. The possible explanation for decreasing price is that the cuts in oil production perceived in the market are not far-reaching enough, or they suggest that OPEC's exercise of market power is not enough to enforce the quota reduction on its members. This apparently counterintuitive story could also indicate expectations about oil supply and demand and market participants' concern of the market power of OPEC as a cartel, as well as the actual oil production. Moreover, the upward pressure on oil prices could be impacted by world economic growth and spare capacity in oil producers.

In the case of maintain decision, the double reactions of oil price to OPEC announcements are related to market fundamentals. On the one hand, in crude oil markets, a maintain decision could be regarded as "firm indecisiveness". In this sense, it is easier to consider that members' expectation to market fundamentals should be a negative, but different interests of OPEC members could make it difficult to change the status of oil production, which in turn flow the oil supply and drive oil price further down. On the other hand, OPEC also focuses on other economic parameters. Specifically, market fundamentals, expectations of economic growth, or geopolitics could change the OPEC production quota. In other words, that the market interprets an unchanged decision in oil production means there is a sufficient level of supply. Thus, oil prices could continue to increase. Taking all these effects together, it is obvious that the oil price reaction is moderate. However, there are heterogeneous reactions of oil price during pre- and post-crisis periods. These results could be interpreted by depicting non-conventional resources, such as shale formations and natural gas production, and the increasing role of non-OPEC oil production in crude oil markets.

Accordingly, this paper proposes the following hypothesis:

Hypothesis 1. *The oil price reactions to OPEC's announcements vary across production decisions during pre- and post-crisis periods. Specifically, the oil price reaction to the increase or cut in production is dramatic, whereas it is moderate when the production remains unchanged.*

There are asymmetric reactions of oil risk to OPEC's announcements and these reactions heavily relate to production decision and quota level. The key reason for oil risk reactions is the uncertainty of oil supply or demand. Obviously, financial risk captures the loss but not profit in crude oil markets [31]. Indeed, oil risks could be defined as the excessive return on oil prices during distinct periods, which is a desirable characteristic in crude oil market applications to capture the market stability [32]. The different OPEC announcements could result in conflicting expectations in the oil markets and promote different investment decisions for speculation or hedging, thereby resulting in the asymmetric reactions of the oil risks [33]. From the perspective of an unchanged decision in oil production, it means that the quota level is tolerable in the oil markets. Meanwhile, the upward pressure in the oil markets caused by economic factors and uncertainty over supply and demand could be regarded as an unstable resource of oil risks. Thus, the oil risk reactions to the maintain decisions are the largest over these decisions. Additionally, the reactions of oil risks to the production increase decisions are larger than those to the cut decisions. This asymmetric picture could be related to the expectation of market participants. Indeed, the production hike decisions could be regarded as "good news" for market investors. Speculation is blamed. It is well known that speculative flows accentuate the oil risks. On the contrary, the production cut decisions will lead to the oil price increase and further ensure the interest of different stakeholders. However, changes in oil production could also lead to the uncertainty of oil supply or demand, which results in the uncertainty of market stability. Therefore, it can be noticed that OPEC's announcements could promote the oil risks instead of being a stabilizing force. As mentioned above, it can be noted that:

Hypothesis 2. *The oil risks reactions depend on the interaction between OPEC's announcements and OPEC oil production.*

Moreover, there are heterogeneous reactions of oil risks to OPEC's announcements during pre- or post-crisis periods. Obviously, the recent global financial crisis could lead to some new changes in oil markets, such as the oil pricing mechanism, oil supply and demand for several countries, and the dependence between oil markets and other financial markets [34]. Therefore, this heterogeneous story may be caused by these differences. At a more specific level, during the pre-crisis periods, the production increase decisions significantly promote the market stability, whereas the oil risk reactions to another production decision are unapparent. As shown in Figure 2, the oil price increases significantly in pre-crisis periods, and its volatility is moderate. It is also interesting to note that the oil price experienced a sharper change for production hike decisions than others. This is not a surprise but due to the determinant role of oil supply factors during pre-crisis periods [35]. Theoretically, in a relatively weak market, the production hike decisions could mean an optimistic attitude for decision makers, which will lead to reasonable expectations of market participants and promote the demand in oil markets. Furthermore, these characters are expected to decrease the oil price volatility and stabilize the crude oil markets.

As the sample moves out to post-crisis periods, the oil risk reactions to different OPEC announcements depict a different picture. Inconsistent with pre-crisis periods, there are obvious reactions of oil risks to the cut decisions, and the oil risk reactions to the production maintain decisions are heavily related to the interaction item between decision and OPEC oil supply. As we all know, the key reason for these results is the uncertainty of oil supply or demand. Additionally, another reasons of oil markets' stability are the attitudes for production change in OPEC announcements. Indeed, these different pictures during post-crisis periods are determined by the sharp increase in oil demand and the change in market share for non-OPEC countries. For another, the maintain decision is often perceived as non-decisions. In this vein, the oil price would tumble further down, leading to different expectations of market participants and promoting different capital flows in the crude oil markets [36]. Additionally, economic parameters or geopolitical events could also lead to the reactions of oil risks to OPEC's production decisions. Furthermore, the diverse interests of OPEC's members make it difficult to reach production decisions and further promote the oil risks. Therefore, this paper concludes with the following hypothesis:

Hypothesis 3. *The oil risk reactions to OPEC's announcements in a sense are heterogeneous during pre- and post-crisis periods.*

3. The Oil Price Reactions to OPEC's Announcements

3.1. Event Study Methodology

To exam the asymmetric price reactions to different OPEC announcements in crude oil markets, we used an event study methodology. It is easier for the event study methodology to assess the significance of global crude oil price reactions to OPEC announcements [37]. Furthermore, the expected return of oil price could be good for capturing the seasonality and rationality features [29]. In addition, because of the change in Brent crude oil demand of emerging countries and the controlling crude oil export of the US government in recent years, Brent has become the international oil benchmark. Although Brent has been activated in Europe, it can also be used to assess the basic price for other grades. In this way, we examined the effects of OPEC announcements on the Brent oil spot price. In this section, we used the daily price covering the period from 1 January 2002 to 31 December 2018. Data was collected from the US Energy Information Administration.

The point of using event study was to forecast the abnormal returns of oil prices during the event window of OPEC announcements. This was measured in Formula (1).

$$AR_t = R_t - \mathrm{E}(R_t) \tag{1}$$

where AR_t is the abnormal return of the oil price at t; R_t is the log-return on crude oil price, and $\mathrm{E}(R_t)$ stands for the expect return, which assumes that the OPEC announcement is not taking place (following Ji and Guo [13] and Lin and Tamvakis [29], $\mathrm{E}(R_t)$ was equal to 0 in this paper, which indicates that there will be no change in the price over the short term without exogenous shocks).

The cumulative abnormal returns (CARs) can be regarded as the sum of the daily abnormal returns over the event window. In this paper, an event window of 11 days (five days before and five days after the event date) was set (see also Loutia et al. [3] and Ji and Guo [13]). The reasons we used this choice are as follows. Firstly, the five days before the event date could better depict the picture before the OPEC announcements. Additionally, the five days after the event date capture the information after the decisions. Furthermore, this choice can also better avoid the interactional effects from other events. Thus, the CARs can be defined as in Formula (2).

$$CARs_i = \sum_{t=-5}^{5} AR_t, \quad i = 1, 2, 3. \tag{2}$$

where i refers to the type of OPEC announcements.

Then, this paper calculated the average $CARs$ for different types of OPEC announcements with Formula (3).

$$\overline{CAR}_t = \frac{1}{N}\sum_{e=1}^{N} CARs_{i_e,t}. \tag{3}$$

where N is the number of different types of OPEC announcements over the sample period, and t is the date of event windows, which equals from −5 to 5. In this vein, we obtained the average CARs of different types of OPEC announcements during the event windows.

3.2. The Reaction of Oil Price to Announcements

In this subsection, we present the average cumulative abnormal returns for different categories. Table 1 represents the OPEC's announcements from 1 January 2002 to 31 December 2018. There were 57 OPEC regular and extraordinary conferences which can be divided into three categories according to different decisions. Of those decisions, 13 announced production cuts, 10 announced production increases, and 34 announced production maintenance. The details in Table 1, such as the dates, the production decisions, and the price series of Brent spot prices (in USD/barrel) are available upon request. We set the OPEC announcement day as $t = 0$ in Formula (2) when the actual announcement was released.

Figure 3 plots the trend in the average CARs for three types of OPEC announcements. According to existing literature, the result that the price reactions to announcements are generally not significant could not be related to the choice of commodity index [38–44]. This phenomenon could be correlated with OPEC's market power. For example, Lin and Tamvakis [29] explored the oil price reactions to OPEC's announcements from 1982 to 2008 and found diverse market reactions to OPEC's announcements under different price bands. Most generally, the oil price reactions to OPEC's announcements may be heterogeneous during distinct periods. Another argument is put forward by Loutia et al. [3].

He explained these heterogeneous results by an explanation that it is easier for market participants to agree to an increase decision, whereas the reactions of oil price to the production cut decision reflects the expectation of market participants. However, economic parameters, such as economic growth, geopolitical events, and spare capacity, can also be regarded as causes of oil price change.

Table 1. OPEC's announcements.

OPEC Meeting	Number of Announcements
OPEC production cut	13
OPEC production increase	10
OPEC production maintain	34
Total OPEC meeting	57

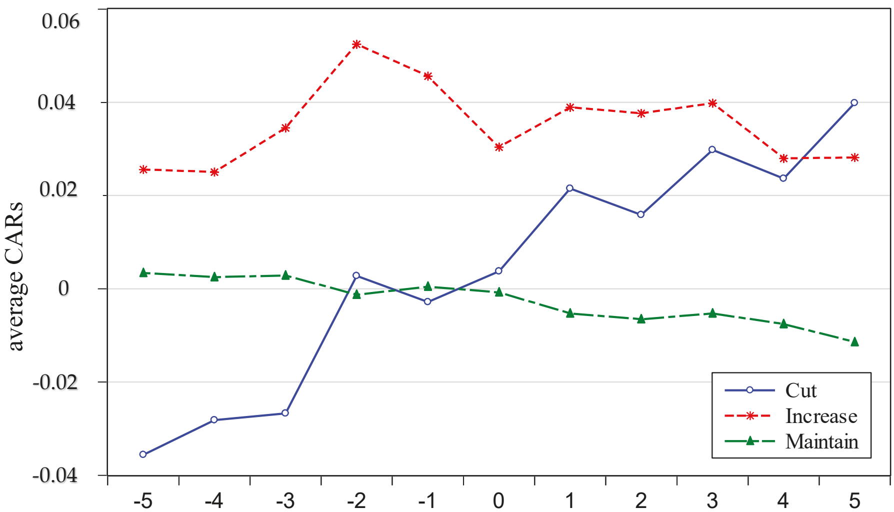

Figure 3. Average CARs of the Brent spot prices for OPEC's announcements from five days before the event to five days after the event.

As expected, the oil price reactions to OPEC announcements display obvious asymmetry. These results follow the expectation that an increase production announcement shows an invert "U" effect, whereas there is a linear reaction to cut decision. In addition, it seems that if the OPEC maintains its production, there is no significant reactions of crude oil prices. This indicates the role of market fundamentals on crude oil markets. On the one hand, market participants focus on digesting the newly released announcements, and the influence of the cut announcement has a strong persistence over a short period of time. On the other hand, the maintain decision often means stability of the market, thus the market responds moderately to it. Furthermore, this paper examed the heterogeneous reaction of oil price to OPEC's announcements during pre- and post-crisis periods. Figure 4 presents the average CARs for the three types of OPEC decisions.

The picture changes a little during different sample periods. As shown in Figure 4, it is clear to note that the oil price reactions to OPEC's announcements were heterogeneous during distinct periods. In particular, an increase decision will drive prices up during pre-crisis periods. However, the increase announcement could drive oil prices to drop first, and then oil prices will go up during post-crisis periods. This is not a surprise due to the fact that OPEC often acts as a marginal producer in order to offset, whereas non-OPEC is generally considered as a price taker during pre-crisis periods [37,38].

Thus, the greater the OPEC supervision is, the greater reaction oil prices have. However, the market power of OPEC could be limited by its market share.

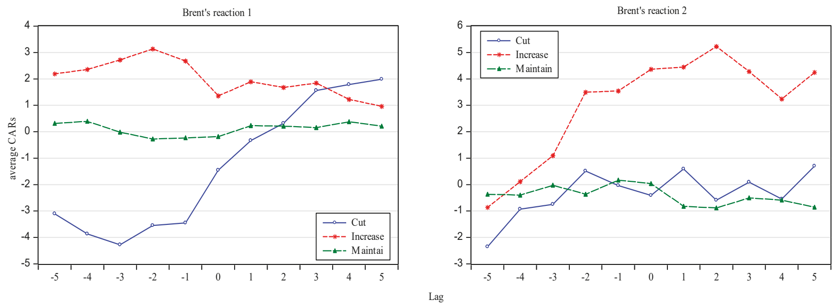

Figure 4. Average CARs of Brent spot price for OPEC's announcements during two periods. Brent's reaction 1 refers to the oil price reaction during pre-crisis periods, whereas Brent's reaction 2 represents the price reaction during post-crisis periods.

When a cut decision is announced, the reaction seems more sensitive to oil price during pre-crisis periods than in the post-crisis periods. Following a cut decision, oil prices should go up, thus the average CARs should be positive. This is indeed the case for the pre-crisis periods for Brent spot price. It is particularly interesting to note that the average CAR is always negative in pre-announcement period ($t = -5, -4, \ldots, -1$) during pre-crisis periods. This interesting information could be depicted by putting the excess return and market power of OPEC into the reasoning. In fact, OPEC's members exercise their market power to manipulate the oil prices down through disseminating the information about production decision for extreme profits. However, during the post-crisis periods, the average CAR is negative. This obviously unreasonable result may indicate considerations about the balance between oil supply and demand and market participants' attention to the power of OPEC as a cartel, as well as the change in production [39]. Additionally, as shown in Figure 2, OPEC's cut decisions announced in 2008 sent oil prices significantly down, and before a sharpened increase in 2009 during post-crisis periods. In fact, from 2009 to 2011, economic parameters such as economic growth and oil demand were active, whereas the lower oil production and spare capacity held by oil producers put upward pressure on oil prices. Finally, it is particularly interesting to note that the oil price reaction is moderate when the production quotas remain unchanged. As mentioned above, we can confirm that Hypothesis 1 is valid.

4. The Oil Risk Reactions to OPEC's Announcements

4.1. Linear Model Specification

Having found an asymmetric reaction to OPEC's announcements of oil price during distinct periods, we further empirically identified the oil risk reactions to OPEC's announcements. Our dataset covered the period from January 2002 to December 2018. Considering the data availability for the control variable, we used monthly data to explore the oil risk reactions to OPEC announcements, retrieved from OPEC. For this purpose, the empirical model to be estimated in this paper is shown in Formula (4). Additionally, we also provide a brief description of all variables in Table 2.

$$\text{Risk} = \text{c} + \alpha\mathbf{D} + \beta\mathbf{X}_{\mathbf{i}}^{'} + \varepsilon \quad (4)$$

where Risk refers to the oil return risks; **D** is a vector of dummy variables to measure the periods of OPEC's announcements; **X** stands for control variables, and ε is the error term.

Table 2. Description of variables.

	Variables	Abbreviation	Description
Dependent variables	Oil risks	Risk	The oil return risks which are measured by the asymmetric slope model.
Explanatory variables	OPEC increase	inc	Dummy variable equal to one if the periods belong to the "increase sample" and zero otherwise.
	OPEC cut	cut	Dummy variable equal to one if the periods belong to the "cut sample" and zero otherwise.
	OPEC maintain	mai	Dummy variable equal to one if the periods belong to "maintain sample" and zero otherwise.
Control variables	Oil supply	OP	OPEC oil production.
	Oil demand	STO	OECD total commercial oil stocks.
	World economy	WGDP	The growth rate of global economy.
	Future returns	FR	The monthly log-returns in the NYMEX WTI
	Product price	PRO	The gasoline price.

The dependent variable Risk is oil return risks. As we all know, value-at-risk (VaR) is defined as the maximum loss in oil markets. A large body of studies pays attention to some alternative methods to forecast the risks [45–49]. Commonly, these methods often assume that the oil return is invariable. In general, the speculative and intra-cluster make oil return risks more dynamic [50,51]. Therefore, we use the CAViaR, proposed by Engle and Manganelli [52], to calculate the oil return risks in this paper. Specifically, compared with other specifications, we forecast the oil return risks based on the asymmetric slope from the results of a dynamic quantile (DQ)test at the 5% level (these results are available upon request).

The main explanatory variables are OPEC's announcements. The OPEC's announcements are coded based on the OPEC decisions on oil production. To solve this problem, we defined three dummy variables. Take increase (inc) as an example: the measurement of inc is shown as Figure 5 (other dummy variables are the same as inc). If an increase production decision is announced at time b, we could regard the period from a to b as an increase sample.

Figure 5. Example for inc: a and b represent the date of the OPEC announcement.

The control variables included commonly used background variables. Referring to the OPEC monthly oil market reports (MOMRs), we considered several main strands of potential factors, including oil supply and demand, world economy, and spillover from other markets. For the perspective of oil supply and demand, we selected OPEC oil production and OECD commercial oil stocks, respectively, because of their market power. Additionally, the growth rate of the global economy could better depict the world economy. In terms of spillover from other markets, it is well known that oil futures or product markets play a dominant role on oil spot price. Thus, we selected the log-return of NYMEX WTI and the gasoline price. All data were monthly observations and collected from OPEC.

Above all, we estimated the following empirical specifications in different periods. Since in Section 3 we found that oil price volatility was low when the production remained unchanged, this paper regarded inc and cut as the regressors. This can be seen in Formulas (5) and (6).

$$\text{Risk} = \text{c} + \alpha_1 \text{inc} + \alpha_2 \text{cut} + \beta_1 \text{OP} + \beta_2 \text{STO} + \beta_3 \text{WGDP} + \beta_4 \text{FR} + \beta_5 \text{PRO} + \varepsilon. \tag{5}$$

$$\begin{aligned} \text{Risk} = \; & \text{c} + \alpha_1 \text{inc} + \alpha_2 \text{cut} + \beta_{11} \text{OP} \times \text{cut} + \beta_{12} \text{OP} \times \text{mai} + \beta_{13} \text{OP} \times \text{inc} \\ & + \beta_2 \text{STO} + \beta_3 \text{WGDP} + \beta_4 \text{FR} + \beta_5 \text{PRO} + \varepsilon. \end{aligned} \tag{6}$$

Our interest mainly lies in the α_1, α_2, β_{11}, β_{12} and β_{13} coefficients which provide information on the asymmetric effect between OPEC's announcements and oil return risks.

4.2. The Reactions of Oil Risks to Announcements

Table 3 shows the estimated results for the full sample. In the first column, the results without the interaction item between OPEC production and announcements are given. In columns 2–5, we augmented the interaction item between OPEC production and its announcements.

Table 3. Estimation results.

Model	(1)	(2)	(3)	(4)	(5)
Variables					
c	2.099 *** (0.593)	0.396 (0.583)	0.614 (0.496)	0.642 (0.534)	1.711 ** (0.648)
inc	−0.014 * (0.008)	−0.007 (0.009)	1.059 *** (0.269)	−0.187 (0.008)	0.197 (0.605)
cut	−0.005 (0.008)	0.281 (0.377)	1.072 *** (0.269)	0.004 (0.175)	0.605 (0.372)
OP × cut		−0.077 (0.106)			0.286 * (0.128)
OP × mai			0.302 *** (0.076)		0.457 *** (0.096)
OP × inc				0.051 (0.175)	0.398 * (0.187)
OP	0.426 *** (0.094)				
STO	−0.378 *** (0.098)	−0.008 (0.073)	−0.151 * (0.069)	−0.038 (0.067)	−0.344 *** (0.101)
WGDP	−0.024 *** (0.006)	−0.018 ** (0.006)	−0.021 *** (0.006)	−0.018 ** (0.006)	−0.023 *** (0.006)
FR	−0.130 *** (0.035)	−0.159 *** (0.036)	−0.138 *** (0.035)	−0.159 *** (0.036)	−0.126 *** (0.035)
PRO	−0.074 *** (0.014)	−0.019 (0.009)	−0.049 *** (0.010)	−0.022 * (0.008)	−0.073 *** (0.014)
Observations	204	204	204	204	204
adjusted-R^2	0.236	0.159	0.219	0.157	0.238
F	9.969 ***	6.506 ***	9.177 ***	6.426 ***	8.079 ***
ARCH	1.152	2.148 *	1.661 *	2.088 *	1.231

Note: standard errors are shown in parentheses. *, ** and, *** indicate significance at 0.10, 0.01, and 0.001, respectively.

Some interesting results, correlated with the OPEC announcement variables, are shown in Table 3. We noted that there were asymmetric risk reactions to different types of OPEC announcements. Actually, the individual OPEC production announcements had an effect, which heavily correlated with the OPEC oil supply. It is worth noting, refer to column 5 in Table 3, that the interaction item between OPEC maintain decisions and its production had the highest positive influence on oil return risks, while it, with cut decision, was the smallest. This is due to the fact that the market participants' attention to different types of production decisions was asymmetric. When a maintain oil production is announced, the OPEC oil production can promote the instability of the oil markets because of the participants' expectations [53–56]. Therefore, oil return risks will increase by impacting the market participants' expectations when the oil supply is opposite to the OPEC announcements. Additionally, oil return risks could be related to forecasting future supply, which is associated to the market conditions [57]. Taking all these considerations together, OPEC's announcements could be regarded as a sign in the oil market, signaling a greater market power of OPEC and, thus, resulting in uncertainty in the oil market.

Considering the increasing market share of non-OPEC producers and the global effect of the financial crisis in 2008, this paper further explored the heterogeneous effects of OPEC's announcements on oil return risks during distinct periods. The estimation of Formulas (5) and (6) are reported in Table 4.

A comparison of Table 4 reveals there are twofold heterogeneous risk reactions to OPEC's announcements during pre- and post-crisis periods: the single and interaction items. From the perspective of the single effect of OPEC's announcements, it is interesting to note that there are significant risk reactions to OPEC increase decisions during pre-crisis periods (this result refers to column 1 during the period 2002M01–2008M08), while the "cut decision" plays a positive role on oil risks (this result refers to the column 5 during the period 2008M09–2018M12). This is not a surprise but is due to the heterogeneous market conditions during pre- and post-crisis periods [58]. Indeed, the change in oil production enhances the demand in the crude oil markets and the participants' expectations, thereby promoting the stability of oil markets during pre-crisis periods. Contrary to this mechanism, the cut decisions in production are more sensitive during post-crisis periods than they are in first sub-periods. Obviously, the cut decision could change the fundamental balance between oil supply and demand in crude oil markets, which can influence the oil return risks level.

Table 4. Estimation results during pre- and post-crisis periods.

Period	2002M01–2008M08 (1)	(2)	2008M09–2018M12 (1)	(2)	(3)	(4)	(5)
Variables							
c	−1.742 (1.158)	−1.788 (1.335)	7.190 *** (1.056)	4.815 *** (1.142)	5.633 *** (0.979)	6.471 *** (1.084)	5.059 *** (1.180)
inc	−0.016 * (0.009)	−0.053 (0.666)	−0.003 (0.014)	−0.004 (0.014)	2.547 *** (0.614)	−0.172 (1.569)	1.028 (1.482)
cut	0.003 (0.010)	0.161 (0.459)	-4.08×10^{-5} (0.010)	2.894 ** (1.001)	2.564 ** (0.616)	0.006 (0.010)	4.077 *** (1.023)
OP × cut		0.199 (0.173)		−0.801 ** (0.277)			−0.451 (0.291)
OP × mai		0.244 (0.157)			0.714 *** (0.172)		0.682 *** (0.191)
OP × inc		0.255 (0.174)				0.047 (0.439)	0.393 (0.447)
OP	0.239 * (0.131)		0.453 * (0.193)				
STO	0.179 (0.145)	0.183 (0.155)	−0.958 *** (0.167)	−0.489 *** (0.130)	−0.886 *** (0.121)	−0.679 *** (0.125)	−0.811 *** (0.166)
WGDP	0.006 (0.015)	0.005 (0.016)	0.004 (0.009)	0.016 (0.009)	0.009 (0.008)	0.008 (0.009)	0.013 (0.009)
FR	0.069 (0.054)	0.068 (0.055)	−0.110 * (0.043)	−0.129 ** (0.041)	−0.095 * (0.041)	−0.136 ** (0.043)	−0.088 * (0.041)
PRO	−0.064 ** (0.020)	−0.063 ** (0.021)	−0.189 *** (0.026)	−0.138 *** (0.025)	−0.178 *** (0.023)	−0.165 *** (0.024)	−0.16 *** (0.025)
Observations	80	80	124	124	124	124	124
adjusted-R^2	0.110	0.086	0.434	0.447	0.484	0.407	0.495
F	2.396 *	1.832 *	14.499 ***	15.215 ***	17.501 ***	13.093 ***	14.395 ***
ARCH	0.588	0.521	0.739	0.729	0.450	0.746	0.569

Note: standard errors are shown in parentheses. *, ** and, *** indicate significance at 0.10, 0.01, and 0.001, respectively.

In terms of the interaction item, OPEC's announcements impose their significant influence on oil return risks only when the production remains unchanged during post-crisis periods (this result refers to column 5 in Table 4). However, other periods were not significantly dependent on the OPEC oil supply. These results indicate that the unchanged decisions were often regarded as non-decisions for different reasons. Economic parameters, such as market fundamentals, economic conditions or geopolitical events could result in OPEC changing its quota. Additionally, it is generally difficult for OPEC members to reach an announcement, and market investors heavily relate to OPEC members' degree of execution [59]. Thus, it could not be concluded that the market power of OPEC to promote the market stability by changing its production level has diminished. On the contrary, its role shows a heterogeneous conditions after global financial crisis [60]. As mentioned above, we can confirm that Hypotheses 2 and 3 are valid.

5. Conclusions and Policy Implications

The market reactions to OPEC's announcements can reflect the market power of OPEC and the expectations of market participants in the global crude oil market. Specifically, the empirical results with the event study methodology and with a framework of a linear model all point to the asymmetric market reactions to different OPEC announcements, as well as heterogeneous reaction during pre- and post-crisis periods. In this paper, we first explored the oil price reactions to OPEC's announcements and the heterogeneity to depict the directional role of OPEC based on the event study methodology. Furthermore, this paper analyzed the oil risk reactions in a framework of a linear model. Specific conclusions are as follows.

The oil price reactions to different OPEC announcements had stronger differences in crude oil markets, as well as during distinct periods. In general, the reactions to the announcements of a production increase showed an invert "U" shape, whereas there was a linear reaction to cut decisions. In addition, when an unchanged decision was formulated, the oil prices had no obvious change over the sample period. According to the diverse mechanisms during pre- and post-crisis periods, this paper found an increase in oil production will drive prices up during pre-crisis periods, whereas it will drive oil prices to drop and then rise again dramatically during post-crisis periods. When a cut decision was announced, the reaction seemed to be more sensitive to oil price during pre-crisis periods than it was in the post-crisis periods. Additionally, the oil price reactions were moderate when the production quotas remain unchanged.

The oil risk reactions to OPEC production decisions behaved quite heterogeneously in the three kinds of decisions. Actually, it is interesting to conclude that the oil risk reactions to OPEC's announcements were heavily related to the interaction item between OPEC decisions and its production over the full sample periods. Specifically, the interaction item between OPEC maintain decisions and its production had the highest positive influence on oil risks because of the market uncertainty. The reactions of oil risks to the production increase decisions were larger than the cut decisions. The picture changed a little during pre- and post-crisis periods. There were twofold heterogeneous reactions of oil return risks to OPEC's announcements: the single and interaction items. From the perspective of the single item, there were significant negative risk reactions to the OPEC increase decision, while the "cut decision" played a positive role on oil risks during post-crisis periods. In terms of the interaction item, OPEC's announcements imposed their significant influence on oil return risks only when the production remained unchanged during post-crisis periods. However, there were no significant reactions to other OPEC announcements.

These interesting results have implications for different stakeholders. On the one hand, the expectations of market participants play a dominant role on monitoring the instability caused by oil prices and risks. Thus, policymakers need to guide a reasonable expectation to ease the oil price volatility and decrease the oil return risks. On the other hand, investors pay attention to the maximization of profits. Thus, investors had better focus on the market conditions and the policy information. Additionally, they should also be familiar with economic parameters and make reasonable investments. Last but not least, the heterogeneous role of OPEC cannot be ignored by market participants in crude oil markets. Therefore, they should focus on the OPEC meeting decisions.

This paper was not without limitations. For example, we neglected the heterogeneous reactions to OPEC announcements during different trends in oil price, such as decrease or increase. This allows investors to make short investments to maximize their profits. Thus, we could further study this reaction by dividing the sample periods into two sub-periods. Additionally, it is interesting to note that the price gap between Brent and WTI fluctuated before and after 2011. Thus, further analysis about the heterogeneous reaction by adding more benchmark oil prices could be regarded as a valuable area. Moreover, the role of investor sentiment in crude oil markets could be further explored with the development of internet finance.

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The Heterogeneous Interconnections between Supply or Demand Side and Oil Risks

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Abstract: Due to the crucial implication of oil risks for economic growth and policy making, the aim of this paper is to explore the heterogeneous interconnections of supply or demand in oil risks over time horizons and different countries. Specifically, we first examine the correlation of supply or demand in oil return risks and show the relationships in different countries based on wavelet coherence. Furthermore, we explore the time-varying interconnections between supply- or demand-side and oil return risks, as well as oil producers and demand countries. The empirical results show that the correlation between supply and oil return risks is relatively stable, whereas the linkage between demand and oil return risks shows greater volatility due to the impact of specific events. Further study indicates that there are heterogeneous interconnections between supply- or demand-side and oil return risks over sample periods. Specifically, the sign of response could be divided into four phases, i.e., 1997–2002, 2002–2010, 2010–2013 and 2014–2018. In addition, the interconnections of the demand side could be divided into three phases due to the sign of it. What is more, the dynamic interconnections of oil producers' or countries' demands behave quite heterogeneously in different countries. Thus policymakers should focus on the coordination level and space capacity in the global crude oil market.

Keywords: interconnection; wavelet coherence; supply and demand; oil risks; heterogeneity

1. Introduction

Since the seminal work by Kilian [1], a large literature has explored the interconnections of supply and demand in the fluctuation of oil price. As we all know, oil price experienced extraordinary volatility from 2007 to 2009 and during the period of 2014–2016. Hamilton [2] noted that demand factors play a dominant role in oil price volatility during the oil price increase period from 2007 to 2008. Moreover, Yu [3] identified global oil supply shocks and China's demand shocks and investigated the impact of China's demand shocks in promoting the volatility of global oil prices after the financial crisis. What is more, other scholars also claimed that some supply and demand factors, such as the US shale oil production, played a crucial role in the oil price drop during the period of 2014–2016 [4,5]. Indeed, the identification of this coherence, which depicts the underlying interconnections of supply or demand in oil risks, is crucial not only for clarifying crude oil markets, but also for explaining the dominant or heterogeneous role of different factors. What is more, changes in the oil price can significantly affect the economy as well as financial markets [6–11]. Therefore, the first goal of this paper is to verify the interconnections by examining the coherence of supply and demand in oil risks and by showing the relationships in different countries.

For instance, there are heterogeneous interconnections of supply and demand in oil risks over time horizons. To understand the different relationships of supply and demand over the time horizon, it is worth noting that the fundamental characteristics of crude oil price series are the result of different types of interconnections in different time windows [12]. Most of current studies obtain the fluctuation mechanism of oil prices by investigating the structural break effect, which could hide the diversity and evolution characteristics of oil price fluctuations [13,14]. It is also obvious that we could obtain detailed information regarding the oil price volatility by exploring the heterogeneous interconnection, which is important to understand crude oil markets. What is more, the stability of crude oil markets could play a major role in the decision making and precautionary behaviors of suppliers and demanders due to different stakeholders [15–17]. The decline of crude oil prices, on the one hand, could cause the dynamic of production decisions and investment strategies, on the other hand, could also drive up the uncertainty of strategies in petroleum enterprises through reducing their profits.

We next assess the heterogeneous importance of supply and demand countries in explaining crude oil return risks. During the last two decades, the landscape of crude oil markets has shifted dramatically. The impact of OPEC members' production level on oil prices fluctuations is a controversial issue with the development of non-OPEC countries. Specifically, this impact has been changing over time, since the dynamic of the market share of non-OPEC oil producers. Otherwise, the change of members' oil production could also strongly influence the global crude oil market as the prices deviate from their competitive level [18]. Meanwhile, the change of oil price has not caused any negative effects on the economic environment, and this sparked some researches to explore the role of consumption in global oil risks [19].

In this article, we explore the question of how supply- or demand-side exerts heterogeneous impacts on global oil return risks. This is a critical issue for academic scholars, as well as policymakers. Sharp movements in the oil price have serious impacts on risk management, hedging strategies and monetary policies. It is also plausible that real economic activities may inherit nonlinearity and instability of the oil price. What is more, the supply or demand status contributes to the global oil markets and then affects the oil return risks.

The main objective of this paper is to investigate the interconnections of supply- or demand-side on global oil risks. To be more specific, the first objective is to test the causal effect of underlying supply or demand on the oil markets. Our next aim is to investigate whether the increased oil risk for oil originates from the supply side shows a heterogeneous impact from the demand side. Having established where the interconnection evaluates, we further analyze the diverse response to oil producers' and countries' consumption of oil risks. The exploration of responses is plausible not just for clarifying the source of global oil return risks, but also for identifying the diverse role of main factors, such as the coordination level and space capacity, associated with global crude oil markets.

The literature that estimates the oil risk factors focuses on explaining the fundamentals and disruptive factors in crude oil markets. From the perspective of the fundamentals, a large body of literature has investigated whether the oil price volatility could be affected by recurrent bubbles and structural breaks [20,21]. Ji [22] indicated the heterogeneous dependence between a bearish and bullish regime. In addition, He [23] estimated the oil risk with the prediction of oil price volatility led by changes in fundamentals, as well as other risk factors. In terms of disruptive factors, oil supply and demand are regarded as fundamental triggers. Before the year of 2000, specifically, it could be better accepted that the equilibrium model is more suitable to depict the production and consumption characteristics in crude oil markets [24,25].

We extend the literature in some folds. First, we examine possible time-varying correlations between supply or demand side and oil return risks, and we further test the causal relationship between oil production or consumption in different countries and oil risks via the wavelet coherence. Based on the wavelet theory, this paper explores the time-varying response of oil return risks to supply or demand side based on the time-varying parameter structural VAR (TVP-SVAR) model. To our best knowledge, no research has further explored this topic, in which the supply or demand shocks are identified using sign restrictions on impulse responses. Furthermore, this study also documents the time-varying response of oil return risks to crude supply countries and to demand countries.

The rest of the paper is organized as follows. After the introduction, Section 2 presents the coherence between supply or demand and oil risks and shows the causal relationship between oil production or consumption in different countries and oil risks. Section 3 discusses the heterogeneous interconnections of the full sample. In addition, the heterogeneous interconnections in different countries are shown in Section 4. Section 5 concludes.

2. Examining the Correlation between Supply or Demand and Oil Risks

2.1. Data and Wavelet Approach

To measure the oil risks, we use Brent oil spot price based on the conditional autoregressive value at risk (CAViaR) [26]. Value-at-Risk (VaR) could be regarded as an effective tool to calculate the oil return risks. The VaR reflects the maximum amount of loss exposed in oil during a specific period. In the existing literature, there are many studies focus on the application and some alternative risk measures based on GARCH-type models [27–31]. However, these approaches often assume that the distribution of oil return is invariable across time. In general, there are speculation and significant intra-cluster in global oil markets, which make oil return risks more dynamic [32,33]. Thus, we use the CAViaR to calculate the oil return risks in this study.

Moreover, the oil return risks could be explained by supply or demand side in crude oil markets. From the perspective of the supply side, those just emphasize the aggregate global oil production and ignore to model OPEC and non-OPEC oil production separately will lead to underestimation of the influence of the supply side on oil risks [34]. In terms of the demand side, global demand shocks, in particular, may have an indirect effect working through the fluctuation of oil. Specifically, we collect monthly Brent spot price, OPEC and non-OPEC oil production and world total oil consumption (million barrels per day) from January 1997 to December 2018 due to the data availability. The data are available from the US Energy Information Administration (EIA).

We rely on an alternative approach to examine the correlation between supply or demand and oil risks: The wavelet coherence analysis. On the one hand, wavelet coherence is a powerful mathematical tool of X_t (in our study, X_t is the oil return risks and other variables series (Other variables include OPEC oil production, non-OPEC oil production, world total petroleum consumption and oil supply or demand in countries)) with the non-stationary and continuous volatility. Recently, this approach has received great attention in crude oil markets [35–40]. On the other hand, numerous studies have attempted to examine the correlation between oil supply or demand and fluctuation in the crude oil price based on Granger tests [41]. Indeed, the increase of the demand side has changed the pattern of the crude oil market. In addition, it is a common belief that the change of oil supply and demand also behaves as the source of oil price volatility, which remains that the dynamic correlation depends on different market characters [42]. Therefore, we use wavelet coherence to examine the dynamic correlation between supply or demand and oil risks and further explore the role of oil producer or countries' demand in oil return risks.

In the following, we briefly introduce the basics of the wavelet coherence approach.

The wavelet family could be written as Equation (1).

$$\psi_{l,m}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-c}{s}\right), c, s \in R, m \neq 0. \quad (1)$$

where c, s represents time and scale for wavelet mother function ψ, respectively.

Let $\{Risk\}_{t=1}^{T}$ be a series of oil return risks and T is the length of sample (Others are similar to oil return risk for obtaining the CWT). As mentioned in (1), we can obtain continuous wavelet transform (CWT) from a particular wavelet mother function for $\{Risk\}_{t=1}^{T}$. It could be written as Equation (2).

$$W_{risk}(c, s) = \int_{-\infty}^{\infty} Risk_t * \frac{1}{\sqrt{s}}\overline{\psi\left(\frac{t-c}{s}\right)}dt. \quad (2)$$

where the bar denotes a complex conjugate.

Moreover, the wavelet power spectrum (WPS) could generate the variance distribution of oil return risks. It could be shown as Equation (3).

$$WPS_{Risk} = \left|W_{Risk}(c,s)\right|^2. \tag{3}$$

The wavelet coherence between oil return risks and one of other variables could be depicted by CWT of oil return risks and OPEC oil production. At a more specific level, take the OPEC oil production as an example, CWT could be shown as Equation (4).

$$W_{Risk,pro} = W_{Risk}(c,s)\overline{W_{pro}(c,s)}. \tag{4}$$

where $W_{Risk}(c,s)$ and $W_{pro}(c,s)$ indicate the CWT of oil return risks and the OPEC oil production. The bar shows complex conjugate.

Following Torrence [43], the squared wavelet coherence could be defined as Equation (5).

$$R^2(c,s) = \frac{\left|S(s^{-1}W_{Risk,pro}(c,s))\right|^2}{S(s^{-1}\left|W_{Risk}(c,s)\right|^2)S(s^{-1}\left|W_{pro}(c,s)\right|^2)}. \tag{5}$$

where S stands for a function that is smoothing procedure over time, with $0 < R^2(c,s) < 1$. A value of $R^2(c,s)$ represents correlation between oil return risks and the OPEC oil production.

2.2. Correlation Analysis in Supply or Demand

To examine the linkage of oil return risks with supply or demand side, a wavelet coherence for monthly oil production or consumption along with Brent oil return risks is developed (as portrayed in Figure 1). Specifically, the wavelet coherence will denote the strength of correlation between examined pairs.

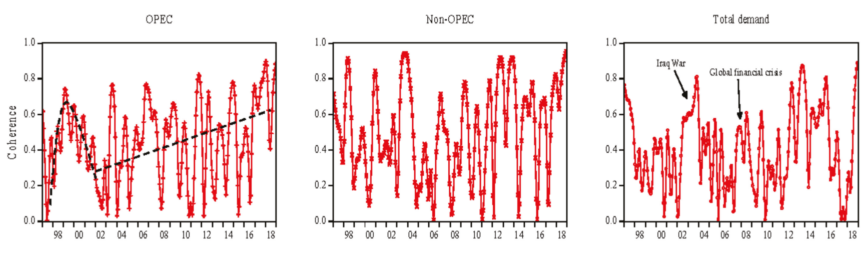

Figure 1. Wavelet coherence between supply or demand and oil return risk. Source: Author estimation. (Notes: The black dotted line shows the trend).

In summary, we find evidence that there is strong correlation between supply or demand and oil return risks. In general, the correlation between supply and oil return risks is relatively stable, whereas the linkage between demand and oil return risks shows greater volatility due to the impact of specific events. From the perspective of the supply side, the correlation of the two types of producers has been differentiated during different phases. In Figure 1, for both OPEC and non-OPEC, we could divide the correlation into two phases. The first stage is 1997–2002. At this stage, the correlation between OPEC oil production and oil return risks shows an "inverted U" trend, while the dependence between non-OPEC oil production and oil return risks is generally stable, but the fluctuation is dramatic. The other phase is 2002–2018. The amplitude of the correlation between non-OPEC oil production and oil return risks is greater than that in OPEC oil supply. It could be explained by the market power and the change in oil production. Hence, to a certain extent, OPEC promotes the stability of crude oil markets through adjusting its production, which changes its market share rather than competitive condition. What is more, the global oil return risks reduce when stable sources of oil supply is more than unstable supplies. In fact, OPEC oil production has been less able than non-OPEC since OPEC has remained its market share at a relatively constant level recently. Thus the correlation between non-OPEC oil supply and oil return risks is greater than that in OPEC.

With reference to the total demand Figure, we show the correlation between demand and oil return risks. It is interesting to note that there are significant effects of external political environment on the correlation [44]. Specifically, it experienced a sharp increase induced by the Iraq war during 2002–2004. During the Iraq war, changes in oil production led to a relative rise in oil demand. Due to OPEC's market power in adjustment, the supply shortage caused by the war is supplemented by other OPEC members. According to the lag of adjustment, however, the correlation between total oil consumption and oil return risks is enhanced. In addition, it also could be seen that the correlation strengthened during the global financial crisis. The scope of the global financial crisis caused by the US sub-prime mortgage crisis has gradually expanded, and the impact has gradually shifted from the virtual economy to the real economy. The total world oil consumption is reduced for the first time, and petroleum companies have also suffered a major impact. As the demand declines, the imbalance between supply and demand in the market is aggravated, which in turn reduces the stability of the market. Another sharp increase is during 2012–2016. Due to weak global economic recovery and rising oil prices, the growth of total world oil consumption is weak. Moreover, the continuous increase in oil supply during this period has made the market supply abundant. The downward pressure on oil prices is affected by the imbalance between supply and demand, which is mainly affected by demand.

2.3. Correlation Analysis in Oil Producers' or Countries' Demand

Since the heterogeneous correlation between supply or demand and oil return risks, we further examine the correlation in oil producers' or countries' demand. On the one hand, we select oil producers based on the oil production at a monthly frequency for both OPEC and non-OPEC countries. More specifically, non-OPEC oil producers are not as strong an impact as OPEC oil producers for reasons such as lack of coordination in different members, to make up for short supply, and high production. On the other hand, the increase in oil consumption from economies such as China and the Middle East has an effect on oil return risks. In this paper, we examine the dynamic correlation of 6 OPEC members, 6 non-OPEC and 6 demand countries (The countries include three categories; they are, OPEC members (Iran (IRI), Iraq (IRQ), Saudi Arabia (KSA), Kuwait (KUW), United Arab Emirates (UAE) and Venezuela (VEN)), non-OPEC countries (Canada (CAN), China (CHN), Mexico (MEX), Norway (NOR), Russia (RUS), United States (USA)) and demand countries or regions (CHN, Central and South America (CSA), Europe (EURO), Japan (JPN), Middle East (ME), USA)). The monthly data could be collected at https://www.eia.gov.

Figures 2–4 show the cross-correlations between variables. It is interesting to note, in general, the global oil market risk is closely related to the state of the country's oil production capacity, and it is highly correlated with major political and economic events in demand countries or regions.

First, we consider the correlation between OPEC members' oil production and oil return risks. It can be seen that OPEC members' oil production serves as heterogeneous producers as it produces large differences of space capability. Overall, the correlation between KSA production and oil return risks is more stable. Its leadership is crucial for decreasing oil risks and achieving its political goals. In addition, it is usually regarded as swing producer which absorbs fluctuations in supply and demand in order to maintain the crude oil market stability. What is more, the tit-for-tat strategy in KSA matches the level of cheating by other members and thus stabilizes the crude oil markets. However, the correlation between IRI, IRQ, UAE and VEN production and oil return risks show a decrease trend over sample periods. In addition, it is also related with major events. For example, during the Iraq war (2003), the correlations between IRQ or IRI production and oil return risks are greater due to geopolitics. The linkage of IRI production with oil return risks is also larger during Iran's nuclear sanctions (2015). For another, the dependence of KUW production with oil return risks shows an "inverted U" shape. This is associated with the compliance with OPEC's administered quotas. As a mid-oil-producer, KUW displays much lower frequencies and magnitudes of noncompliance with OPEC's oil production cut [45]. In 2002, affected by the crude oil market environment, OPEC made a large adjustment to oil production quotas, which caused KUW oil production to fluctuate, thereby expanding its correlation with oil return risks.

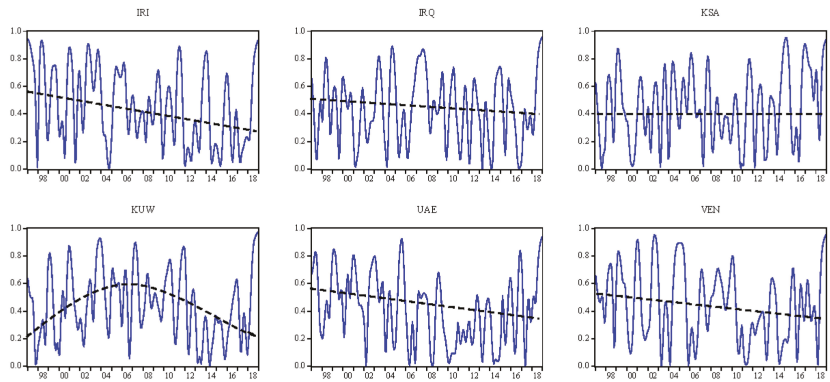

Figure 2. Wavelet coherence between OPEC members' oil production and oil return risks. Source: Author estimation. (Note: The black dotted line shows the trend).

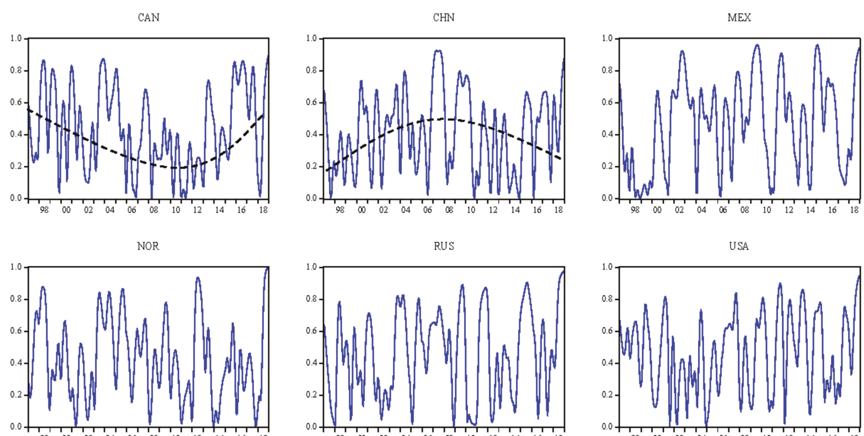

Figure 3. Wavelet coherence between non-OPEC countries oil production and oil return risk. Source: Author estimation. (Note: The black dotted line shows the trend).

It should be noted that Figure 3 implies that the policy environment is the main reason for the fluctuations in the correlation between non-OPEC counties' production and oil return risks. Specifically, the correlations between MEX and NOR production and oil return risks display the highest fluctuation, whereas RUS and USA have the lowest volatility. Moreover, the amplitude of correlation between CHN production and oil return risks shows an "inverted U" trend. The fluctuation of the linkage of CAN production and oil return risks decreases first and then increases over the sample period. These results could be explained by the market foundation. Hence, the excessive dependence of MEX or NOR economic development on oil production makes the correlation between oil production and return risks fluctuate greatly. The global economic state and the monetary status of the US dollar protect its volatility in relation to oil return risks. Otherwise, the rapidly increasing position of RUS in the crude oil market has made its correlation with oil return risks relatively stable. The imperfection of the CHN oil market is vulnerable to the spillover effects of other market policies, which increases the uncertainty of the domestic policy environment, and thus the fluctuation changing over sample period. However, the time-varying correlation between CAN production and oil return risks is related to the oil market share over time.

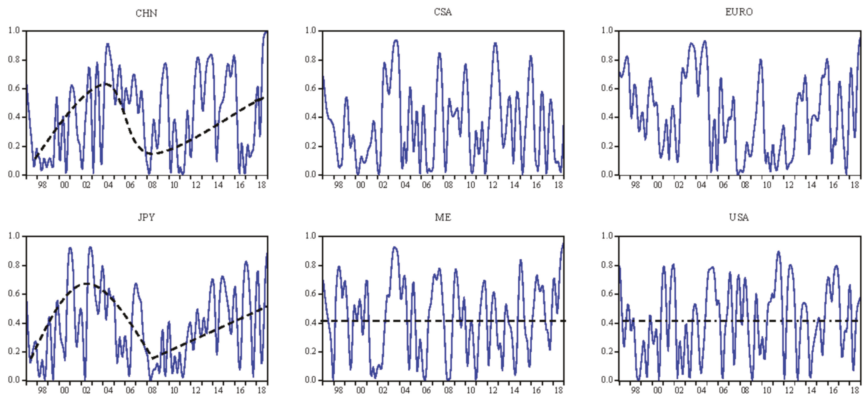

Figure 4. Wavelet coherence between demand countries or regions' oil consumption and oil return risk. Source: Author estimation. (Note: The black dotted line shows the trend).

Furthermore, we turn to the relation between demand countries or regions' consumption and oil return risks. It is obvious that there are differences in the correlation between demand countries and oil return risks. Overall, the correlation between USA and ME consumption and oil risks is more stable, while there are phases in the relation between JPY and CHN consumption and oil return risks. Specifically, the role of USA consumption in the crude oil market is connected with the presidential election. In addition, with reference to Figure 4-JPY, it is interesting to note that the correlation shows an "inverted U" shape before the global financial crisis, then it increases over the time periods. In terms of the correlation between CNY consumption and oil return risks, it could be divided into three phases. The first stage is 1997–2004. We could clearly note that it shows an increase trend due to the economic growth. Then, the relationship decreased during 2004–2008. Moreover, China carried out the Four-Trillion-Yuan stimulus plan in 2008 to promote the domestic economy. Thus the correlation between CNY consumption and oil return risks has increased since 2008. These results indicate that major events and the announcement of both policies could potentially be a part of the relationship between demand countries' consumption and oil return risks at a particular point of time.

3. The Heterogeneous Interconnections between Supply- or Demand-Side and Oil Risks

While informative, the dynamic causal effect does not completely depict the relationship between supply- or demand-side and oil return risks for two reasons: It does not hint on the sign of the response to supply or demand of oil return risks, and there are heterogeneous responses in different time windows. Thus, this section presents the TVP-SVAR model and explores the response to supply or demand in the crude oil market [46].

3.1. TVP-SVAR

In order to explore the response of supply- or demand-side in a time-varying fashion, this study uses the TVP-SVAR to empirically research the oil return risks. Particularly, we mainly focus on the short-term response to supply or demand of oil return risks since the significant effects of oil price on economy and financial markets. In fact, the impact of oil production or consumption on the crude oil market mainly refers to the short-term, whereas long-term response will be regulated by the market. Thus, the impulse response functions could be used to measure the impact of oil production and consumption on oil return risks in the short-term. Some alternative analyses are variance decomposition and the coefficient of different variables based on VAR models. As we all know, the result of variance decomposition could be affected by the number of variables. In addition, the coefficient could also be impacted by the rank of variables in VAR models. Thus we focus on the impulse response functions. What is more, some alternative methods, such as ECM and Cointegration tests, have ignored the evolution of response to oil production or consumption of oil risks.

Otherwise, the baseline model explores the joint behaviors of OPEC oil production (*opro*), non-OPEC oil production (*npro*), total world oil consumption (*wcons*) and oil return risks (*risk*). Another advantage in TVP-SVAR compared with the constant basic VAR includes in the sense that we can obtain the time-varying response in different oil producers' or countries' demand over the sample period. As we explained above, the TVP-SVAR is very useful to investigate the time-varying response to supply or demand of oil return risks. In this paper, we estimate the parameters in the TVP-SVAR model based on the Markov Chain Monte Carlo (MCMC).

As we all know, a basic structural VAR could be defined as (6).

$$A\mathbf{y_t} = \alpha_1 \mathbf{y_{\tau-1}} + \cdots + \alpha_p \mathbf{y_{t-p}} + u_t, t = p+1, \ldots, n. \tag{6}$$

where $\mathbf{y_t} = [opro, npro, wcons, risk]'$. $A, \alpha_1, \ldots \alpha_s$ are 4×4 matrices of different lag order p, and n is the length of sample period. In addition, u_t is the error item with $u_t \sim N(0, \Sigma\Sigma)$. In addition, $\Sigma = \begin{pmatrix} \sigma_{opro} & 0 & 0 & 0 \\ 0 & \sigma_{npro} & 0 & 0 \\ 0 & 0 & \sigma_{wcons} & 0 \\ 0 & 0 & 0 & \sigma_{risk} \end{pmatrix}$, $A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 \\ a_{31} & a_{32} & 1 & 0 \\ a_{41} & a_{42} & a_{43} & 1 \end{pmatrix}$.

The reduced form of Equation (6) could be written as Equation (7).

$$\mathbf{y_t} = B_1 \mathbf{y_{\tau-1}} + \cdots + B_p \mathbf{y_{t-p}} + A^{-1}\Sigma\varepsilon_t, \varepsilon_t \sim N(0, I_4). \tag{7}$$

where $B_i = A^{-1}\alpha_i$, $i = 1, \ldots, p$.

Theoretically, the TVP-SVAR updated from Equation (7) by allowing the parameters to change over time. Thus, the expression of Equation (7) to the TVP-SVAR model with stochastic volatility is given as Equation (8).

$$\mathbf{y_t} = B_{1,t}\mathbf{y}_{t-1} + \cdots + B_{p,t}\mathbf{y_{t-p}} + A_t^{-1}\Sigma_t\varepsilon_t, t = p+1, \ldots, n \tag{8}$$

Furthermore, (8) can be written as (9) (We stack in a vector for all the R.H.S coefficients. In addition, the symbol ⊗ in Equation (9) denotes the Kronecker product).

$$\begin{aligned} \mathbf{y_t} &= X_t' B_t + A_t^{-1}\Sigma_t\varepsilon_t, \\ X_t' &= I_n \otimes [1, \mathbf{y}_{\mathbf{t-1}}', \ldots, \mathbf{y}_{\mathbf{t-p}}']. \end{aligned} \tag{9}$$

Moreover, there are assumptions of estimating the TVP-SVAR. First, we assume that oil risk is associated with OPEC and non-OPEC oil production, and non-OPEC oil production has impact on the OPEC production in current period. Second, we define the parameters following a random walk process as Equation (10).

$$\begin{cases} B_t = B_{t-1} + \nu_t, \\ a_t = a_{t-1} + \varsigma_t, \\ \log\sigma_t = \log\sigma_{t-1} + \eta_t. \end{cases} \tag{10}$$

where the distributional assumptions as regards $(\varepsilon_t,\ \nu_t,\ \varsigma_t,\ \eta_t)$ are stated as Equation (11).

$$\begin{pmatrix} \varepsilon_t \\ \nu_t \\ \varsigma_t \\ \eta_t \end{pmatrix} \sim N(0, \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \Sigma_B & 0 & 0 \\ 0 & 0 & \Sigma_a & 0 \\ 0 & 0 & 0 & \Sigma_{\ \sigma} \end{pmatrix}). \tag{11}$$

3.2. The Interconnections between Supply-Side and Oil Return Risks

Exploring impulse responses is a standard way of the VAR model to measure lag effects between the supply side and oil return risks. However, the responses vary with time in the TVP-SVAR model over the sample period. Figure 5 shows the time-varying impulse response to *opro* and *npro* of *risk* after 0 months (simultaneous), 1 month and 3 months (We have tested that the response after 6 months is same as it after 3 months. In addition, the response over 6 months is approximated to zero).

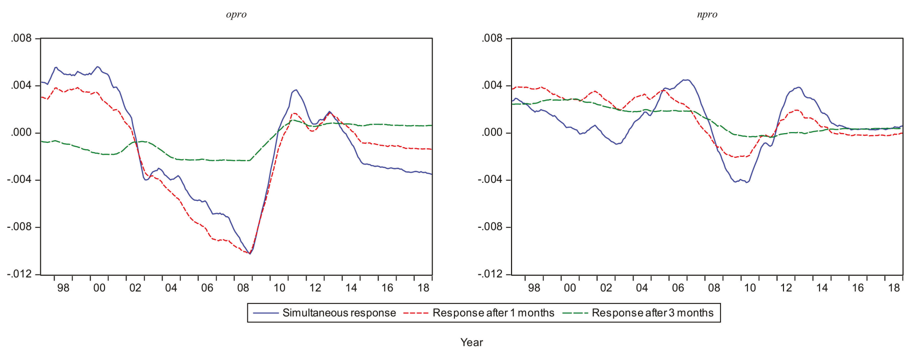

Figure 5. Time-varying impulse response to supply-side of oil return risks. Source: Author estimation.

The dynamic impulse response to the supply-side of oil return risks shows a significant change over the sample period. Overall, the sign of simultaneous response is almost the same as the 1-month one in the OPEC production. Moreover, the degree of response in the OPEC production is greater than that of the non-OPEC one, suggesting that OPEC plays more significant role in the crude oil market. This is not surprising, and due to the fact that there is heterogeneity about the absence of enforcement mechanisms and market power. Apart from that, it is obvious that the response after 3 months is approximate to zero. This suggests that the non-OPEC is more complaisant against the crude oil market and the oil return risk is similarly more reactive to the OPEC production during the same time horizon.

At a more specific level, there are differences in the sign of the response to OPEC or non-OPEC production of oil return risks in different phases. As shown in Figure 5, we divide the correlation into four phases. The first stage is 1997–2002. At this stage, the response to the supply side is positive and shows a decrease trend in OPEC or non-OPEC production. This indicates that OPEC, as a cartel, plays a dominant role in the crude oil market. The next stage is 2002–2010. It is interesting to note that the response to the OPEC production is negative and shows an "inverted U" trend in crude oil markets, which was increasing before 2008 and switched to decrease after 2008. The response fluctuation to the non-OPEC production, however, is dramatic. This result is associated with the coordination behavior. Before the 2008 financial crisis, OPEC determined the quota by using the resolution of the basic situation of the crude oil market, and then achieved the effect of stabilizing the market. Since the financial crisis occurred in 2008, the determinant role of OPEC announcements gradually decreased due to the misjudgment of the crude oil market by the OPEC meeting. Moreover, the lower coordination level in the non-OPEC production makes more volatility of the response of oil return risks. The other stage is 2010–2013. It is worth noticing that the sign of response to the OPEC production of oil return risks is the same as the one in the non-OPEC production. This is not surprising either due to the increase of cooperation in OPEC and non-OPEC. The final phase is 2014–2018. The response to OPEC production of oil return risks is negative and shows an increase trend, whereas the one in non-OPEC production is approximated to zero. It also could be explained by the market adjustment in the oil supply market. Hence, there is an asymmetric process in oil price adjustment between OPEC and non-OPEC. This indicates that the oil return risk is more reactive to the OPEC production.

3.3. The Interconnections between Demand-Side and Oil Return Risks

The response value to world oil consumption, as shown in Figure 6, shows more than ten times higher than that of oil production on risks. It is worth noticing that the impulse responses to the demand side of oil return risks significantly vary over the sample period, and it could be divided into three phases due to the sign of it. Before 2002, the simultaneous response to the demand side of oil return risks is positive, whereas the response after 1 month is negative. In addition, the differences between the simultaneous response and the one after 1 month gradually narrow. This could be explained by the influence of major events. After the "9.11" incident, the world economic growth was sluggish, causing the world oil demand to shrink and international oil prices to fall. The trend of international oil prices in 2002 mainly depends on the development trend of the world economy, especially the recovery of the US economy, and the improvement of the European and Asian economies.

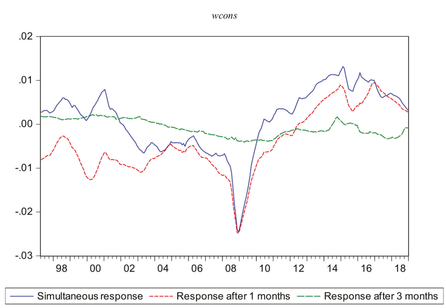

Figure 6. Time-varying impulse response to demand-side to oil return risks. Source: Author estimation.

Moreover, oil return risks have become more reactive to total world consumption during 2002–2008 and switched to decrease during 2008–2010. During the former period, the sign of response to world consumption is negative and shows an increase trend. Economic growth in emerging countries has led to a sharp increase in global demand for crude oil. Indeed, emerging developing countries, especially China, have a sharp increase in demand for oil, while the world is known oilfield production capacity begun to decline. At the same time, since non-OPEC countries have weak growth in output and global surplus capacity has shrunk, the crude oil market has entered a period of imbalance between supply and demand. During the latter period, the total world oil consumption reduced after the 2007 financial crisis due to the weak world economy. In addition, because of the environment of the global crude oil market, the response to world consumption of oil return risks decreased during 2008–2010.

Finally, the sign of the responses after 2010 is significantly different from that before the period during distinct time windows. It is obvious that the response to world consumption of oil return risks is positive. This is not surprising and due to the volatility of economic policy uncertainty and world consumption [47–49]. On the one hand, the crude oil market was strongly developed since the economic recovery in 2010. What is more, the oil supply was also sufficient, and the petroleum inventory was at a high level. Thus, the global oil market was in a relatively loose equilibrium. However, the total world oil consumption shows strong uncertainty and is easily affected by the internal petroleum environment, causing fluctuations in the oil demand, which in turn affects the stability of the oil market. On the other hand, it is well-known that there is significant linkage between economic policy uncertainty and oil consumption, which in turn impacts the stability of crude oil market [32]. Hence, the global economic policy uncertainty has become more volatile, causing the increase of uncertainty in the external economic environment since 2010, which results in the expansion of the uncertainty of the global oil demand. Affected by fluctuations in world oil demand, there is a phenomenon of imbalance between oil supply and demand, thereby reducing the stability of the crude oil market and increasing the oil return risks.

4. The Heterogeneous Interconnections between Oil Producers' or Countries' Demand and Oil Risks

Additionally, countries with high oil production levels have significantly more influence on oil return risks. In order to explore the time-varying interconnections between oil producers' or countries' demand and oil return risks, we reconstruct the TVP-SVAR, mentioned in Section 3.1 and further focus on the impulse response of oil return risks in this section.

4.1. The Heterogeneous Interconnections between Oil Producers and Oil Return Risks

Figure 7 portrays the impulse response to OPEC members' production of oil return risks. It is worth noting that the signs of responses to different OPEC countries present different characteristics. Overall, they could be divided into three categories. Firstly, although the negative response occurs on simultaneous response, the responses of KUW and VEN oil consumption to the oil return risks are positive on the other lagged months. The next category includes IRI and UAE. Specifically, the sign of simultaneous and lagged 3 months response are negative and stable, whereas the one after 1 month is positive. This result could be explained by the geopolitics. From the perspective of the strategic position of the oil market, KUW, UAE and VEN account for a small share of the oil market. Together with the operating mechanism of OPEC, the responses of production in these members to oil return risks are stable and play a negative role in market risks. Otherwise, the relevant policies implemented in IRI have expanded Iran's role in the oil market and reduced the uncertainty of the Iranian oil market, thereby stabilizing oil revenue risks.

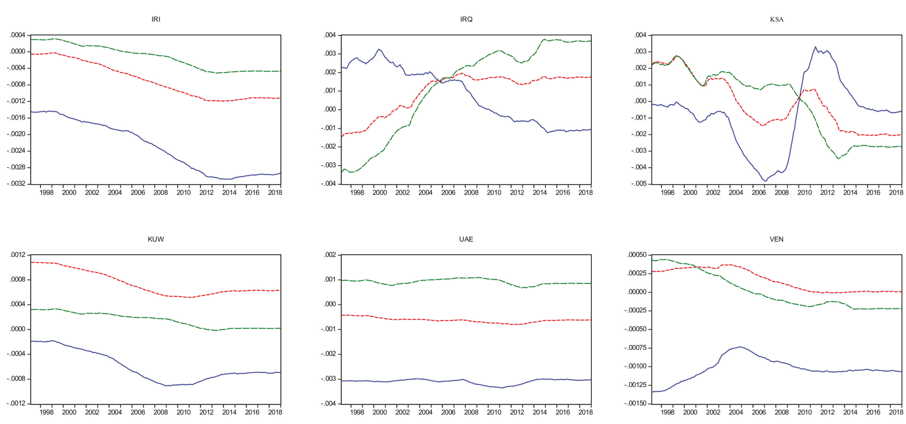

Figure 7. The time-varying impulse to OPEC members' production of oil return risk. Source: Author estimation.

Finally, the sign of response to IRQ and KSA of oil return risks changed over time. It is not surprising and due to the geographic location and space capacity. On the one hand, it is obvious that the sign of simultaneous response to IRQ production changed in 2008, which is positive before 2008 and switches to negative after 2008. In addition, the sign of response switches from negative to positive on the other lagged months. Due to the important role of Iraqi oil in economic development, the restoration and development of the Iraqi oil industry is an important cornerstone of economic development after the financial crisis. In addition, the Iraq war and the global financial crisis have caused enormous obstacles to the development of the Iraqi oil market. In order to stabilize the economic development, in 2009, Iraq publicly auctioned the mining rights of oil and gas fields and formulated the "Oil and Gas Law" to achieve the purpose of controlling risks in the crude oil market. On the other hand, the sign of simultaneous response to KSA production changed over time, whereas it is almost positive before 2010 and switches to negative after 2010 on the other lagged months. These results are associated with the market mechanism and the space capacity. As a fringe of non-cooperative producer, KSA used to cut its oil production to neutralize the partial conformity by the other OPEC member nations, while it tends to offset its peers' conduct. However, because of the higher volatility of economic policy uncertainty in KSA, the simultaneous response to KSA production of oil return risks changed over the sample period. Moreover, spare capacity is imperative for decreasing the oil risks and remaining KSAs' leadership as a price maker.

Since the increasing market power of non-OPEC oil producers, we further explore the heterogeneous relationship between non-OPEC oil producers and oil return risks. Figure 8 traces out the time-varying impulse response to non-OPEC producers of oil return risks. It is obvious that the dynamic response to non-OPEC oil producers of oil return risks behaves quite differently in different countries. While the positive response occurs on CAN and NOR, the response of RUS and USA production to oil return risks is negative. Specifically, the positive response after 1 month to CAN production of oil return risks is the largest compared to other lagged months. Moreover, the main response of USA production to oil return risks is negative and after 3 months, where the one of RUS production is simultaneous. The results confirm that the response is related to economic fundamentals in different oil producers. Indeed, when the oil demand increases, USA and RUS may correct any market imbalance that may occur due to the economic states through a unified strategic reaction.

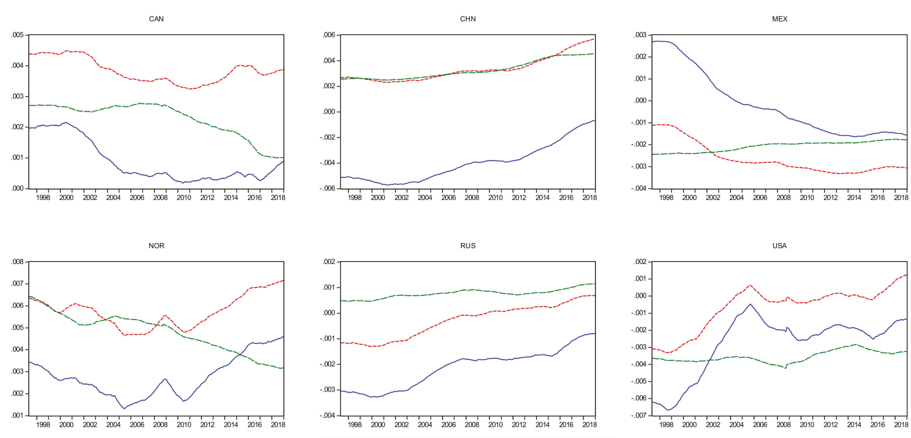

Figure 8. The time-varying impulse to non-OPEC producers of oil return risk. Source: Author estimation.

It is particularly interesting to note that the negative response to CHN production of oil return risks is gradually decreasing, and one is mainly positive on other lagged months. In addition, MEX is just the opposite. This is not surprising and due to the major events and geopolitics in different markets. For one thing, major events play a main role in the response of CHN production to oil return risks. Affected by the policy, China's oil supply has greater uncertainty. In addition, due to the correlation between the oil futures market and spot market and the "herd effect" of investors, the uncertainty of oil production further reduces the stability of the market. Thus, the responsiveness increases for the oil return risks while the rise for the CHN oil production. For another, the response to MEX production in the crude oil market is related to the geopoliticsl. In fact, there is a significant decline in Mexican crude oil production and reserves over the sample period. In addition, due to the influence of the external policy environment on MEX's oil production, its simultaneous response is gradually reduced. In addition, oil production has a lag effect on the crude oil market stability. This is mainly because of the state of the domestic oil market in MEX. Specifically, the oil supply in MEX can basically meet internal demand since MEX oil consumption is relatively stable. Thus it is less affected by the spillover effects of other international oil markets, which can better protect the development of the domestic oil market and further promote the stability of the global oil market.

4.2. The Heterogeneous Interconnections between Countries' Demand and Oil Return Risks

It is particularly interesting to study how the observed time variations affect the transmission of countries' oil consumption. Figure 9 points out the time-varying impulse response to countries' demand and oil return risks. It is obvious that the responses of various countries present different phases characteristics. In general, the impulse responses to CHN consumption of oil return risks significantly vary after 2013. A significant change is also noticeable in 2012. We clearly notice that the negative responses on all lagged show decrease before 2012, and the response after 3 months switches to positive while the other response is also negative and increase. This finding could be explained by the change of the economic state, as well as the reform of the policy.

Figure 9. The time-varying impulse response to countries' demand to oil return risk. Source: Author estimation.

The impulse response to CSA consumption of oil return risks has significantly weakened in generation. However, impulse responses to JPN consumption of oil return risks are relatively steady, indicating that the JPN consumption is beneficial to decreasing the oil risks. Additionally, despite the positive response took place before 2004, the response to ME consumption of oil return risk is negative. This result indicates that the appreciation of the ME consumption decreased the oil return risks. By contrast, the sign of the impulse to EURO consumption of oil return risks eventually varies during different periods. Specifically, the simultaneous response is almost the same as the 1-month one, which is negative during 2002–2010 and switches to positive in other periods. This phenomenon may be a result of the development of emerging markets during 2002–2008 and the change of the global economic and financial environment after 2008. On the contrary, the simultaneous impulse responses to USA consumption of oil return risks is positive from 2004 to 2010 and negative during other periods. However, the response after 1 month to oil return risks is positive before 2013 and switches to negative after 2013. What is more, the negative impact of the oil demand on the market in the USA shows an increasing trend. This indicates the growing dominant role of the US oil demand on the global crude oil market. This finding also reflects that this feature in the USA oil market exists in the global.

5. Discussions and Conclusions

The relationship between supply or demand and oil price volatility may reflect the importance of supply or demand in global crude oil markets. By applying the structural VAR model, Kilian [1] found that the synchronization between demand or supply shocks and the oil real price. Following Kilian [1], Yu [3] discovered the strong effect of the China demand on global oil price volatility after the financial crisis. Moreover, Aastveit [19] found that the impact on the real oil price is more than twice of demand from emerging economies compared with that in developed counties. However, there are many reasons that result in such reactions, such as the major events mentioned in Section 2.2, as well as coordination levels and space capacity of countries [50,51].

Unlike these studies, the empirical results from wavelet coherence and the impulse response functions all point to the heterogeneity of oil return risks response to supply or demand-side, as well as different countries. In this paper, we first examine the correlation of supply and demand in oil return risks and show the relationships in different countries based on wavelet coherence. Furthermore, we explore the time-varying interconnections between supply- or demand-side and oil return risks. What is more, we also study the heterogeneous role of oil producers or demand countries on the global crude oil market via the TVP-SVAR model. Specific conclusions are as follows.

The interconnection between supply or demand and oil return risks has stronger differences in the global crude oil market. In general, the correlation between supply and oil return risks is relatively stable, whereas the linkage between demand and oil return risks shows greater volatility due to the impact of specific events. According to Antonakakis [52], specific events have a direct effect on firm investment, in turn affecting the oil consumption and its risks. At a more specific level, the global oil market risk is closely related to the state of the country's oil production capacity, and highly correlated with major political and economic events in demand countries or regions. Specifically, due to space capacity, the correlation between the KSA oil production and oil return risks is relatively stable, and IRI, KUW, UAE, and VNE show a decrease trend. In addition, because of the policy environment, the oil supply of MEX, USA and CHN is inconsistent with the fluctuation of oil return risks. In terms of demand countries, the correlation between USA and ME consumption and oil risks is more stable, and it shows an "inverted U" shape on the JPN market. In addition, the relationship between CNY consumption and oil return risks could be divided into three phases.

There are heterogeneous interconnections between supply- or demand-side and oil return risks over sample periods. In the perspective of the supply side, the sign of response could be divided into four phases, i.e., 1997–2002, 2002–2010, 2010–2013 and 2014–2018. Since differences of coordination behavior and market adjustment existing in the OPEC and non-OPEC countries, there are further differences role of OPEC and non-OPEC during 2002–2010 and 2014–2018. According to the differences in geopolitical factors, non-OPEC countries adjust the crude oil market fluctuation that could be resulted in the lag effects of the OPEC when the oil price changed. In terms of the demand side, the interconnections could be divided into three phases due to their signs. Especially, the simultaneous response to the demand side of oil return risks is positive, whereas the response after 1 month is negative before 2002. During 2002–2010, the sign of response is negative and oil return risks have become more reactive to total world consumption during 2002–2008 and switch to decrease during 2008–2010. In addition, the signs of the responses after 2010 are significantly different from those before that period.

The time-varying interconnections of oil producers or countries demand behave quite heterogeneously in different countries. Different local markets show global and regional status of the global oil market. For oil producers, the sign of response to IRQ and KSA oil return risks changed over time due to the market power. While the negative response occurs on simultaneous response, the responses of CHN, KUW and VEN oil consumption to the oil return risks are positive on the other lagged months, which are opposite to those of MEX, IRI and UAE. In addition, the positive response occurs on CAN and NOR, whereas the response of RUS and USA production to oil return risks is negative. For countries demand, the impulse responses to CHN consumption of oil return risks significantly vary in all lagged months after 2013. Otherwise, the impulse response to CSA consumption of oil return risks has significantly weakened in generation. However, impulse responses to JPN consumption of oil return risks are relatively steady. By contrast, although the positive response occurs before 2004, the response to ME consumption of oil return risks is negative. On the contrary, the signs of the impulse to EURO and USA consumption of oil return risks eventually vary during different periods.

These findings have implication for policymakers and investors in the global crude oil market. On the one hand, coordination levels and space capacity play a dominant role in improving the stability of the global oil market. Thus, Policymakers have stabilized the fluctuations in the oil market by formulating relevant cooperation policies to ease the imbalance between supply and demand in the domestic oil market. In addition, they also should strengthen the research and development of petroleum innovation technology and give full play to the space capacity of the oil market to meet the dependence role of oil in economic development, which in turn realizes the coordinated co-movement of the oil market and economy. On the other hand, the main concern of investors is the maximization of profits. Thus, investors need to focus on the market characteristics and the evolution of policies before investing in the decision-making, and they should further be familiarised with the operating mechanism of the market. Moreover, they also need to pay attention to the major events of major countries or organizations in the market, such as OPEC meetings and reports. What is more, they should make a reasonable assessment of the investment location and eliminate as much as possible the decision-making mistakes caused by geopolitical factors.

This paper is not without limitations. For instance, we ignored the difference between WTI and Brent oil price. It is also worth noting that the difference between WTI and Brent price has been expanded since 2011, thus we could further study the heterogeneous correlation by adding more global benchmark oil prices. In addition, further analysis about the asymmetric effects of investor sentiment and oil return risks in different regimes would be a valuable area to explore.

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Economic Competitiveness Evaluation of the Energy Sources: Comparison between a Financial Model and Levelized Cost of Electricity Analysis

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Abstract: The levelized cost of electricity (LCOE) is used widely to compare the economic competitiveness of the energy mix. This method is easy to understand and simple to apply, which makes it preferable for many energy policymakers. However, the method has several disadvantages from the energy business perspective. First, the LCOE approach does not consider revenue, and a high-interest rate usually correlates with the tariff growth rate. Thus, if a high-interest rate increases the cost, that high rate increases the revenue, which can affect economic competitiveness. Second, the LCOE does not consider different stakeholders. Equity investors and loan investors have different interests depending on different financial indicators, which influence the same energy sources' differential economic attractiveness. This study analyzes and compares the LCOE, Project Internal Rate of Return (Project IRR), Equity Internal Rate of Return (Equity IRR), and Debt Service Coverage Ratio (DSCR) of an illustrative wind, coal, and nuclear power project using Monte-Carlo simulations. The results show that energy sources' economic competitiveness can vary depending on financial indicators. This study will help energy policymakers develop more economically realistic energy portfolios.

Keywords: energy business; energy source; project finance; financial model; levelized cost of electricity; internal rate of return; tariff growth rate; loan period; sensitivity analysis

1. Introduction

The energy mix throughout the world has changed very quickly as renewable energy has emerged [1–3], and energy mix policies must consider many factors, such as economic competitiveness, climate change, public acceptance, safety, and energy security [4]. Thus, in many cases, it is difficult to determine whether one specific energy source necessarily is better than others. Further, when only their economic competitiveness is compared, the results can vary according to the uncertainty of input variables, such as discount and interest rates, overnight capital cost, and capacity factor. For these reasons, many researchers have compared energy's economic competitiveness with probabilistic distribution variables using Monte Carlo simulations [5–7]. Most of these articles have analyzed this economic issue using the levelized cost of electricity (LCOE), which is adopted as a metric to estimate power generation technologies' competitiveness [6–9]. The LCOE is an indicator used widely, in that it can compare different lifecycle energy sources easily [8,10]. LCOE provides us with remarkable information with regard to the cost side in that LCOE itself is a concept of the minimum required tariff to cover the project costs. However, despite its worldwide and traditional use, the LCOE itself is not a perfect approach, particularly from the financial point of view in an actual business [11,12].

LCOE usually is calculated as follows: the total project life-cycle cost divided by the total lifetime energy production [13]. The biggest issue of the LCOE calculation from the energy business is that it only deals with the costs which naturally exclude the concept of revenue and profit. The basic concept of finance comes from both the cost and the revenue which leads to the final outcome known as net income or profit. As the revenue side is not applied in the LCOE calculation, LCOE naturally does not take into consideration the revenue-related variables such as *TGR* which is corresponding to the *IR* of cost as the value for money. Another issue is that the financial attractiveness can be varied depending on the financial stakeholders. Equity investors pursue their profit from their financial investment and long development. They try to find the optimum equity-debt portfolio to maximize the profit leverage effect. This profit varies according to the *CP*, the ratio between *LP* and *OP*, *IR*, *TGR*, and so on. Whereas, loan investors weight not only the amount of interests but also the payback stability over the long *LP*. This stability also varies according to volatility of *CF* and *TGR*, *CP*, cash flow, the ratio between *LP* and *OP*, dividend arrangement, and so on. For these reasons, LCOE cannot sufficiently explain the various interests of different stakeholders. Thus, if the financial model is used, the various financial indicators can help provide the various values to various different stakeholders. These various financial values can be helpful to establish a realistic and balanced economic energy mix. This paper aims to explain how the economic and financial competitiveness of each energy generation can be varied depending on the various conditions using not only the LCOE calculation but also the financial model approach. This study does not aim to reveal which energy source itself is more competitive or not because it can be varied depending on the assumptions of input variables and project condition. Thus, the various assumptions of this study aim to explain the principles of its variable economic attractiveness. If this study changes the assumptions, the priority results of economic competitiveness can be varied. In order to achieve this objective, this article shows the following contents. First of all, this study briefly introduces the concept of LCOE and financial model in background section. Second, this article explains the various input variables and assumptions in methodology section. Third, the results section analyzes the economic and financial competitiveness depending on various conditions. Then, this article summarizes the findings and suggests insights in discussion section. Last, the conclusion section expresses the value, limitation and future study of this study.

2. Background

2.1. LCOE Approach

The LCOE is a widespread indicator used to compare cost competitiveness and identify the grid parity among different energy generation technologies [14–18]. It presents the per-MWh cost of constructing and operating a generating plant over the assumed project life. The LCOE value usually is calculated as follows: total lifetime cost divided by total lifetime energy production [13]. It also is calculated by dividing the total capital investment's Net Present Value (NPV) by the discounted energy yield, which results in the average cost per energy unit [9,14,19]. If the NPV reaches zero, a break-even situation occurs, which is referred to as grid parity [15,18,20]. Many variable inputs also are considered in the LCOE's calculation, such as *OCC*, *F_OM*, *V_OM*, *CF*, *CRF*, *FC*, and *HR*. The formula below shows the way the LCOE is calculated with various input variables [6]:

$$\text{LCOE (\$/MWh)} = \frac{OCC \times CRF + F\_OM}{8760 \times CF} + FC \times HR + V\_OM \quad (1)$$

Typically, the *CRF* is referred to as the ratio of the constant annuity to the present value of receiving that annuity at a given time [21]. The *CRF* equation consists of the *IR* (i) and *OP* (n). The formula for the *CRF* is expressed below [6]:

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

LCOE has become a key indicator which is utilized worldwide to compare the unit cost of each other generation especially thanks to its easiness and simplicity. LCOE is still quite useful in that it shows the economic competitiveness of each energy generation in its simple way. However, despite its worldwide and traditional utilization, LCOE equation itself is not the perfect approach if it comes to the financial business perspective [12]. First, LCOE evaluates the economic strength based upon only the costs which are different from the general finance concept which should consider both the cost and the revenue side. Even though LCOE provides the minimum required tariff to recover the total costs, LCOE cannot reflect well that the *TGR* offsets the effect of the *IR*. Second, the same *IR* is usually applied for comparing the LCOE of each energy source [12]. However, the *IR*s can vary depending on the cash flow, *LP*, *D_ER* and guarantee agreement. Thrid, the traditional LCOE usually assumes that the *LP* is same as the lifecycle *OP*. The LCOE calculation measured under the discounting method should consider the real *LP*, though [22]. The LCOE formula in this paper does not take into consideration the real *LP*. In reality, the *LP* of NPP or coal projects is shorter than the whole lifecycle. As a result, such LCOE's simplicity leads to overlooking the actually complicated finance world. In reality, the more the projects are getting complicated, the more realistic input variables are to be used.

2.2. Various Approaches for Better Economic Competitiveness Evaluation

Two kinds of LCOE methods are most popular in energy economics [8]. The US Department of Energy's National Renewable Laboratory defines LOCE using Equation (1), which is called as "annualizing" method [8,22]. This method is simple and easy but assumes that the *LP* is same as the *OP*. On the other hand, the UK defines LCOE as "the discounted lifetime cost of ownership and use of a generation asset, which considers every year's different cost of every variable [23]. This approach is more complicated but can consider the differences between *LP* and *OP*. However, this one has to assume or calculate the discount rate, which sometimes evokes the subjective evaluation issues [24,25]. So, some researchers suggested several alternative metrics such as undiscounted cost of energy approach, discounted cost of energy approach and total cost of energy [8,26]. These tried to improve the weakness of the traditional LCOE approach but are not used much until now [8].

Many researchers mentioned the energy economic issues related to the *TGR* [14,22,27,28]. First, tariff growth variation has an effect on the economic value of grid parity. Both the LCOE and tariff have to be considered simultaneously [14,27,28]. Second, the economic value of electrical energy storage is affected by tariff growth variation. As the volatility of tariff growth increases, the value of electrical energy storage also increases [22]. Third, tariff growth has an influence on increasing the lower NPV of energy business, but the LCOE does not change and keeps the same value, which induces the policymaker or investor to make wrong decision [14]. However, they did not explain the value of *TGR* comparing the *IR* from the financial feasibility perspective.

The *LP* is an important issue to evaluate project feasibility in all investment industries [29–31]. Investors usually prefer the shorter *LP* rather than long one. So, short *LP*s request low-*IR*s, whereas long *LP*s induce high-*IR*s. This means that the reduction of *LP* has an effect on increasing profitability [11]. However, energy industry has not studied this area much even if each energy project has different cash flow structures, and requires different *LP*s and *IR*s.

When the LCOE is calculated, the value of many input variables is uncertain. Input variables such as *OCC*, *CP*, *F_OM*, *V_OM*, and *CF* are difficult to be determined by one value. So, many researchers prefer using probablistic approach rather than deterministic approach [5–7,9,25]. Particularly, Monte Carlo simulation is preferred to predict and compare the energy competitiveness with uncetain situations [5–7]. This study also uses Monte Carlo simulation to compare the value of LCOE, Project Internal Rate of Return (Project IRR), Equity Internal Rate of Return (Equity IRR), and Debt Service Coverage Ratio (DSCR).

2.3. Financial Model

The financial model adopts all possible necessary financial input variables, which make it more suitable for real businesses, as it considers not only the cost but the revenue as well. In addition, the financial model provides various financial indicators, including the Project IRR, Equity IRR, DSCR, and NPV, which explains the various attributes of a project's financial feasibility and economic competitiveness. IRR is the *IR* that makes an investment's NPV equal to zero. Thus, if the IRR is larger than the *IR*, NPV becomes greater than zero. In this sense, the Project IRR is the *IR* at which the NPV of the project cash flows equals zero, which also is referred to as Return on Investment (ROI). The Project IRR is calculated assuming that no debt is used for it [32], for example, that the annual cash flow for the Project IRR is calculated from the Cash Available for Debt Service (CAFDS), which is the amount of cash a project keeps within one year. This study analyzes Project IRR, as it is a type of yield rate expected from the project investment overall. In this sense, the Project IRR must be higher than *IR*, which is an important criterion for loan investors. Meanwhile, the Equity IRR is calculated by considering principal and interest, and also is referred to as the Return of Equity (ROE). Shareholders give more weight to Equity IRR rather than Project IRR because it is related directly to the shareholders' profit. Generally, Equity IRR is the leveraged version of Project IRR and the former will be lower than the Project IRR only when the cost of debt exceeds the Project IRR, which happens rarely [21]. In addition to the Project IRR and Equity IRR, DSCR is an important financial indicator from loan investors' perspective, because they must confirm that the borrowers can afford the amount of debt every time. This is calculated as the CAFDS divided by the debt service, which includes both the principal and interest. Lenders normally request that project owners maintain between 1.2 and 1.5 the value of DSCR at least [33]. This study analyzes and compares the Project and Equity IRR, and DSCR of each energy source to understand its economic and financial competitiveness depending on equity and loan investors. The energy mix preference can vary depending on these results.

3. Methodology

3.1. LCOE Variables

To compare the economic competitiveness between the LCOE and the financial model, we chose three representative energy sources: coal, wind, and nuclear. Coal and nuclear represent conventional energy while wind does renewable energy. Especially, these energy sources are chosen due to their distinctive characteristics in terms of the financial structure. Renewable energies such as wind, solar and biomass request lower capital cost, shorter *CP* and *LP*, but yields relatively low and voltaic cash flow. In contrast, nuclear energy requires very huge capital cost, long *CP* and *LP*, but yields high and stable cash flow. Coal energy positions between wind and nuclear from the financial structure perspective. These clear differences among three energy sources provide better comparison with the calculated financial results between the LCOE approach and the financial model.

The LCOE normally is calculated according to a basic formula (1) that uses the *OCC*, *F_OM* and *V_OM*, *CF*, *IR*, and *OP* as the primary input variables. The *FC* and *HR* variables are added to calculate the LCOE of coal and nuclear power, as they also are considerable input variables. The data for input variables in coal, wind, and nuclear plants are gathered from the journal [5] and this journal article used the data sources [34–38]. The data set is based upon the U.S. energy market and gathered from the operating power plants in all 50 states and one district in the U.S. The *OP* is needed to calculate the *CRF* in formula (2) and the *OP* of coal, wind, and nuclear facilities are assumed to be 30, 20, and 60 years, respectively. The *IR* also is included in the LCOE calculation as the discount rate [8]. This paper uses the term 'interest rate' henceforth to prevent any confusion because it also is used in the financial model.

The *IR* has a significant influence on the LCOE, and the rate varies depending on the country and energy source. High-income and upper-middle-income countries normally have lower *IR*s than do low and lower-middle-income countries because there is relatively less market volatility with respect both to economics and politics. Therefore, this study assumes three different *IR*s, i.e., 3%, 7%, and 10%. Normally between 3% and 10% *IR*s are widely in journal papers for comparison. Tran and Smith utilized 3% and 10% IRs in their journal paper as they are commonly used [6]. A 3% rate would be used by government-owned utilities with fine bond ratings. The 7% rate would be considered as the rate available to an investor with a low risk of default in a relatively stable market. The 10% rate can be considered as the investment cost facing substantially higher risks. [9] As a result, 3% rate represents a relatively stable market and less risky project among three rates, while 10% rate represents the most unstable market and risky project under volatile circumstances [9].

3.2. Financial Model Variables

This study develops the financial model to compare its economic competitiveness to the LCOE calculation by performing the financial feasibility analysis of each energy source: coal, wind, and nuclear. It is necessary to use as many and the most appropriate financial input variables as possible to derive more precise financial cash flow in the financial model. Tables 1–3 summarize the input variables used for coal, wind, and nuclear in the LCOE and financial model.

Table 1. Coal Input Variables.

Input Variables	Range	Distribution	Input Arguments	References
OCC ($/kW)	1584–8071	Log-normal	μ =8.182, σ = 0.407	[5,34,35,38]
F_OM ($/kW-year)	19.67–30.80	Normal	μ = 25.27, σ = 2.80	[5,34,35,38]
V_OM ($/MWh)	2.2–6.1	Normal	μ = 4.15, σ = 0.975	[5,34,35,38]
CF (%)	93.0	Constant	-	[5,34]
IR (%)	3.0, 7.0, 10.0	Uniform	Min. = 3, Max. = 10	[6,9]
OP (years)	30	Constant	-	Assumption
FC ($/MMBtu)	1.27–2.41	Normal	μ = 1.84, σ = 0.285	[5,34,36,37]
HR (Btu/kWh)	8755–12,005	Normal	μ = 10,380, σ = 812.5	[5,34–37]
TGR (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IF (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IT ($/MWh)	53.71 (48.83 × 110%) 67.94 (61.76 × 110%) 80.20 (72.81 × 110%)	Log-normal	In case of *IR* 3% In case of *IR* 7% In case of *IR* 10%	Based upon LCOE Calculation
LP (years)	30	Constant	-	Assumption
CP (years)	5	Discrete	Min. = 4, Max. = 6	Assumption
D_ER (%)	70.0–80.0	Uniform	Min. = 70, Max. = 80	[39]

#NOTE: Input variables in the highlighted are additionally applied in the financial model.

Table 2. Wind Input Variables.

Input Variables	Range	Distribution	Input Arguments	References
OCC ($/kW)	1270–2670	Normal	μ = 1,970, σ = 350	[5,34,35,38]
F_OM ($/kW-year)	12.00–60.00	Triangular	Min. = 12, Max. = 60	[5,34,35,38]
V_OM ($/MWh)	5.86–21.50	Log-normal	μ = 2.418, σ = 0.325	[5,34,38]
CF (%)	22.75–50.75	Normal	μ = 36.75, σ = 7	[5,34,38]
IR (%)	3.0, 7.0, 10.0	Uniform	Min. = 3, Max. = 10	[6,9]
OP (years)	20	Constant	-	Assumption
TGR (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IF (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IT ($/MWh)	70.20 (63.82 x 110%) 88.52 (80.47 × 110%) 103.94 (94.49 × 110%)	Log-normal	In case of *IR* 3% In case of *IR* 7% In case of *IR* 10%	Based upon LCOE Calculation
LP (years)	20	Constant	-	Assumption
CP (years)	1	Discrete	Min. = 0.8, Max. = 1.5	Assumption
D_ER (%)	70.0–80.0	Uniform	Min. = 70, Max. = 80	[39]

#NOTE: Input variables in the highlighted are additionally applied in the financial model.

Table 3. Nuclear Input Variables.

Input Variables	Range	Distribution	Input Arguments	References
OCC ($/kW)	4146–8691	Log-normal	μ = 8.7, σ = 0.185	[5,34,35,38]
F_OM ($/kW-year)	54.19–121.19	Normal	μ = 87.69, σ = 16.75	[5,34,35,38]
V_OM ($/MWh)	0.42–2.14	Triangular	Min. = 0.42, Max. = 2.14	[5,35,38]
CF (%)	85.0–95.0	Normal	μ = 87.5, σ = 1.25	[5,34,38]
IR (%)	3.0, 7.0, 10.0	Uniform	Min. = 3, Max. = 10	[6,9]
OP (years)	60	Constant	-	Assumption
FC ($/MMBtu)	0.65	Constant	-	[5,34]
HR (Btu/kWh)	10,420–10,480	Normal	μ = 10,450 & σ = 15	[5,34,36]
TGR (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IF (%)	0.0, 3.0	Uniform	Min. = 0, Max. = 5	Assumption
IT ($/MWh)	52.66 (47.87 × 110%) 82.84 (75.31 × 110%) 107.97 (98.15 × 110%)	Normal Log-normal Log-normal	In case of *IR* 3% In case of *IR* 7% In case of *IR* 10%	Based upon LCOE Calculation
LP (years)	60	Constant	-	Assumption
CP (years)	7	Discrete	Min. = 5, Max. = 15	Assumption
D_ER (%)	70.0 - 80.0	Uniform	Min. = 70, Max. = 80	[39]

#NOTE: Input variables in the highlighted are additionally applied in the financial model.

The financial model uses more varied input variables than does the LCOE calculation while most of them are derived from previous papers and sources as in the LCOE calculation. In fact, the *OCC*, *F_OM* and *V_OM*, *CF*, *IR*, *OP*, *FC*, and *HR* also are used in the same way as in the LCOE calculation. On the other hand, *D_ER*, *CP*, *LP*, *IT*, *TGR*, and *IF* are new variables used only in the financial model. These additional variables are used rarely in the traditional LCOE calculation, and thus, they make the financial model's outcome more practical and suitable in the real business environment.

The *IR* also has a significant influence on the financial results, as it does in the LCOE calculation. As mentioned in the previous section, *IR* is assumed at 3%, 7%, and 10% respectively to show each influence on the results. In the case of distribution and tornado diagrams, the graph results are shown based upon the 7% rate representatively, which is the in-between value of 3% and 10%. The *LP* and *TGR*, which are used exclusively in the financial model, are also used differently depending on each situation. For example, the *LP* will be used differently to find its effect on the financial model, while *TGR* and *IF* will be used to assess revenue's effect. As mentioned previously, these two input variables make the financial model distinctive and more practical. The *LP* is based primarily upon the *OP* and can be shortened depending on the given circumstances. The *TGR* plays a strong role in the revenue side, while the *IR* does so on the cost side. The financial model's consideration of the tariff is one of its important features. The *TGR* normally is lower than the *IR*. Therefore, this paper assumes different *TGR*s that are lower than *IR*s to find their large influence on the financial indicators' results. 0% and 3% *TGRs* are assumed, respectively, to identify its drastic effect on the financial values. This paper equates the *IF* and *TGR* because both are typically coupled, although the *IF* actually is a different concept from the *TGR*. It is normal for economically stable countries to have lower economic growth rates, including *TGR*, *IF*, and *IR*. This paper also assumes that the *IT* is proportional to the LCOE's simulated distribution. For instance, the median LCOE values at 7% *IR* are 61.76$/MWh for coal, 80.47$/MWh for wind, and 75.31$/MWh for nuclear, respectively which will be analyzed in the LCOE calculation. LOCE can be understood as the minimum electricity price or tariff represented in $/MWh. Since the LCOE is the cost concept, the electricity price or tariff, which is the revenue concept, should be larger than the LCOE to yield profit. In this sense, this paper uses the *IT* price with each LCOE value with 10% profit margin, so each 110% of LCOE values calculated is used for coal, wind, and nuclear power. For this reason, the price of each energy source starts differently although it does not make sense in open electricity market. However, this study uses this assumption for explaining the effect of *LP* and *TGR* depending on the attributes of each energy source. The *D_ER* is assumed to range from 70 to 80 percent with uniform distribution similar to actual financing projects [39].

3.3. Financial Sensitivity Analysis

Financial sensitivity analysis evaluates financial input variables' effect on the financial indicators' resulting values when other conditions remain constant. To improve financial viability and feasibility, more sensitive input variables are considered in the financial analysis. This analysis helps prioritize and manage the financial factors that affect a project's financial success. Monte Carlo simulation is the tool used most widely and is based on random generation and a probabilistic distribution. Spinney and Watkins proposed using Monte Carlo simulation techniques to analyze energy resource decisions and evaluate each decision's advantages and disadvantages [6,40]. This kind of simulation also is a relatively simple and established technique to account for uncertainty in quantitative models [5]. All financial input variables except for those that are held constant are included in the financial sensitivity analysis.

This study uses the @risk commercial tool that provides the Monte Carlo Simulation, and tornado and spider diagrams [6]. The study uses the tornado diagrams to show each input variable's degree of sensitivity. This is represented with a coefficient value, and the most sensitive variable is located at the top of the Y-axis. A tornado graph from a sensitivity analysis displays a ranking of the input distributions that affect output. Inputs that influence the output's distribution most have the highest bars in the graph. A tornado graph also shows the change in the output statistic's value overall. The financial sensitivity analysis shows which financial feasibility factors to prioritize by determining how much they affect the financial indicators' values. Different investors have different financial concerns that various input variables represent in the financial model. Based on the results of the financial sensitivity analysis, they can determine their priorities of which factor they must consider the most.

4. Results

4.1. Interest Rate Effect

It is simple to compare energy sources' cost competitiveness using the LCOE calculation. The probabilistic distribution graphs in Figure 1 show each LCOE value of coal, wind, and nuclear power at 3%, 7%, and 10% *IR*s.

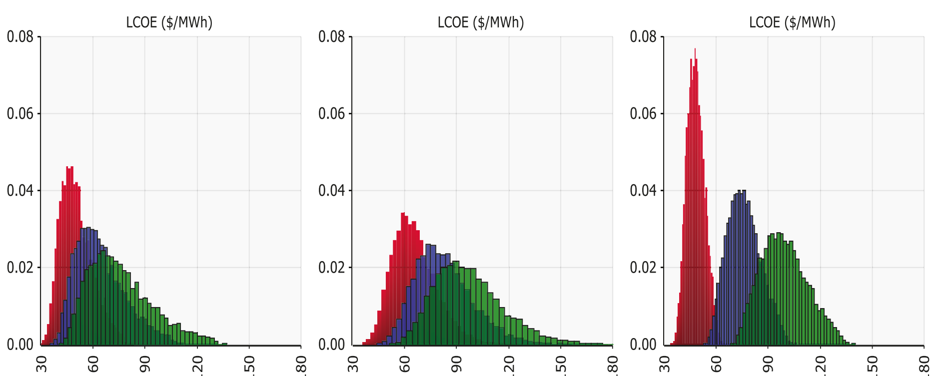

Figure 1. LCOE distributions of Coal (**left**), Wind (**middle**), and Nuclear (**right**) at 3%, 7% and 10% IR.

Red represents the LCOE distributions at the 3% *IR*, blue represents it at the 7% rate, and green does at the 10% rate. It is clear that the LCOE values with the 3% *IR* are the smallest, as they are located on the left side in each graph. When the three energy sources are compared, coal appears to be the most competitive in overall, in that the graphs generally are skewed to the left compared to those in the wind and nuclear. In fact, the LCOE value of coal at 7% *IR* is the lowest, with 61.76$/MWh median LCOE value. As for 3% *IR*, coal also has high-cost competitiveness along with nuclear power although it ranks the 2nd by little gap. This low cost encourages energy project investors to develop independent power plant projects in low and middle-income countries. On the other hand, it is complicated to compare the LOCE between wind and nuclear; the LCOE values of nuclear at the 3% and 7% *IR* are more competitive than those of wind under the same condition. In contrast, with the 10% *IR*, the LCOE median value for wind is slightly smaller than that of nuclear, although the distribution's width is wider in the case of wind. The distribution's width indicates uncertainty, and therefore, it can be concluded that wind is the most volatile energy generation source in this sense. Nuclear power is the most stable source among the three, as its narrow distribution shows. As a result, competitiveness with respect to the LCOE value differs depending on the *IR*. In particular, that of nuclear power increases drastically when the *IR* goes up from 3% to 10%. Table 4 summarizes each energy source's median LCOE values at 3%, 7% and 10% *IR*s.

Table 4. Median LCOE values of Coal, Wind, and Nuclear at 3%, 7% and 10% *IR*.

Rank	3% *IR*		7% *IR*		10% *IR*	
1	Nuclear	47.87$/MWh	Coal	61.76$/MWh	Coal	72.91$/MWh
2	Coal	48.83$/MWh	Nuclear	75.31$/MWh	Wind	94.49$/MWh
3	Wind	63.82$/MWh	Wind	80.47$/MWh	Nuclear	98.15$/MWh

Nuclear power is the most competitive energy source at 3% *IR* with its lowest median LCOE value among three technologies. However, nuclear power's LCOE value has increased so much that it becomes the least competitive one with respect to the LCOE at the 10% *IR*. In general, the NPP projects require an enormous *OCC* compared to other power plants. Further, the long *CP* induces even more financial cost, and the *IR* affects high-intensity *OCC* greatly. In this sense, nuclear power's LCOE value at 3% *IR* seems plausible. However, 7% and 10% IR affect the huge capital even further, which leads to less competitive LCOE values. It is common for low and lower-middle-income countries to have relatively high *IR*s. It is clearly shown in Figure 1 that relatively bigger gap exists among the colored graphs in the distribution of the nuclear which means a drastic increase of LCOE as *IR* goes up. Under these circumstances, NPP projects cannot be economically competitive without other countries' financial support. This is a weakness of the LCOE calculation attributable to its simplicity.

With respect to wind power, the relatively higher LCOE value is attributable primarily to its low *CF*. Renewable energy sources inevitably have a relatively less attractive *CF* compared to conventional power sources, including coal and nuclear. This is the weakest point in renewable energy at present that limits the locations that provide it. Combined with the low *CF*, high *V_OM* is one of the reasons that they have a high LCOE value. It gets worse if the *IR* goes up from 3% to 10%. As a result, *IR* plays an important role in calculating the LCOE value. The higher the *IR* is, the worse the LCOE value becomes depending on each energy sources' own characteristics.

The *IR* has a strong effect on the financial outcome, not only in the LCOE calculation but also in the financial model. The financial model explains *IR*'s influence better than the LCOE approach does. For example, interest accrues during both the *CP* and *LP*, and the former one is frequently prolonged. The *LP* often is equated with the *OP*. Table 5 shows the comparison of the total interests both during the *CP* and *LP* per each energy source's *OCC*.

Table 5. Interests incurred during *CP* and *LP* for Coal, Wind, and Nuclear.

Category	*IR*	Coal	Wind	Nuclear
(a) Interests during *CP*	3%	$148,972,648	-	$608,699,932
	7%	$358,902,236	-	$1,499,114,109
	10%	$525,160,182	-	$2,230,836,458
(b) Interests during *LP*	3%	$1,349,353,799	$54,263,910	$8,157,248,404
	7%	$3,843,264,845	$139,926,502	$25,196,153,620
	10%	$6,206,961,123	$212,632,737	$41,572,681,388
(c) Total Interests (a) + (b)	3%	$1,498,326,447	$54,263,910	$8,765,948,336
	7%	$4,202,167,081	$139,926,502	$26,695,267,729
	10%	$6,732,121,305	$212,632,737	$43,803,517,846
(d) *OCC*	-	$3,030,000,000	$197,000,000	$8,121,400,000
(e) Total Interests per *OCC* (c) / (d)	3%	49.45%	27.55%	107.94%
	7%	138.69%	71.03%	328.70%
	10%	222.18%	107.94%	539.36%

Because wind facility construction requires 1-year, no interest is incurred and the interest accrued during the *LP* also is relatively small with its small *OCC* compared to other energy sources. On the other hand, the *IR* has serious effects on NPP projects' cost especially as it increases to 10%, largely because of their high *OCC* and long *CP*. This result is quite similar to that in the LCOE calculation. However, in the real energy business, most countries that construct NPP plants have a budget with an approximately 5% rate. This interest can be reduced by shortening the *LP*, which will be addressed in the next section.

4.2. Loan Period Effect

The traditional LCOE calculation does not distinguish the *LP* from the *OP* [21]. However, in reality, some projects with reasonable cash flow can afford to pay back the debt earlier than the estimated *OP*. Because the debt amount is proportional to the *IR* and *LP*, it is much better to repay the loan as soon as possible if the project cash flow can afford it. From this perspective, the minimum DSCR (MDSCR) is used to assess the worst time to repay with respect to cash flow. The MDSCR always must be larger than 1.0×; otherwise, the project cannot afford the debt at that time. On the other hand, the Average DSCR (ADSCR) calculates the project owners' ability to repay the loan overall. The project developer or borrower must maintain a minimum degree of DSCR to show that they have no financial problems during the *LP*. Project financing usually requires a 1.2×~1.5× ADSCR depending on the project and the situation's characteristics. As mentioned previously, this paper assumes that the *IT* price of coal, wind, and nuclear power starts at 110% of the LCOE of each energy source. Thus, the *IT* price is different from the value of the real energy market.

ADSCR values for each energy source during the original *LP* are at least over 1.2×, which indicates that it is possible for them to shorten the *LP*. For instance, in case of the 7% *IR*, the coal has the highest ADSCR value, 1.551×, followed by wind with 1.457× and nuclear power with 1.240×. Among various factors which affect the amount of debt service, the *LP* can be adjusted by distinguishing it from the *OP*. ADSCR values also can be optimized with such shortened *LP* by meeting the minimum ADSCR criterion. The shortest possible *LP* is shown in Table 6 with adjusted ADSCR values which still remain above 1.2×. Adjusted ADSCR values are 1.220× for coal with 17 years, 1.203× for wind with 14 years, and 1.201× for nuclear power with 45 years. ADSCR and MDSCR have no differences in value as no *TGR* is applied. Nuclear power's *LP* is shortened the most, in that its ability to repay the debt originally was originally divided by the *OP*, which is the longest among the three sources. In other words, nuclear power's decent cash flow affords the earlier repayment of the debt service. In addition, Figure 2 shows that nuclear power's distribution has the narrowest range, which indicates that it has the lowest possible volatility. This implies that nuclear power is likely to shorten *LP* the most with satisfying the minimum ADSCR. In Figure 2, red graphs mean ADSCR values during the adjusted *LP* while blue ones mean during *OP*. The delimiter is fixed at 1.2 ADSCR which means that the percentage on the right side is the possibility of ADSCR over 1.2×. For example, the likelihood of having over 1.2× ADSCR value during the shortest possible *LP* for wind is 57.5%. Since the ADSCR value becomes lower close to 1.2× during the adjusted *LP*, the probability over 1.2× naturally gets lower accordingly.

Table 6. ADSCR values of Coal, Wind, and Nuclear during original and adjusted *LPs*.

LP	*IR*	Indicator	Coal	Wind	Nuclear
LP as Same as *OP* - Coal: 30 years - Wind: 20years - Nuclear: 60 years	3%	ADSCR	1.718×	1.490×	1.409×
	7%	ADSCR	1.551×	1.457×	1.240×
	10%	ADSCR	1.454×	1.439×	1.142×
Shortest possible (Adjusted) *LP*	3%	ADSCR	1.206×	1.258×	1.207×
		LP	18 years	16 years	42 years
	7%	ADSCR	1.220×	1.203×	1.201×
		LP	17 years	14 years	45 years
	10%	ADSCR	1.207×	1.201×	1.142×
		LP	16 years	13 years	60 years

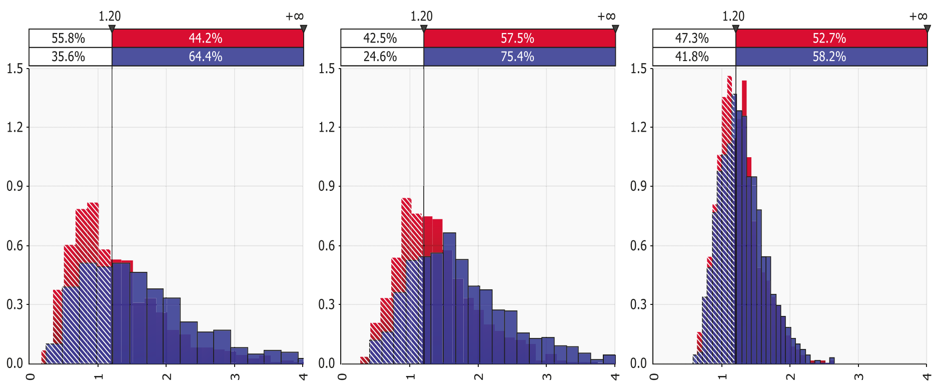

Figure 2. ADSCR distributions of Coal, Wind, and Nuclear during original and adjusted *LP*s at 7% *IR*.

The reduced *LP*s of each energy source has an influence on the value of the Equity IRR. Shortening the *LP* naturally reduces the amount of the debt service, which includes the interest and principal. To validate the extent to which it affects each energy source, Figure 3 shows the variations in Equity IRR between the original and shortened LPs.

For instance, the Equity IRR values during the original LP for each energy source are 12.58% for coal, 15.62% for wind, and 4.25% for nuclear at 7% *IR*. Relatively a large gap exists among energy sources because Equity IRR involves both the debt and interest concepts. Wind power has the highest Equity IRR value for all *IR* cases, in that its debt service is the smallest because of its small *OCC* and short *OP*. In contrast, nuclear generation, with its huge *OCC* and long *OP*, has the lowest value. As the *LP* gets shorter different from the *OP*, each Equity IRR changes, respectively.

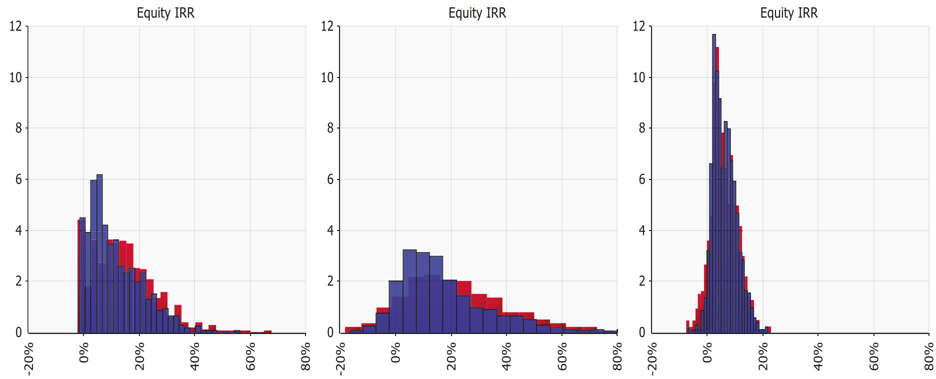

Figure 3. Equity IRR distributions of Coal, Wind, and Nuclear for original and adjusted LPs at 7% *IR*.

The *LP*s are shortened the most with satisfying the minimum ADSCR, 1.2×. With respect to the distribution shown in Figure 3, the blue graphs show that Equity IRRs with the *OP*, while the red graphs indicate Equity IRRs with the shortest possible *LP*. The graphs show that nuclear power has the narrowest distribution, while wind has the widest. Because the range is related strongly to uncertainty, nuclear power has the lowest possible uncertainty with respect to Equity IRR. Thus, regardless of these relatively low values, it has the lowest uncertainty. In contrast, wind generation has enormous potential volatility, even though its values are somewhat high. Further, the adjusted values are 11.11% Equity IRR with 17 years of *LP* for coal, 12.81% with 14 years for wind, and 5.82% with 45 years for nuclear. Nuclear power's Equity IRR has increased, while that of coal and wind has decreased. This result means that Equity IRRs for coal and wind are better when the *LP* is the same as the *OP*. With the shortened *LP*, the annual payment of debt service increases compared to that of the *OP*. This is natural so that the debt is repaid quickly by paying more annual debt service, as the project can afford to do so by satisfying the minimum ADSCR, 1.2×. In case of coal and wind, repaying the debt service during the whole *OP* ironically becomes more profitable with respect to Equity IRR. This is mainly because they have relatively short *OP*s that last only up to around half of nuclear power and the annual operation profit per *OCC* also is relatively high. As a result, the optimal *LP* to yield the most profitable Equity IRR is 27 years for coal, which is a decrease of only 3 years from the *OP* and 20 years for wind, which remains the same as the *OP*.

With respect to the Project IRR, energy sources in most cases have at least the same or higher *IR* than each assumed *IR*. Normally, *CP* has an enormous influence on Project IRR values. For example, NPPs, with the longest *CP* (7 years) induce more interest and yield a late operation revenue after the construction competition. Even the *IF* is applied to the *OCC* during the *CP* which leads to a drastic increase in cost. This is why nuclear power has the lowest Project IRR value among three generations. From this perspective, if three energy sources had the same *CP* with 1 year, for instance, coal would be the first, with the highest Project IRR, as it has the highest operating profit per *OCC*. In reality, wind power has the best Project IRR, in that it requires only 1 year *CP*, while coal requires 5 years. Because the Project IRR itself does not consider the debt concept, it does not change in value even if the *LP* is shortened. Therefore, the *LP* effect occurs with the Equity IRR. Table 7 summarizes the IRR values for different *LP*s at each 3%, 7%, and 10% *IR*s.

Table 7. IRR values of Coal, Wind, and Nuclear for original, adjusted, and optimal *LP*.

Equity IRR	*IR*	Indicator	Coal	Wind	Nuclear
LP as Same as *OP* - Coal: 30 years - Wind: 20years - Nuclear: 60 years	3%	Equity IRR Project IRR	11.21% 5.17%	11.73% 4.98%	4.41% 3.43%
	7%	Equity IRR Project IRR	12.58% 8.62%	15.62% 9.06%	4.25% 6.69%
	10%	Equity IRR Project IRR	12.94% 11.11%	18.24% 12.16%	3.49% 8.87%
Shortest possible (Adjusted) *LP*	3%	Equity IRR Project IRR *LP*	8.25% 5.17% 18 years	9.10% 4.98% 16 years	4.21% 3.43% 42 years
	7%	Equity IRR Project IRR *LP*	11.11% 8.62% 17 years	12.81% 9.06% 14 years	5.82% 6.69% 45 years
	10%	Equity IRR Project IRR *LP*	12.85% 11.11% 16 years	16.01% 12.16% 13 years	3.49% 8.87% 60 years
Optimal *LP*	3%	Equity IRR Project IRR *LP*	11.21% 5.17% 30 years	11.73% 4.98% 20 years	4.58% 3.43% 54 years
	7%	Equity IRR Project IRR *LP*	12.78% 8.62% 27 years	15.62% 9.06% 20 years	5.82% 6.69% 45 years
	10%	Equity IRR Project IRR *LP*	13.80% 11.11% 24 years	18.65% 12.16% 18 years	3.49% 8.87% 60 years

With respect to the Project IRR, energy sources in most cases have at least the same or higher *IR* than each assumed *IR*. Normally, *CP* has an enormous influence on Project IRR values. For example, NPPs, with the longest *CP* (7 years) induce more interest and yield a late operation revenue after the construction competition. Even the *IF* is applied to the *OCC* during the *CP* which leads to a drastic increase in cost. This is why nuclear power has the lowest Project IRR value among three generations. From this perspective, if three energy sources had the same *CP* with 1 year, for instance, coal would be the first, with the highest Project IRR, as it has the highest operating profit per *OCC*. In reality, wind power has the best Project IRR, in that it requires only 1 year *CP*, while coal requires 5 years. Because the Project IRR itself does not consider the debt concept, it does not change in value even if the *LP* is shortened. Therefore, the *LP* effect occurs with the Equity IRR. Table 7 summarizes the IRR values for different *LP*s at each 3%, 7%, and 10% *IR*s.

The actual *LP* can have an enormous effect on the Equity IRRs, and the optimal *LP* is that most suitable to achieve the most profitable Equity IRR. Even though the optimal *LP*s are longer than the shortest possible periods for coal and wind power in this paper, shortening the *LP* itself has a huge advantage in the real world, in that it also can decrease loan investors' investment risk. Thus, loan investors can require more attractive *IR* if the *LP* is reduced. In this sense, the *IR* naturally goes down with the shortened *LP*s. As a result, the optimal *LP* would be the same as the shortest possible period in a real world by satisfying the minimum criterion, 1.2× ADSCR.

4.3. Tariff Growth Rate Effect

The *TGR* usually has an effect on the revenue side. The revenue itself will increase drastically under the circumstances with longer *OP*. From this perspective, nuclear generation, with a 60 year *OP*, can take advantage of the *TGR* effect. However, the rate usually accompanies the *IF* and the operation cost increase annually with the *IF*. Therefore, the *TGR* effect when operating profit is calculated as operation revenue minus operation cost, becomes offset. Nevertheless, considering the tariff concept itself is very useful and necessary in project finance. The assumptions in the previous section is based upon a 0% *TGR*, which means that the *TGR* effect is not considered. This section compares a 0% and 3% constant *TGR* with each energy source's optimal *LP*. This can clearly show the way the *TGR* influences the financial model's financial results.

In Figures 4 and 5, the red graphs indicate that the *TGR* is not considered while the blue graphs consider a 3% rate. It is shown that both Equity and Project IRR values increased as *TGR* is applied. The *TGR* is adapted to the tariff every year which leads to an enormous increase of revenue during the whole lifetime. This makes the improved IRR values with a decent cash flow. As a result, the consideration of *TGR* improves financial feasibility. The *TGR* effect also covers the weakness of the LCOE calculation. As mentioned in Section 4.1, the LCOE value is highly dependent on the *IR*. The financial feasibility gets worse if the *IR* increases especially under the circumstances with the enormous *OCC* and a long *CP*. This negative change in LCOE value can be mitigated by the *TGR* effect. *IR* is closely related to the *TGR* in that both of the rates move coupled. In other words, high *IR* market also provides a high *TGR*. Thus, the annual increase of the revenue with the *TGR* reduces the IR effect. This is one of the strong points for the financial model to consider the revenue.

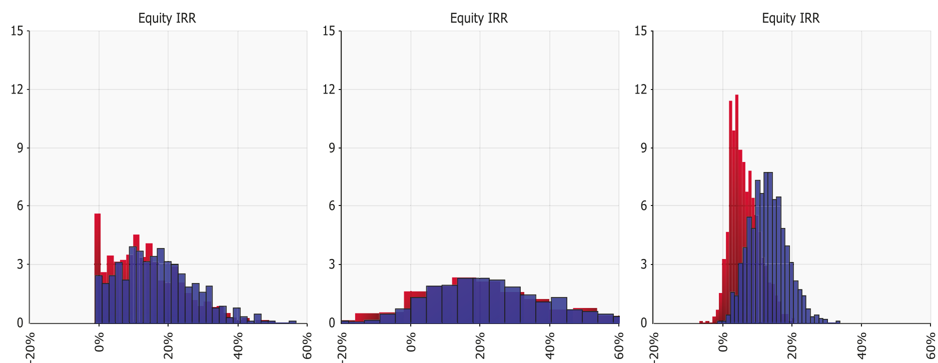

Figure 4. Equity IRR distributions of Coal, Wind, and Nuclear under 0% and 3% *TGR*.

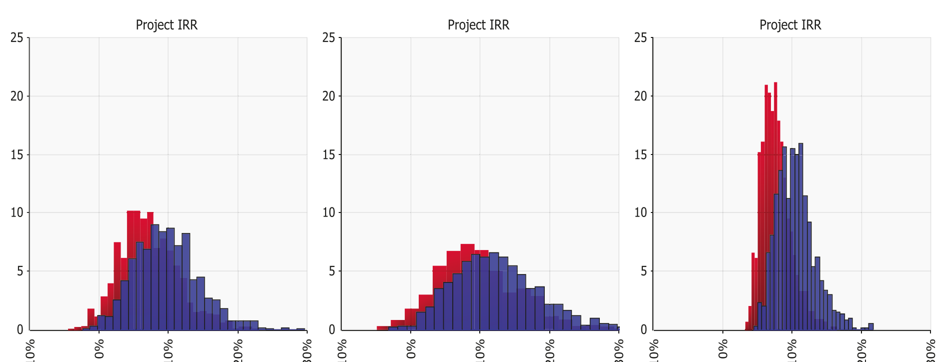

Figure 5. Project IRR distributions of Coal, Wind, and Nuclear with 0% and 3% *TGR*.

In addition, increasing the *TGR* affects both the Project and Equity IRR, while the *LP* effect influences only the Equity IRR. When comparing the influence on each power source, Project IRR increases quite proportionally for three sources. Equity IRR differs somewhat because it involves debt service. An increased *TGR* increases the revenue side, which leads ultimately to the rapid debt repayment. In this way, the Equity IRR can improve greatly if the *TGR* is considered. Increased IRRs improve the project's cash flow and even the DSCR values with respect to Equity IRR. Table 8 summarizes the *TGR* effect with regard to the IRR and DSCR values. The data are based upon each optimal *LP* in Table 7 for each IRs.

Table 8. IRR and DSCR values of Coal, Wind, and Nuclear with 0% and 3% *TGR*.

TGR	*IR*	Indicator	Coal	Wind	Nuclear
Not consider (0%)	3%	Equity IRR	11.21%	11.73%	4.58%
		Project IRR	5.17%	4.98%	3.43%
		ADSCR	1.718×	1.490×	1.353×
	7%	Equity IRR	12.78%	15.62%	5.82%
		Project IRR	8.62%	9.06%	6.69%
		ADSCR	1.498×	1.457×	1.201×
	10%	Equity IRR	13.80%	18.65%	3.49%
		Project IRR	11.11%	12.16%	8.87%
		ADSCR	1.386×	1.386×	1.142×
3%	3%	Equity IRR	17.80%	20.05%	11.42%
		Project IRR	8.33%	8.13%	6.53%
		ADSCR	2.979×	2.062×	3.703×
		MDSCR	1.878×	1.535×	1.525×
	7%	Equity IRR	20.60%	25.11%	14.22%
		Project IRR	11.88%	12.34%	9.89%
		ADSCR	2.474×	2.017×	2.799×
		MDSCR	1.641×	1.501×	1.358×
	10%	Equity IRR	22.35%	28.47%	15.35%
		Project IRR	14.44%	15.53%	12.14%
		ADSCR	2.180×	1.858×	3.520×
		MDSCR	1.520×	1.428×	1.295×

As *TGR* is applied, ADSCR is no longer the same as MDSCR. Overall, DSCR values are improved and it is quite remarkable in case of nuclear power. This is mainly due to its long *OP* which lasts up to 60 years. The *TGR* has an effect during the whole *OP* which yields a constant increase in the revenue. Thus, the improved revenue or net income naturally leads to better DSCR values with decent CAFDS. Moreover, these enhanced DSCR values can shorten the *LP* again, as was the case with the *LP* effect, which eventually yields better Equity IRR values. Similarly, considering the *TGR* offers a more attractive and profitable yield rate for all energy sources, particularly for those that operate for a long while with high debt service, such as nuclear power.

4.4. Financial Sensitivity Effect

A financial feasibility analysis evaluates the financial results based on input variables. It treats various input variables according to their distribution and shows the way they react sensitively to the financial results. The input variables for sensitivity effect in the LCOE calculation are *OCC*, *F_OM* and *V_OM*, and *CF*. *HR* and *FC* also are added for coal and nuclear generation. Constant variables are not included in the sensitivity analysis. This study assumes that the *CF* is a constant 93% in coal, and *FC* is a constant 0.65$/MMBtu in nuclear. The *CF* in coal and *FC* in nuclear are quite stable, so that their sensitivity to the LCOE value is relatively quite low. The tornado diagrams in this section are shown with the 7% *IR* with the uniform distribution of minimum 3% and maximum 10%. The full analysis with each 3%, 7%, and 10% *IR* are provided in Table 9 in the Discussion section. As for variables in the LCOE, the financial sensitivity analysis yields relatively simple tornado diagrams as the LCOE calculation formula itself is simple and includes fewer input variables. The tornado diagrams in Figure 6 represent the degree of sensitivity of the coal, wind, and nuclear input variables on each LCOE values.

Table 9. Summary of the results of the LCOE approach and financial model analysis.

Approach	Indicator	Conditions		Coal	Wind	Nuclear
LCOE Approach	LCOE ($/MWh)		(a) *IR* = 3%	(2) 48.83	(3) 63.82	(1) 47.87
			(b) *IR* = 7%	(1) 61.76	(3) 80.47	(2) 75.31
			(c) *IR* = 10%	(1) 72.91	(2) 94.49	(3) 98.15
			(d) = (c-a) / (c)	(3) 33.03%	(2) 32.46%	(1) 51.23%
		Financial Sensitivity Tables 1–3 (excluding highlighted)		(1) *OCC* (2) *IR* (3) *FC*	(1) *CF* (2) *OCC* (3) *IR*	(1) *IR* (2) *OCC* (3) *F_OM*
Financial Model	Equity IRR	*IR* = 3%	(e) Original *LP*	(2) 11.21%	(1) 11.73%	(3) 4.41%
			(f) Optimal *LP*	(2) 11.21%	(1) 11.73%	(3) 4.58%
			(g) = (f-e)/(f)	(2) 0%	(2) 0%	(1) 3.71%
		IR = 7%	(h) Original *LP*	(2) 12.58%	(1) 15.62%	(3) 4.25%
			(i) Optimal *LP*	(2) 12.78%	(1) 15.62%	(3) 5.82%
			(j) = (i-h)/(i)	(2) 1.56%	(3) 0%	(1) 26.98%
		IR = 10%	(k) Original *LP*	(2) 12.94%	(1) 18.24%	(3) 3.49%
			(l) Optimal *LP*	(2) 13.80%	(1) 18.65%	(3) 3.49%
			(m) = (l-k)/(l)	(1) 6.23%	(2) 2.14%	(3) 0%
		Financial Sensitivity Tables 1–3 (including highlighted)		(1) *OCC* (2) *IT* (3) *IR*	(1) *IT* (2) *CF* (3) *OCC*	(1) *TGR* (2) *OCC* (3) *IT*
	Project IRR	*IR* = 3%	(n) *TGR* = 0%	(1) 5.17%	(2) 4.98%	(3) 3.43%
			(o) *TGR* = 3%	(1) 8.33%	(2) 8.13%	(3) 6.53%
			(p) = (o-n)/(o)	(3) 37.94%	(2) 38.75%	(1) 47.47%
		IR = 7%	(q) *TGR* = 0%	(2) 8.62%	(1) 9.06%	(3) 6.69%
			(r) *TGR* = 3%	(2) 11.88%	(1) 12.34%	(3) 9.89%
			(s) = (r-q)/(r)	(2) 27.44%	(3) 26.58%	(1) 32.36%
		IR = 10%	(t) *TGR* = 0%	(2) 11.11%	(1) 12.16%	(1) 8.87%
			(u) *TGR* = 3%	(2) 14.44%	(2) 15.53%	(3) 12.14%
			(v) = (u-t)/(u)	(2) 23.06%	(3) 21.70%	(1) 26.94%
		Financial Sensitivity Tables 1–3 (including highlighted)		(1) *IT* (2) *OCC* (3) *TGR*	(1) *IT* (2) *CF* (3) *OCC*	(1) *TGR* (2) *CP* (3) *IT*

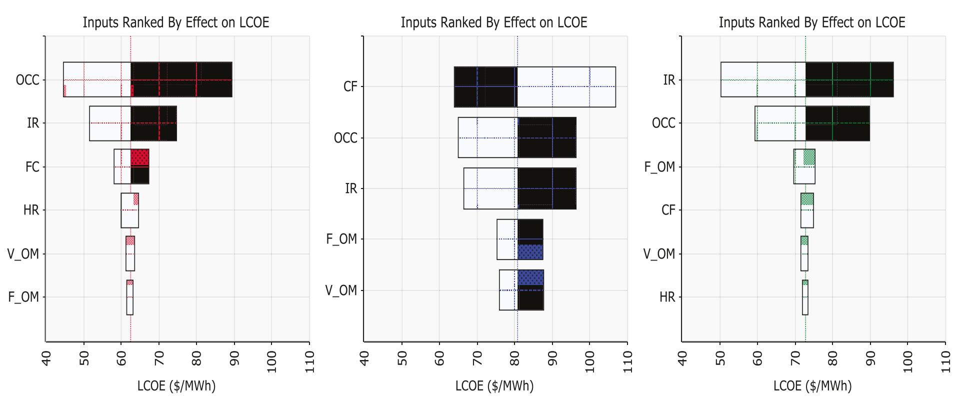

Figure 6. LCOE tornado diagrams of Coal, Wind, and Nuclear.

From the left, the red diagrams refer to coal, the blue to the wind, and the green to nuclear. The diagrams show that the ranking of each power generation source differs depending on its distinctive characteristics. *OCC* is one of the most critical input factors for all energy sources. It is the most sensitive input variable for coal and rank 2nd for wind and nuclear power because its ratio is relatively high. On the other hand, *CF* is the most sensitive input variable for wind generation, followed by *OCC*. In fact, the climate and natural conditions affect renewable energy sources, including wind power, quite strongly. Therefore, their *CF* is significantly lower than that of conventional power sources and their volatility increases naturally. The *CF* has an even greater influence than does the *OCC* in wind power. On the other hand, it is not such a sensitive input variable for nuclear because its *CF* is quite stable and high and is assumed constant even in coal power. Nuclear power's *IR* becomes the most sensitive input variable, also followed by *OCC*. This is quite reasonable, in that *IR* plays an important role in the projects with high *OCC* and long *OP* which is closely related to the cost side. In this sense, *IR* ranks 1^{st} in nuclear, 2^{nd} in coal, and 3^{rd} in wind source in order by *OCC* and *OP*. Also high *OCC* usually is one of the critical factors in NPP projects. Because these are quite complicated projects that involve various kinds of new technologies, they always have a huge amount and high proportion of *OCC* compared to other projects. In this sense, *F_OM* costs also compose a relatively high proportion of the cost of nuclear power, as nuclear generation technology itself is first-of-its-kind engineering that requires periodic maintenance. Therefore, except for *IR* which is decided by the owner's side, to manage the *OCC* and *F_OM* cost within a limited budget is a very important task for NPP projects. With respect to coal power, the *OCC* remains the most sensitive input variable and *IR*'s sensitivity also is high.

To determine any differences between the LCOE calculation and the financial model approach with respect to each input variable's degree of sensitivity, the financial sensitivity analysis is based largely upon the same situation as the LCOE calculation. The tornado diagrams for the financial model are shown at *TGR* 3% with a uniform distribution of minimum 0% and maximum 5%. Full analysis with 0% and 3% *TGR* are provided in Table 9 in the *5. Discussion* section and *IR* remains the same as utilized in the financial sensitivity for LCOE. The *IT*, *CP*, and *D_ER* are added in the financial model. This paper uses Equity IRR and Project IRR as financial indicators, which are the most representative, as they show the project's projected total yield rates during the total lifetime from the perspective of equity investors and project developers, respectively. The financial model's consideration of various financial indicators, such as Equity and Project IRR, is one of its strongest points. Further, it considers various stakeholders related to the project, while the LCOE calculation considers only the project developer.

In this sense, the Project IRR can be compared directly to the LCOE, as both consider the project developers' perspectives. The degree of sensitivity of input variables in Equity IRR is relevant particularly to equity investors. Therefore, the differences between the degree of sensitivity in Project IRR and Equity IRR eventually indicate the way different input variables should be considered depending on the stakeholders. The tornado diagrams in Figures 7 and 8 show each degree of sensitivity in the Equity and Project IRR of coal, wind, and nuclear power.

From the left, the red diagrams indicate coal, the blue wind, and the green nuclear, as in the LCOE calculation. Because the financial model considers more input variables, more ranked variables exist than in the LCOE calculation, and their degree of sensitivity differs considerably based upon their distinctive characteristics. First, for the Equity IRR, the tariff-related input variables which are exclusively utilized in the financial model generally rank high. For instance, *IT* has strong sensitivity in all sources; ranks 1st in wind, 2nd in coal, and 3rd in nuclear power. This means that the electricity price should be regarded very important in terms of revenue. *OCC* still has a huge influence on all three sources. Especially, *OCC* becomes the 1st sensitivity input variable, in that operating profit per *OCC* is the highest in coal power. As for *TGR*, it becomes the most sensitive input variable for nuclear power. As nuclear has the longest *OP* which leads to the yield of revenue for a long time, *TGR* plays a very important role in this sense. The *IT* and *TGR*'s high sensitivities indicate that considering the input variables with respect to the revenue side is very important. As a result, this demonstrates that the financial model, which considers not only the cost but also revenue, is more practical in the real business world. Other than *TGR* and *IT*, the remaining input variables have similar degrees of sensitivity, as in the LCOE calculation. The *IR* still ranks high especially for nuclear source and the *CP* relatively ranks higher in nuclear, because the 7-year *CP* affects the NPPs to a greater degree.

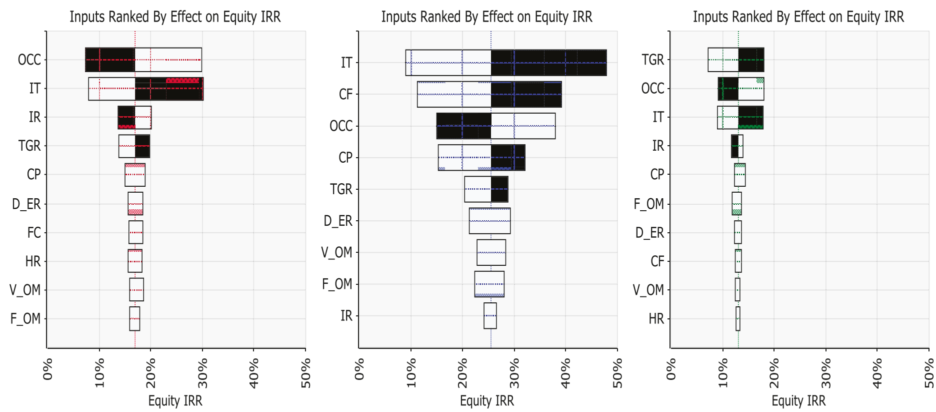

Figure 7. Equity IRR tornado diagrams of Coal, Wind, and Nuclear.

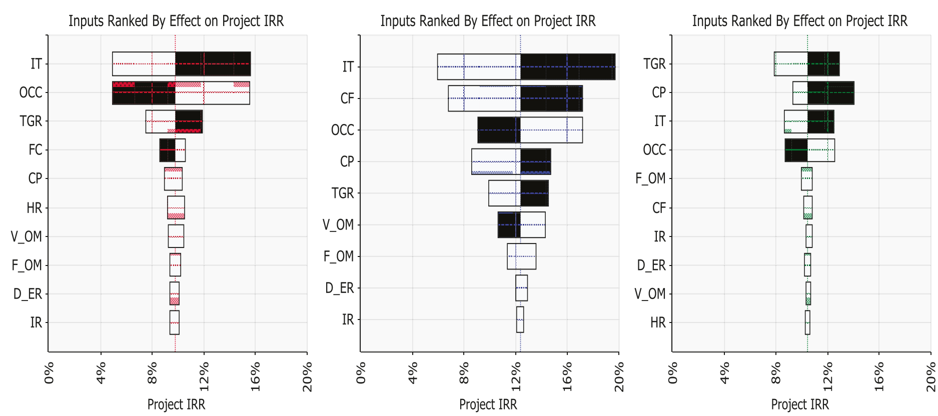

Figure 8. Project IRR tornado diagrams of Coal, Wind, and Nuclear.

Second, Project IRR shows some notable changes compared to Equity IRR. The *IT* becomes the 1st sensitive input variable for coal, while it is 2nd in the Equity IRR. This largely is because Project IRR does not consider any debt and interest. *OCC* becomes more sensitive with interest, but as the Project IRR is unrelated to interest, it becomes the 2nd with respect to sensitivity. For nuclear, the *CP* becomes a highly sensitive variable. This also is related to Project IRR's features. As the *CP* increases, the annual *OCC* divided by the *CP* increases with the *IF*. Even the revenue comes late, as the operation should begin after the completion of the *CP*. As a result, a long *CP* invariably has a strong influence on Project IRR, and ranks high in nuclear. The *IR* and *D_ER*'s degree of sensitivity also becomes relatively less important in Project IRR. Thus, *IR* and *D_ER* are quite important in the Equity IRR, which considers the debt service. As for wind power, most of the important input variables rank the same in the financial sensitivity analysis of the Equity IRR and Project IRR. It is mainly because it has the shortest *OP* with small *OCC*.

What the tornado diagrams in Figures 6–8 show are that nuclear power has the shortest length of bars compared to the other two sources, in which wind has the highest. This is attributable primarily to its distinctive features. Because there is high uncertainty in wind power, as the distribution graphs also show, each input variable has a relatively huge range. This is a weak point of wind power. Although it has competitive value, its uncertainty and high risk can be less attractive to the stakeholders. In contrast, despite its relatively small values, nuclear power's strong point is that it is less volatile and carries a small risk. Therefore, not only the indicators' financial results but also the power source's uncertainty and volatility should be considered together.

5. Discussion

This study shows various illustrative examples to reveal how the evaluation of the economic competitiveness for energy mix can be varied using the financial model and LCOE approach. Table 9 shows a summary of the results. First, the *IR* is a very sensitive variable to calculate the LCOE. Depending on the *IR* in the energy business market, renewable energy can be more economically competitive than non-renewable energy as shown (c) in Table 9. However, most country's *IR* is around 5%. Thus, conventional energy sources such as coal and nuclear can be still more economically completive than renewable energy in most cases. Second, if the *IT* price can be proportional to LCOE by government support, wind energy is more competitive than coal and nuclear shown (e), (h), and (k) in Table 9. Wind energy power plant has a shorter *CP* and lower costs compared to other coal and nuclear plants, which means that wind energy plant can deliver the required funding with relatively little financial costs. This enables the wind energy to yield high Equity IRR and Project IRR. Third, *LP* is not equal with the *OP* in most energy projects. Thus, if the *LP* is shortened given that DSCR meets the minimum specific criteria, Equity IRR can be increased in most cases shown (f), (i), and (l) in Table 9. The nuclear energy has a long *OP* and relatively stable operation income compared to renewable energy. Thus, the effect of adjusted *LP* in nuclear energy is higher than others. Fourth, *TGR* in revenue is similar to the *IR* in cost from the time value for money perspective. *IR* is usually correlated with *TGR*. Thus, the negative effect of high *IR* in LCOE can be offset by high *TGR* in Project IRR as shown in (d), (p), (s), and (v) in Table 9. Last, sensitive variables can be varied depending on the intrinsic attributes of the energy plants and utilized financial indicators. If the stakeholders are equity investors or government officers, the sensitivity variables of the LCOE and Equity IRR must be more important, whereas if the stakeholders are loan investors, the sensitivity variables of Project IRR can be more emphasized. For these reasons, energy preference from the economic perspective which eventually affects the decision of the energy mix cannot be explained by only LCOE method. If the energy policymaker considers these various indicators, the energy mix plan would be more efficient and effective.

6. Conclusions

LCOE method is a useful way to compare the lifecycle cost considering energy production, which enables many policymakers to refer this value for their energy mix. However, this way is sometimes not complete to reflect realistic business issues. Thus, this study shows what kinds of factors should be considered more important in order to evaluate better the economic and financial competitiveness for energy mix. First, the *LP* is usually different from *OP*. This *LP* can be shortened depending on the amount and stability of cash flow. This shortened *LP* can reduce the total amount of interest and eventually improve the Equity IRR. It is not applied the same to all energy sources because some energy plants have low cash flow and high revenue volatility. Thus, the reduction of *LP* is different depending on the energy plants. Second, *TGR* should be considered in real business. The energy market in high *IR* usually accompanies the high *TGR*. High *IR* has a negative effect on project cost. Similarly, high *TGR* means positive in terms of project revenue. This effect is varied depending on the *CP* and *OP*. Last, sensitive variables are varied depending on the financial indicators. Each stakeholder has different interests in different financial indicators in the energy economy and business. So, most important variables can be varied depending on the financial indicators. Thus, the stakeholders should try to improve the variables depending on their interesting financial indicators.

Even though the contributions above mentioned, this study has several limitations. First, this study assumed that the *IT* price in the financial model is equal to 110% of LCOE. This assumption is not realistic. Regardless of the LCOE of each energy source, the tariff price is almost the same in open electricity market. Governments support the subsidiary or incentive to specific energy to promote this energy being more popular. At this moment, this incentive or subsidiary has an effect on reducing the gaps among the LCOEs of different energy sources. However, it does not mean that the *IT* price increases as much as the profit. Second, the probabilistic distribution of input variables can be varied depending the country and project. Even though this study used the well known previous study produced based on the US energy market [5], the results can be varied to some degrees depending on the referred data. Third, the comparative cost analysis between the renewables and none-renewables can be more complete with the life-cycle cost such as emissions costs due to trading schemes or carbon taxes. Last, the effect of *LP* and *D_ER* might depend on the expected opportunity costs of investments according to Modigliani-Miller theorem [41,42]. This study just showed the principles and illustrative explanations depending on the different analysis methods and energy sources. In the future, the parametric variables including external cost can be applied to show these principles more quantitatively and to suggest the optimization value for a better energy mix.

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Nomenclature

OCC	Overnight Capital Cost ($/kWh)
F_OM	Fixed O&M cost ($/kW-year)
V_OM	Variable O&M cost ($/MWh)
CF	Capacity Factor (%)
IR	Interest Rate (%)
OP	Operation Period (years)
FC	Fuel Cost ($/MMBtu)
HR	Heat Rate (Btu/kWh)
TGR	Tariff Growth Rate (%)
IF	Inflation Rate (%)
IT	Initial Tariff ($/MWh)
LP	Loan Period (years)
CP	Construction Period (years)
D_ER	Debt to Equity Ratio (%)
CRF	Capital Recovery Factor (%)

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Design of Power Supply Package for Electricity Sales Companies Considering User Side Energy Storage Configuration

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Abstract: With the deepening of the reform of the power system, electricity sales companies are required to explore new business models and provide multi-faceted marketing programs for users. At the same time, with the reduction of energy storage (ES) costs and the gradual maturity of technology, user side ES, especially Battery ES, has become an effective means for enhancing users' power supply reliability and reducing electricity bills. Battery ES, as the standby power supply, has a vast user side application. The configuration of ES can help users to ameliorate power quality and reduce electricity cost. It is a critical strategy for electricity sales companies to improve their competitiveness as well. Firstly, this paper analyzes the user side ES and introduces the user side ES development status and relevant policies. Then, we establish an ES configuration optimization model based on the cost–benefit system. To determine the optimal ES capacity of the system's storage capacity, non-dominated sorting genetic algorithm with elite strategy (NSGA-II) is used as the method solving model. Finally, according to the cost-effectiveness of ES and the period of a contract signed by users, a price package with ES configuration is designed for users to choose.

Keywords: electricity sales company; ES configuration; power supply reliability; power supply package

1. Introduction

In March 2015, the State Council of CPC(the Communist Party of China) Central Committee adopted the Several Opinions on Further Deepening the Reform of China Electric Power System (Zhongfa (2015) Document #9) [1] to further enhance operational efficiency and break up monopoly in the power market. The central document signified the launch of new electricity market reforms in China. By the end of 2017, China's power trading institutions were finished, and the market competition mechanism in the power-selling market was initially formed [2,3]. In September 2018, domestic electricity market in Guangdong Province, China began the first test run.

As the principal part of the electricity retail market, the electricity sales company purchases electricity and sells it to the end-users for profit. After the announcement of the new power reform plan, a large number of electricity sales companies flooded into the power market, the market competition of electricity sales increased. Due to the fact that power users can choose and replace power suppliers, electricity sales companies must explore new business models to foster customers' loyalty and satisfaction. In addition to price concessions, diversified value-added services have become a major tool for electricity sales companies [4]. Value-added services can take many forms and will have broader prospects for development [5].

Energy storage (ES) is such a productive technology for space-time distribution of electric energy that is developing rapidly. Since its small size, fast response speed and low terrain requirements, electrochemical ES is widely used in the user side ES system [6]. Applications of electrochemical ES have many categories, like lithium batteries, sodium-sulfur batteries and liquid sulfur batteries. It is commercially viable thanks to its excellent performance [7]. In the last couple of years, ES materials technology has also made breakthroughs. Brian Huskinson of Harvard University has developed a non-metallic liquid-flow battery based on benzoquinone [8]. The cost is as low as 27 US dollars/(kWh), almost one-third of that of vanadium batteries, which shows economic promise. John Goodenough, a professor at the University of Texas in Austin, and his team of engineers have developed a new type of lithium-ion battery [9]. The Lithium-glass battery, which not only triples the energy density of lithium ions, but also recharges quickly in a few minutes, with a rechargeable cycle of more than several thousand times. In addition to breakthroughs in ES materials technology, ES control technology has also made promising progress. In [10], the authors designed a novel control strategy for a hybrid energy storage system (HESS). This strategy balanced power surges with the cooperation of batteries and supercapacitors, which overcame the slow response of battery system. In [11], an energy-based (EB) control method to control the converter of a battery ES system was proposed. The case simulation results demonstrate that the method has better tracking and anti-disturbance performance compared with the classic PI (Proportional-Integral) method.

On the scale of ES applications, China's electrochemical ES maintained a strong momentum of development [12]. At the 9th China International ES Conference, the ES Application Branch released the ES Industry Application Research Report in 2019. It shows that, by the end of 2018, the cumulative installed power of electrochemical ES in China increased by 146% from a year ago to 1033.7 MW, and the cumulative installed capacity, increased by 127% from a year ago to 3103 MWh. In addition, the installed capacity of user side ES was up to 1583.0 MWh, accounting for 51.0% of the total installed capacity. According to the statistics of the China ES Network (ESCN), there were 103 new electrochemical ES projects within 2018. The user side ES project of Jiangsu Taojing Co., Ltd. was designed with a scale of 0.75 MW/6 MWh. It covers approximately 120 square meters, adopted centralized container construction, which possesses ES capacity of about 219,000 kWh annually. The Conghua Wanli Tire ES Project (lead-carbon battery 6 MW/36 MWh), built by Guangzhou Power Supply Bureau, covers approximately 120 square meters with a maximum power of 6 MW. It can provide 36 MWh of reserve power with a millisecond response and saves nearly one million in electricity costs per year for Wanli tires. Due to the maturity of ES technology and the reduction of cost, user side ES will be applied.

Given that literature [13] introduces the battery selection criteria for ES power stations, this paper in view of the user side, deals with user side ES and makes up for that literature about battery selection. According to the statistics of ES projects, the commonly used ES batteries are divided into lead-acid batteries, ternary lithium batteries, lithium iron phosphate batteries, etc. Literature [14] has pointed out that the lead-acid battery has a problem of low energy density, and [15] quantified the problem of poor thermal stability of ternary lithium batteries. In contrast, lithium iron phosphate batteries are suitable for ES on the user side due to their safety and environmental protection [16]. ES has multiple business operational modes. Literature [17] compared the cost–benefit of user side ES and several other ES business operations models. In this paper, the sales company acts as the investor of the user side ES to cut costs. The sales companies sign the electricity contract with the user, considering the ES configuration to set the electricity price.

The main contributions of this paper can be summarized as follows.

(1) Incorporating ES configuration, this paper proposes a novel business model as a value-added service into retail electricity contracts. All that mattered is that power customers and electricity sales companies can be benefit from the innovative business model. For customers, the business model helps them to improve power supply reliability while reducing electricity bills. For electricity sales companies, the business model helps them to cultivate customer loyalty

to enhance their competitiveness in the retail market. In addition, the model reduces the power supply costs of electricity sales companies by load shifting.

(2) This paper creates a charging model of ES surcharge. The electricity sales companies add the ES cost to the electricity bill by additional electricity charges. Not only does it reduce the pressure of the user's initial investment, but it can also promote signing long-term power purchase contracts with each other.

The remainder of the paper is organized as follows: in the introduction, this paper mainly analyses the general situation and introduces the development status of user side ES. Section 2 adds supporting policies in China. Then Section 3 analyzes the cost–benefit and investment mode of the ES system. In Section 4, we establish an optimal allocation model of ES capacity, which balances the interests between users and electricity sales companies. Then, a solution process for the model was given based on the non-dominated sorting genetic algorithm with elite strategy (NSGA-II) to search for the optimal ES capacity for the user side. Finally, according to the duration of the electricity sales contract, we design a power supply with energy storage configuration package for users to choose.

2. Development of User Side ES in China

According to the mode of ES, it can be divided into three types: mechanical, electromagnetic and electrochemical [18,19]. Mechanical ES includes pumped storage, compressed air storage and flywheel storage; Electromagnetic ES includes superconducting, supercapacitor and high energy density capacitor; Electrochemical ES includes battery ES such as lead-acid, nickel-hydrogen, nickel-cadmium, lithium-ion, sodium-sulfur and liquid flow.

The ES on the user side mainly refers to the ES system that can be stored, converted and released in the vicinity of the users [20]. Taking the user's requirements for the ES system's floor space, response time and investment cost into account, electrochemical ES is the dominant form of ES on the user side.

As an essential part of ES technology, electrochemical ES is widely used due to its high energy density, short response period and long life [21]. According to the incomplete statistics of the national ES project library, the installed capacity of China's newly-invested electrochemical ES projects in 2018 was about 650 MW. By the end of December 2018, the cumulative installed capacity of China's electrochemical ES project was 1039.8 MW [22].

In recent years, the government has launched many national energy policies, because of these ES will be one of the critical areas of research and development. These policies encourage the development of user side ES and provide distinct application paths [23] in China. Some policies for the development of ES on the user side in China are shown in Table 1.

Table 1. Partial support policy of user side energy storage (ES) in China.

Policy Name	Content Focus
Guidance on promoting energy storage technology and industrial development [24].	(1) The construction of distributed ES systems on the user side are encouraged, ES configuration by electricity sales companies with distribution network management rights and qualified residential users is supported in China. (2) ES is allowed to participate in electricity trading through the market-oriented way in China.
Notice on piloting market-based trading of distributed power generation [25].	Distributed power generation projects to install ES facilities to improve power supply flexibility and stability are encouraged in China.
Opinions on innovation and improvement of the price mechanism for promoting green development [26].	Market participants to sign trading contracts that include peak, valley and flat time prices and electricity are encouraged in China.

User side ES has a rapid development with technical support and policy encouragement, but some users may be deterred from ES, as the early involvement is too high. If electricity sales companies consider the enormous economic potential of user side investment and the need to enhance their competitiveness, they can form a new mode of ES for user side investment by cooperating with the power users.

3. ES System Cost–Benefit Analysis

3.1. ES Investment Cost Analysis

The annual cost of ES system C mainly includes the cost of the ES battery C_B and the cost of the ES converter C_T and the cost of system's operation and maintenance C_M, as shown in Equation (1).

$$C = C_B + C_T + C_M \tag{1}$$

The calculation equations of C_B and C_T are as follows.

$$C_B = Q_B \times I_B \frac{r(1+r)^N}{(1+r)^N - 1} \tag{2}$$

$$C_T = P_T \times I_T \frac{r(1+r)^N}{(1+r)^N - 1} \tag{3}$$

where Q_B is the capacity of ES, I_B is the unit cost of an ES battery, P_T is the power of ES converter, I_T is the unit cost of ES converter, r is the discount rate and N is the system service life.

3.2. Benefits of ES

Electricity sales companies design and invest in user side ES, which can reduce the user's electricity charge and the capacity charge, guarantee the reliability of power supply and reduce the economic loss caused by power outage [27–29]. The main benefits of user side ES are as follows.
(1) Reduce users electricity expenditure

An ES system can discharge during a peak period of electricity price, and charge from the power grid during a low period of electricity price. This can reduce the electricity expenditure of users. This part of annual revenue B_1 is the main revenue of user side ES. It can be expressed as follows:

$$B_1 = n \sum_{t=1}^{24} \left(Q(t)^+ - Q(t)^- \right) \rho_t \tag{4}$$

where $Q(t)^+$ and $Q(t)^-$ are the charging capacity and discharging capacity of the ES system during the period t, ρ_t is the real-time electricity price in the t period and n is the annual number of days of ES.

For large and medium-sized industrial users with special distribution transformer power supply, they also need to pay a certain amount of electricity according the peak load. After installing the ES system, users can reduce the peak load, thereby reduce the monthly capacity charges. This part of annual earnings B_2 can be expressed as follows:

$$B_2 = \sum_{m=1}^{12} p_T \rho_m \tag{5}$$

where P_T is the power of an ES system and ρ_m is the unit capacity price that users need to pay monthly.
(2) Improve user power supply reliability

According to the research in the literature [30], the interruption of power supply in the power grid will bring huge losses to users, and the application of standby power supply can save losses to a certain extent. Distributing a certain capacity in the ES system as a standby power supply for users can ensure continuous power of important loads when there is a power outage. This can improve the reliability of service in total (RS-1) for important loads of industrial users and avoid further expansion of power outage accident losses.

(3) Ameliorate load curve of users

For electricity sales companies, there is no essential difference between selling more electricity and reducing electricity costs to profit. The electricity sales companies will increase the purchase cost if the peak–valley difference of user load is enormous. Investing in user side storage can ameliorate the curve of user load, thereby reducing the electricity purchasing cost of electricity sales companies.

For users, the direct economic benefit of additional storage is $B = B_1 + B_2$. That means two methods can reduce the electricity charges, by paying through peak and valley price arbitrage, another trick is by reducing capacity electricity charges.

3.3. *Analysis of Investment Mode of ES*

Considering the high one-time cost of ES, it is difficult for power users to invest ES independently. The company doing the purchase and sale of electricity has the capital and technical strength to invest in user side ES professionally. To reduce the pressure of investing in ES, we adopt the contract energy management mode [31] as the ES investment method. This can also enhance the loyalty of customers to the electricity sales company.

In the contract energy management mode, the electricity sales company provides users with a full range of services including ES design, equipment procurement, installation and commissioning, and maintenance. Users only need to provide the venue and other related auxiliary work. During the contract period, the customer's electricity cost saved by the ES operation is used as the source of income for both parties. The sales company recovers the ES investment cost, and the user obtains the residual income. After the expiration of the contract, the user obtains the ownership and management rights of the ES system and enjoys the ES income exclusively. The result of the installation of ES is compared with that of not having ES installed in Figure 1.

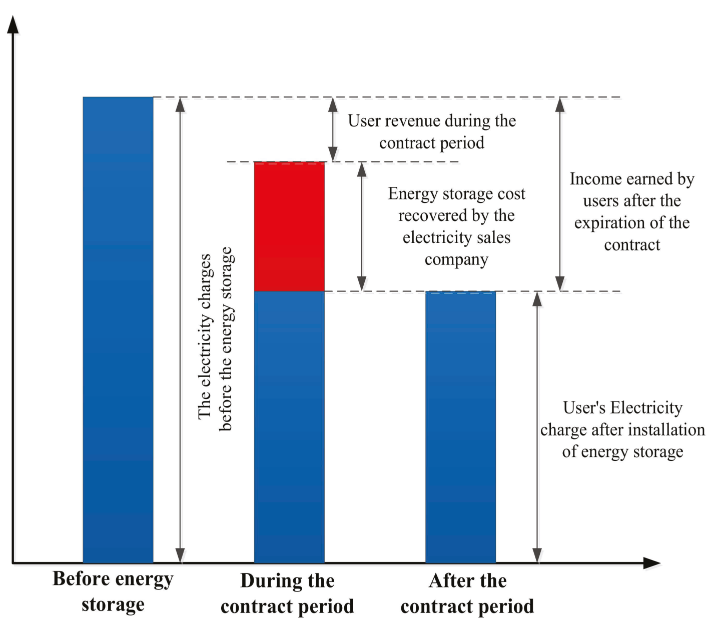

Figure 1. Schematic diagram of benefits before and after the installation of ES.

4. ES Configuration Model and Solution Method

4.1. Objective Function

According to the analysis of ES by the electricity sales company, an ES capacity optimization configuration model is established. Considering the interests of both the electricity sales company and the power user, the optimization objectives are as follows:

(1) Maximum annual income

$$\max W = B - C \tag{6}$$

(2) Minimum user load volatility

$$\min f(P_B(t)) \tag{7}$$

The load volatility $f(P_B(t))$ is the objective function for characterizing the load peak-to-valley difference of the user, and $P_B(t)$ is the charge–discharge power of the ES system at period t. The mathematical expression of the objective function $f(P_B(t))$ is shown in Equation (8).

$$f(P_B(t)) = \sqrt{\int_{t=0}^{T} (P_L(t) + P_B(t) - P_{ave})^2 / T} \tag{8}$$

where $P_L(t)$ is the load of the user at time t, and P_{ave} is the average load of the user in T time after the installation of the ES system. When $P_B(t) > 0$, the ES system discharges, when $P_B(t) < 0$, the ES system is charged, if $P_B(t) = 0$, then the ES system is neither charged nor discharged. T is the evaluation period.

4.2. Constraint Condition

4.2.1. Energy Constraint

To ensure the reliability of power supply for users' important loads and gain some benefits from that electricity generation while the electricity price is high and electricity storage while the electricity price is low. The capacity of ES includes content from two aspects, one is the reserve capacity Q_{RE} for the power supply of essential equipment, and the other is the adjustable capacity Q_{AD} for peak and valley power consumption adjustment.

$$\begin{cases} Q_B = Q_{RE} + Q_{AD} \\ Q_{RE} \geq Q_{RE.\min} \end{cases} \tag{9}$$

where Q_{RE} is the ES capacity configured for the reliability of power supply, and Q_{AD} is the ES capacity configured to adjust the user's peak and valley power consumption. $Q_{RE.\min}$ is the minimum ES capacity required according to the situation of users.

$$Q_{RE.\min} = \int_{0}^{T} P_{RE}(t)dt \tag{10}$$

where $P_{RE}(t)$ is the load power of the essential equipment, and T is the time required for the power failure recovery.

4.2.2. Power Constraint

When configuring an ES converter, the power requirements of important loads need to be considered.

$$\begin{cases} P_C \geq P_{B.\max} \\ P_C \leq P_{L.\max} \end{cases} \tag{11}$$

where P_C is the configured ES converter power, $P_{B.\max}$ and $P_{L.\max}$ are the maximum load power of the important load and the maximum power of the factory load supplied.

4.2.3. Peak Load Shifting Constraint

$$\begin{cases} Q_{AD} \leq Q_{L.peak} \\ Q_{AD} \leq Q_{L.\text{valley}} \end{cases} \tag{12}$$

where $Q_{L.peak}$ and $Q_{L.\text{valley}}$ are the user's load under the peak electricity price and the valley electricity price.

4.2.4. Preventing Peak-to-Valley Inversion Constraints

The proper capacity of ES can effectively reduce the load volatility of the user. However, when the ES is higher than a certain capacity, the peak-to-valley difference of the user load may be reversed, and the load volatility is further increased. In order to prevent the peak-to-valley difference inversion problem, the ES capacity has the following constraints.

$$\begin{cases} f(P_{B0}(t)) = F_0 \\ Q_0 = \int\limits_{t=0}^{T} P_{B0}(t)dt \\ Q_{AD} \leq Q_0 \end{cases} \tag{13}$$

where F_0 is the load volatility when the user is not configured with ES, and Q_0 is the peak–valley difference inverted critical ES capacity.

4.2.5. Battery Performance Constraints

Considering that the energy of the ES battery has an upper limit SOC_{max} and a lower power limit SOC_{min}, when the ES system is actually operating, the state of charge $SOC(t)$ has the following constraints:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{14}$$

4.3. Model Solving

In the optimization model, it is necessary to consider the economic benefits and the reliability of the power supply need. Furthermore, the storage battery type, the ES system capacity and the ES system power are optimized and selected.

The traditional multi-objective optimization methods mainly transform the multi-objective optimization problem into one target optimization problem and then solve it using mathematical planning tools. The traditional optimizations currently available include a weighted sum method, ε-constraint method, maximum and minimum decision making method, etc. The main disadvantages of conventional optimization algorithms are as follows.

(1) They can only find the optimal local solution of the optimization problem;
(2) The result of the solution is strongly dependent on the initial value.

Modern heuristic algorithms are more prominent in solving multi-objective optimization problems. Among them, based on the non-dominated sorting genetic algorithm (NSGA), NSGA-II has become a popular multi-objective genetic algorithm [32] by Srinivas and Deb. The algorithm has the following characteristics.

(1) Fast non-dominated sorting algorithm. On the one hand, it reduces the complexity of the calculation. On the other hand, it combines the parent population and the offspring population.

It can select excellent individuals from the combined population to improve the reliability of selection.

(2) Introducing an elite strategy. It can reduce the rate of abandonment of elite individuals in the evolutionary process, thereby improving the accuracy of the optimization results.

(3) Taken congestion and congestion comparison operators. There is no need to specify shared parameters manually. Not only can the diversity of the population be ensured, but individuals can also diffuse from the quasi-Pareto domain to the Pareto domain.

Due to the characteristics of the algorithm itself, NSGA-II has a better advantage in solving multi-objective problems than other meta-heuristic algorithms [33]. Firstly, the computational complexity is reduced significantly. Secondly, the algorithm has an optimal reservation mechanism. Thus we do not need to add additional parameters. Finally, the algorithm has higher efficiency with the convergence and stability of the algorithm being better. Therefore, NSGA-II is chosen as the solution method of the ES configuration model in this paper.

The solution process for solving the optimal configuration of the ES system using NSGA-II is shown in Figure 2.

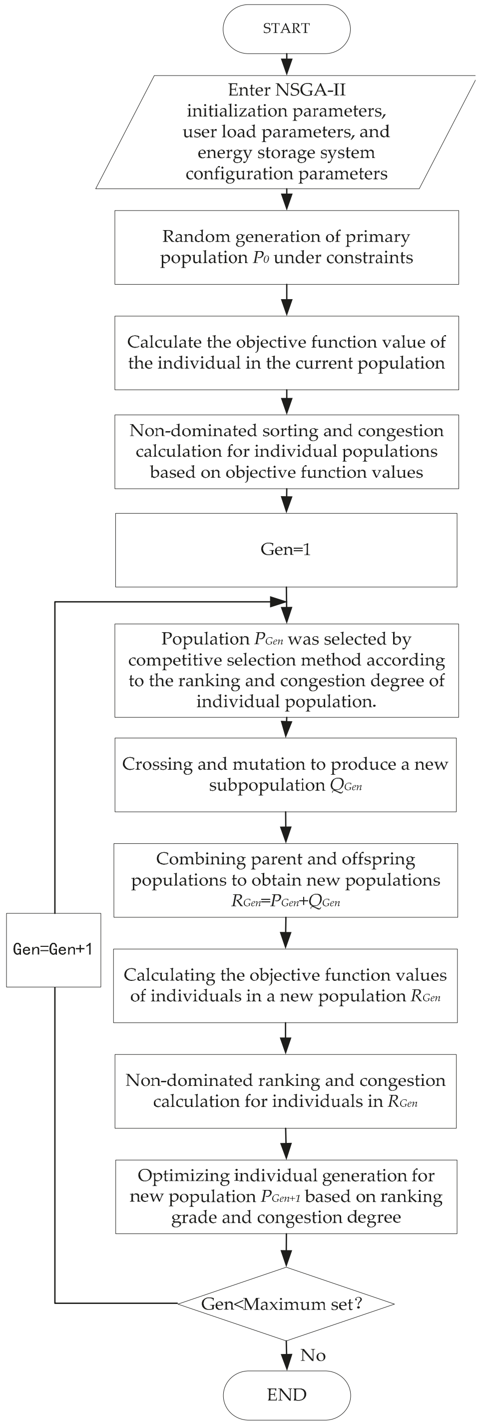

Figure 2. ES system optimization configuration solution process.

5. Electricity Storage Price Setting

The power sales company installs an ES system for users to improve the reliability of power supply and obtain a part of the revenue from peak–valley electricity price arbitrage.

According to the discussion on the ES investment model in Sections 2 and 3, the electricity sales company will recover the ES investment cost during the contract period. To reduce the financial pressure on the user's one-time cost investment, they add the ES cost to the contract in the form of additional electricity charges. After the contract period, the electricity price returns to normal levels.

The electricity purchase price ρ set by the electricity sales company is as follows:

$$\rho = \rho_0 + \rho_a \tag{15}$$

where ρ_0 is the electricity purchase price before the ES system investment, ρ_a is the additional electricity price of the ES investment and ρ_a is expressed by Equation (16).

$$\rho_a = C\frac{r(1+r)^n}{(1+r)^n - 1}/Q \tag{16}$$

where C is the average annual investment cost of the ES system during the contract period, Q is the annual average electricity consumption of the users during the contract period, r is the discount rate and n is the contractual life of the electricity purchase.

The electricity price chart of the power supply package under the different contract periods is shown in Figure 3.

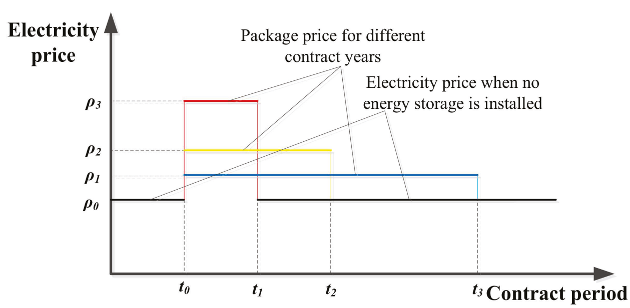

Figure 3. Schematic diagram of electricity supply price for different contract years.

6. Case Analysis

The case selected in this paper is an electronic equipment company in Guangdong Province, which produces PCB (printed circuit board) products such as soft board, soft-hard bonding board, multilayer printed circuit boards, backplane, packaging substrate and so on. It is a typical electronic enterprise in Guangdong. Before signing the contract with the electricity sales company, the company did not add equipment for power supply. The time-of-use tariff policy of industry and commerce in Guangdong is relatively complete, and the price gap between peak and valley is huge. So there is a massive space for ES arbitrage, which meets the requirement of the electricity sales company to install an ES system for the user.

6.1. Brief Introduction to the Case

The company has two distribution transformers with a single capacity of 3150 kVA and 4000 kVA, and a rated voltage of 10/0.4 kV. The maximum operating power of important loads is 2000 kW. It is stipulated that the standby power supply should be able to ensure the normal operation of these important loads for 0.6 h. The user's daily load curve is shown in Figure 4.

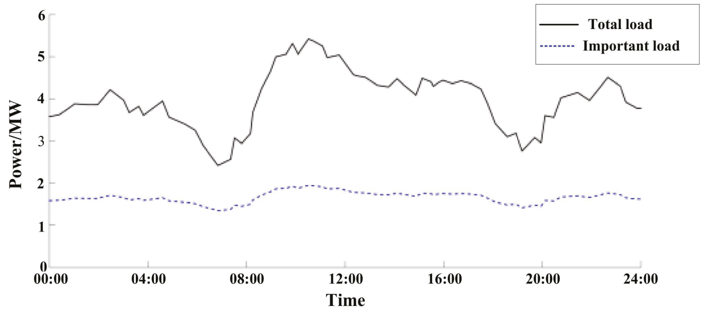

Figure 4. User's typical daily load curve.

It can be obtained from the daily load curve that the user peak load is 5.4 MW, the valley load is 2.9 MW, the peak-to-valley difference is 2.5 MW and the load fluctuation rate is 0.894.

The electricity price list of the company's location [34] is shown in Table 2.

Table 2. Step price list in a certain area of Guangdong.

Electricity Price Category		Flat Section Price	Valley Price	Peak Price
Basic electricity price	Transformer capacity (Yuan/kVA.month)		23.00	
	Maximum demand (Yuan/kW.month)		32.00	
Electricity price (Cent/kWh)		60.84	30.42	100.39

Among them, the price period of each electricity price is divided as shown in Table 3.

Table 3. Step price list in a certain area of Guangdong.

Time Division	Time Range
Peak	09:00–12:00; 19:00–22:00
Valley	00:00–08:00
Flat section	08:00–09:00; 12:00–19:00; 22:00–24:00

6.2. ES Capacity Configuration

6.2.1. Spare Capacity Q_{RE} and Power Configuration

In this case, the maximum operating power of the user's important loads is 2000 kW. The backup power supply is required to provide 0.6 h of off-grid power supply. So it can be obtained that the ES spare capacity is Q_{RE} = 1200 kWh.

According to the above analysis, the power of the ES converter should meet the minimum power requirement of the important loads, that is, not less than 2000 kW. At the same time, considering that the user peak-to-valley difference is 2.5 MW, the ES converter is configured to 2000 kW, which can completely meet the needs of user.

6.2.2. Adjustable Capacity Q_{AD} Configuration

According to the above analysis, the configuration of Q_{AD} needs to consider the ES gain and the peak clipping effect comprehensively. The NSGA-II intelligent algorithm is used to optimize the selection, and the optimal configuration capacity is obtained.

Lithium iron phosphate batteries [35] are widely employed equipment due to their high safety, long life and environmental protection. In this paper, the electricity sales company configures the ES system with a lithium iron phosphate battery as the main component.

According to the average unit price of ES in the latest market, the average cost of a lithium iron phosphate battery is 1.2–1.8 yuan/Wh, and the average rate of an ES converter is 0.8–1.2 yuan/W. The storage battery maintenance cost is considered to be 1% of the total cost of the ES system. The depth of discharge (DOD) of the ES battery is 90%. At this time, the life of the ES battery is about 3000 cycles.

In combination with the company's local electricity tariff policy and typical daily load curve, the ES system is scheduled to be charged every day from 0:00 to 08:00 and discharged at 09:00 to 12:00 and 19:00 to 22:00.

The company runs 300 days a year, and the evaluation period is 10 years. In combination with battery life, there is no need to replace the battery during the evaluation period. The battery cost is 1.5 yuan/Wh; the ES converter price is 1.0 Yuan/ W; the discount rate is 3.24%.

According to the ES capacity optimization configuration model proposed in this paper, the model is solved by NSGA-II, and the obtained Pareto frontier is shown in Figure 5.

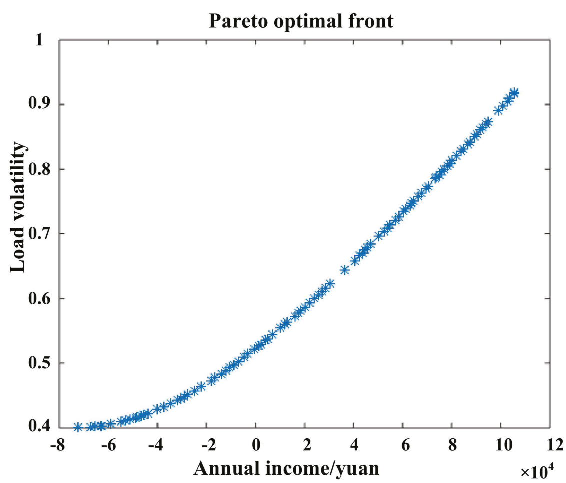

Figure 5. User's load volatility–annual income relationship diagram.

The annual revenue of ES is increased as the capacity of the configuration increases. The volatility of the load is not a simple positive correlation with the ES capacity. A certain capacity of ES can cut the peaks and fill the valley to reduce the fluctuation of the load curve. Along with the continued increase of the ES capacity, the peak-to-valley difference of the load curve will increase.

According to the analysis of the curve in Figure 5, to ensure that the ES system can be profitable, the Q_{AD} is higher than 6.89 MWh. At the same time, to make sure the user load volatility is lower than the level before the installation of ES, the Q_{AD} needs to be lower than 10.31 MWh.

6.3. Improved Power Supply Reliability

According to the user's electricity consumption statistics over the years, the RS-1 of the important loads of the company is 99.818% before the installation of the ES system. After the installation of ES, the RS-1 of the users can be evaluated by the following equation.

$$Ke_Q = Ke_0(1 - \sum Qt_{fa}/T_e) \quad (17)$$

where Ke_0 is the RS-1 before the installation of the ES system, $\sum Qt_{fa}$ is the time when the ES system fails during the evaluation period and T_e is the evaluation period.

According to the failure time statistics of the ES system during T_e, the RS-1 of the power supply is increased to 99.996% after the installation of the ES system, which effectively guarantees the power supply of important loads.

The installation of ES improved the RS-1 of the user significantly, which reduces the impact of power outages on the user's equipment and production. Thereby the loss of user will be reduced.

6.4. Electricity Sales Package of the Electricity Sales Company

After discussion and analysis in Section 3.2, the final ES capacity is 9.8 MWh, and the average electricity price is 0.75 Yuan/kWh before installing the ES system. According to the survey, the average annual electricity consumption of this user is 28,800 MWh.

Taking the contractual period of 5 years as an example, before installing the ES system, the electricity price is $\rho_0 = 0.75$ Yuan/kWh. Annual electricity consumption is Q = 28,800 MWh, and contract length is $n = 5$ years. Bringing the data into Equation (15), the user's ES investment additional electricity price is $\rho_a = 0.13$ Yuan / kWh, and then the electricity price of the power supply package with ES configuration is ρ = 0.88 Yuan / kWh.

Similarly, the electricity price of the power supply package is set for different contract years, and the electricity price data in Table 4 is obtained.

Table 4. Package price of different contract periods.

Contract Period (Years)	1	2	3	4	5
Electricity Price (Yuan/kWh)	1.37	1.07	0.96	0.91	0.88
Contract Period (Years)	6	7	8	9	10
Electricity Price (Yuan/kWh)	0.86	0.84	0.83	0.82	0.81

According to the electricity price data of different contract years in Table 4, the relationship between the package electricity price and the contract period is shown in Figure 6.

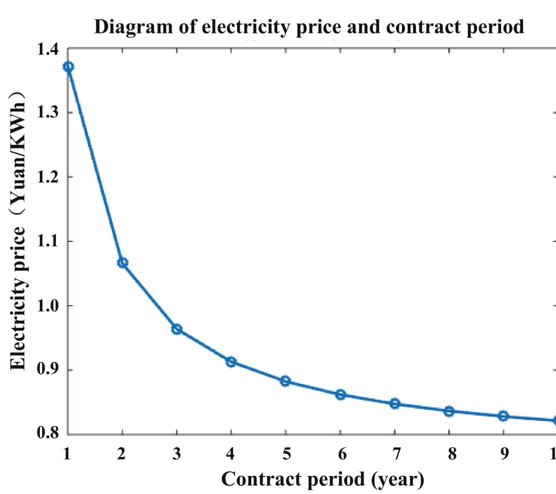

Figure 6. User's purchase electricity price–contract period relationship diagram.

It can be seen from Figure 6 that during the life of the ES system, the user's power supply price decreases with the increase of the power purchase contract period, and the electricity price fluctuates to 0.81–1.37 yuan/kWh. Electricity sales companies gain loyalty with large users and enhance their competitiveness in the electricity market.

7. Conclusions

Given the improvement of the competitiveness of electricity sales companies under the new power reform situation, this paper provides users with electricity price packages with ES configuration considering the power supply reliability requirements of users. In this paper, the ES of the required configuration is of two categories: spare capacity and adjustable capacity. The base is reserve spare capacity used for ensuring the off-grid operation of the user's important loads. For an effective remedy, we built a model that established the maximum ES revenue and the minimum user load volatility. It is called the adjustable capacity configuration optimization model and aims to obtain the flexible capacity. Finally, the electricity price for users is customized based on the cost, the expenditure in the ES and the period of the contract signed for the purchase and sale of electricity. The following conclusions can be drawn from the case study users' ES allocation and the price of packages.

(1) A novel business model incorporating ES configuration as a value-added service into retail electricity contracts is proposed in this paper. In the case study, it was confirmed that the user side ES plays a significant role in improving power supply reliability and reducing electricity expenses.
(2) The NSGA-II is used to optimize the configuration of the ES capacity on the user side in this paper. Combined with the case study, the optimized ES can reduce the user's electricity bill and reduce the user load fluctuation.
(3) This study models the charging system that allocates the ES configuration cost to the user's electricity bill. In this model, it can not only reduce the pressure on users to invest in ES, but also promote the signing of long-term power supply contracts between users and electricity sales companies. The latter can enhance the competitiveness of electricity sales companies as well.

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Abbreviations

ES	Energy storage
ESCN	The statistics of China ES network
HESS	hybrid energy storage system
EB	energy-based
NSGA	The non-dominated sorting genetic algorithm
NSGA-II	The non-dominated sorting genetic algorithm with elite strategy
RS-1	The reliability of service in total
DOD	The depth of discharge

Notations

C_B	The cost of the ES battery
C_T	The cost of the ES converter
C_M	The cost of the system's operation and maintenance
r	The discount rate
Q_{RE}	The reserve capacity
Q_{AD}	The adjustable capacity

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The Dynamic Impacts of Oil Price on China's Natural Gas Consumption under the Change of Global Oil Market Patterns: An Analysis from the Perspective of Total Consumption and Structure

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Abstract: In recent years, China's energy structure has been adjusted unceasingly, where the proportion of natural gas has been increasing year by year, and its external dependence has also been increasing. Therefore, it is necessary to discuss the correlation between China's natural gas market and the international energy market. This paper studies the dynamic relationship between China's total natural gas consumption, consumption structure, and the international price of oil from the perspectives of mutation and time-variance, using the cointegration test with regime shifts and a state space model. The results show that during the global financial crisis in 2008, the cointegration relationship between China's total natural gas consumption and the international oil price has undergone structural changes. January 2012 and March 2015 are potential structural mutation points. After the structural mutation, the impact of the international price of oil on China's total natural gas consumption has weakened. From a structural point of view, urban gas and power generation gas have both been greatly affected by the change of oil price, while industrial gas and chemical gas are less affected. The conclusion here will provide an important empirical reference for optimizing the structure of natural gas consumption and maintaining energy security in China.

Keywords: energy structure; natural gas consumption; Cointegration test with regime shifts; State space model

1. Introduction

In recent years, environmental pollution and climate change have been widely concerned, and the contradiction between the use of fossil energy and environmental protection has become increasingly prominent. The consumption of fossil energy, especially coal, is still high in China, and the consumption of clean energy is still at a low level. Elucidating how to improve the proportion of clean energy and optimize the structure of energy consumption is of great strategic significance for the sound and rapid development of China's economy [1,2].

In the long run, renewable energy will be the primary means of energy transformation, but in the short term, natural gas can be used as a transitional choice. As a bridge fuel for the transition from combustible fossil energy to zero-emission renewable energy, natural gas not only can reduce the emission of standard pollutants and greenhouse gases, but also has the potential to change into 100% renewable fuel (such as biogas and renewable hydrogen) [3,4]. As clean energy, China's natural gas is widely used in power generation, the chemical industry, urban gas, and other industrial production and residential areas, and its consumption is also multiplying [5]. The BP Statistical Review of World Energy 2018 shows that China's apparent consumption of natural gas in 2018 was 283 billion cubic meters, accounting for 7.5% of total energy consumption, an increase of 18% over 2017, of which the import volume reached 121.3 billion cubic meters, an increase of 30.7%, and the external dependence reached 43%. China's natural gas market is expanding, and the external dependency is increasing. This puts forward higher requirements for the development of natural gas and energy security [6].

China's economy is heavily dependent on the international energy market, especially the international crude oil market, which accounts for more than half of China's oil consumption [7]. In China, natural gas prices are linked to international oil prices. International oil prices affect not only natural gas prices, but also upstream investment and mid-stream infrastructure construction in the natural gas industry chain, which in turn affects natural gas consumption. At the same time, China's natural gas supply sources are diversified, and the linkage effect between natural gas from different sources and the international oil price is also different. Therefore, the international oil price has a complicated influence on China's natural gas consumption market. The instability of the international energy market, including recent oil price changes and international conflicts in the Middle East, may have a significant impact on China's economy. China's policymakers should focus on energy security and the role of energy in sustainable economic growth.

According to the 13th Five-Year Plan, China's natural gas consumption will reach 360 billion cubic meters in 2020, accounting for 8.3–10% of primary energy. Under such a policy background, it is of practical significance for China's energy security and the optimization of energy structure to analyze the dynamic impact of the international oil price on China's total natural gas consumption and structure. Through the cointegration test with regime shifts, this paper studies the dynamic cointegration relationship between China's natural gas consumption and crude oil price, and then analyzes the impact of the international oil price on China's natural gas consumption in different periods. By using a state space model, this paper studies the dynamic and time-varying impact of the international price of oil on China's different types of natural gas consumption and then analyzes the influence of the international oil price on China's natural gas consumption structure. We believe that the work of this paper will help us to grasp the evolution law and characteristics of China's natural gas consumption and structure under the change of global oil market patterns, and this has important guiding significance for the optimization of China's natural gas consumption structure and the reform of natural gas marketization.

The remainder of the paper is organized as follows: Section 2 presents a review on China's natural gas consumption, which is involved in the cointegration test with regime shifts and consumption structure. In Section 3, we analyze the influence mechanism of international oil price on the total and structure of natural gas consumption in China. In Section 4, we explain the data source and model selection. Section 5 of this paper presents our empirical results and some analysis of the causes of breakpoints and structural changes. Section 6 provides our conclusions and policy discussion on this topic.

2. Literature Review

There is abundant literature about the relationship between the oil price and natural gas price, and the analysis and prediction of natural gas consumption varies. In the context of existing research, this paper discusses the consumption of natural gas from multiple perspectives and levels. The leading research focuses on the following three aspects: The relationship between the natural gas price and oil price, the influencing factors of natural gas consumption, and the structure of natural gas consumption.

2.1. The Relationship between Natural Gas Price and Oil Price

As two essential components of the world energy, oil and gas prices have always been the focus of the international energy industry and researchers. The price of natural gas is affected by the oil price, which can be followed from the perspective of exploitation and transportation. Because of the substitution of natural gas and oil in the field of industrial fuel and chemical raw materials, some scholars believe that there is a common trend of change between the natural gas price and oil price. In recent years, considering the long-time span of the research samples, most scholars who study the relationship between natural gas price and oil price take into account the significant economic policies and system changes, along with technological revolutions and innovations that may lead to shifts of economic structure.

Villar and Joutz used the Chow test to find the structural breakpoint of the natural gas price series and the crude oil price series and studied the relationship between the North American natural gas price and the international crude oil price through the Johansen cointegration test and Vector Error Correction Model. The results show that the US natural gas price series and the oil price series feature stable cointegration in the long run, even if there has been a decoupling phenomenon between them in some periods [8]. Erdos applied an error correction model to find that the price of natural gas and oil in North America decoupled around 2009 [9]. Ramberg and Parsons used the cointegration test with regime shifts to endogenously test whether there was a structural breakpoint between the natural gas price and the oil price sequence of 1997–2010. They found two structural breakpoints in March 2006 and 2009. Their conclusion shows that the relationship between the natural gas price and oil price is unlikely to remain stable for a long period. They will decouple from one relationship and form a new relationship [10]. Huang Zhuo, Li Chao, and Chen Wei divided the whole sample range into two stages and carried out the cointegration test with segmentation in January 2006. They believed that there was a long-term equilibrium relationship between the crude oil price and natural gas price in the US before 2006, but due to the sharp increase in shale gas production in the US, the North American natural gas market became independent of oil prices around 2006 [11]. Boqiang Lin and Jianglong Li detected that 2008 was an important structural breakpoint between natural gas prices and crude oil prices [12]. Ji Qiang, Liu Minglei, and Fan Ying applied a cointegration test with regime shifts and a time-varying parameter model to test the dynamic relationship between natural gas prices and crude oil prices. The results show that the cointegration relationship between international natural gas prices and crude oil prices has undergone two structural shifts during the hurricane season of 2005 and the financial crisis of 2008. In addition, the influential power of oil price on gas price has presented an inverse U-shaped relationship [13].

2.2. Factors Affecting Natural Gas Consumption

Shi Lijun and Zhou Hong considered population, economy, the environment, and other factors, establishing a forecast model of China's natural gas supply and demand trend using a system dynamics method. The forecast results show that China's natural gas supply and consumption will experience rapid growth. However, because of the limitation of recoverable reserves, the natural gas supply will start to decline year after year, where it is predicted to reach a maximum in 2028. The demand for natural gas continues to rise, leading to a continuous increase in imports, and the external dependence of natural gas will continue to increase [14]. Wang and Lin believe that the exploitation of unconventional natural gas will greatly improve China's annual natural gas production and thus promote natural gas consumption [15]. However, Zeng believes that the natural gas price and household population are important factors influencing the consumption of residential gas [16]. Zhang and Yang deem that factors affecting China's natural gas consumption include the GDP, urbanization rate, energy efficiency, energy consumption structure, industrial structure, and exportation of goods and services [17]. Mukhtar used Structural Vector Auto Regression model (SVAR) to study the impact of macroeconomic variables on natural gas consumption. They found that the devaluation of the exchange rate could boost local production, which in turn would lead to more gas consumption and improved growth in the country [18].

2.3. The Structure of Natural Gas Consumption

More than 50% of China's natural gas was used for the chemical industry before 1995. In recent years, with the acceleration of China's urbanization process as well as the improvement of environmental protection and infrastructure, China's natural gas consumption structure has gradually changed from chemical and industrial fuels to become more diversified. The structure of natural gas consumption has continuously been optimized, with the development of urban gas, natural gas power generation, liquefied natural gas (LNG) vehicles, and other consumption. Figure 1 presents China's natural gas consumption structure. According to Figure 1, the consumption structure of natural gas in China was 13% urban gas, 45% industrial fuel, 2% power generation, and 40% chemical industry in 1994. While, by 2017, the consumption structure of natural gas in China was 33% urban gas, 32% industrial fuel, 15% chemical industry, and 20% power generation. At present, the average gasification rate of urban natural gas in China is only about 25%, which is expected to increase to 40–50% by 2020. According to the national general plan for natural gas development, 76% of the cities in China will use natural gas by the middle of the 21st century, and natural gas will gradually become the main fuel of the urban gas market. The share of urban gas consumption in natural gas is expected to further close to developed countries' levels of around 40%.

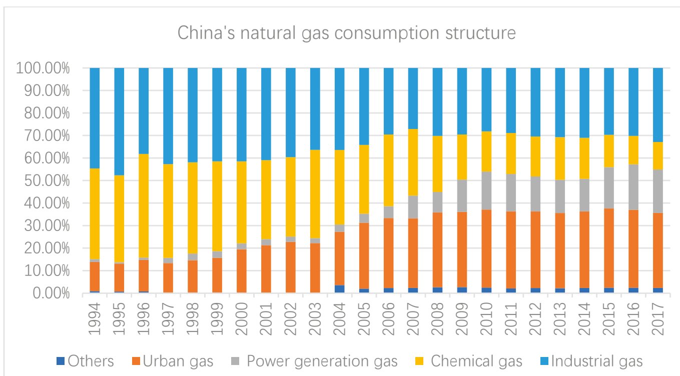


Figure 1. China's natural gas consumption structure.

Wang and Lin divided China's natural gas consumption into three sectors, namely, residential, industrial, and commercial. The study found that the sensitivity of residential sectors to the natural gas prices is higher than that of industrial and commercial sectors in the long run [19]. Zhang and Ji constructed an autoregressive distributed lag model to study the elasticity of natural gas demand in various sectors of China. Their research shows that natural gas in the industrial and power generation sectors complements coal, while natural gas in the residential sector lacks price elasticity, but, similar to developed countries, it has high income-elasticity [20]. Yan and Qin, using an approach based on particle swarm multi-objective optimization theory, built a natural gas consumption structure model considering supply uncertainty and the peaking capacity constraint. The results show that the optimization of natural gas consumption structure can not only meet the demand of all parties for natural gas consumption but also increase the total revenue and enhance the capacity of gas turbine peak shaving and wind power absorption [21].

Based on the summary of the existing research, it can be seen that the theoretical and empirical research of China's natural gas consumption mostly studies the price of natural gas and the influencing factors of natural gas consumption from the perspective of total consumption. It is less useful to study the consumption structure of natural gas from the perspective of four industries, especially to take the factors of the international energy market into account. China's natural gas dependence on foreign countries is increasing day by day, and the influence of the total amount and structure of natural gas consumption on the international energy market is increasing day by day. This paper aims to analyze the dynamic influence of international oil price on the total amount and structure of China's natural gas consumption under the change of global oil market patterns, which can particularly enrich the existing research of the current natural gas consumption market.

3. Theoretical Analysis

China's natural gas consumption is affected by the international oil price in three aspects. The first is the income effect. China's natural gas price is linked with the international oil price, so that the international oil price affects natural gas price, and then affects its consumption. The second is the substitution effect, where, as vital energy in China, oil is the primary alternative energy of natural gas, and the price of alternative energy will affect natural gas consumption. Finally, the change of the international oil price will affect the prediction of producers on the natural gas market, further affecting the upstream investment of the natural gas industry chain and the infrastructure construction in the middle reaches, and ultimately affecting gas consumption.

China's natural gas consumption mainly falls into four categories, namely, urban gas, natural gas power generation, chemical raw materials, and industrial fuel. The international oil price will have different impacts on different consumption types, and then consequently affect China's natural gas consumption structure. The main characteristic of urban gas consumption is consumption for heating. In southern cities, residents use air conditioning and other heating equipment more frequently in winter, and the alternative energy is mainly electric power. Daily gas consumption is also affected by electricity consumption, so the primary alternative energy sources of urban gas are liquefied petroleum gas and electric power [19]. With the increase of social electricity consumption, natural gas power generation has become the primary substitute for coal-fired power plants under load limitations [22]. At the same time, under the dual pressure of environmental protection and primary energy consumption, the proportion of new energy power generation, such as water energy, wind energy, and solar energy, has gradually increased [23]. Therefore, the gas consumption of power generation is mainly affected by international oil price, coal price, and new energy price. Compared with coal, natural gas has the advantages of environmental protection and full combustion. Although China vigorously promotes gasification projects and speeds up the pace of natural gas replacement, coal is still the fundamental industrial fuel in China. Coal and petroleum products account for 70% and 14% of industrial fuel, respectively. Therefore, the consumption of industrial fuel gas is affected by both coal and oil [19]. Natural gas is mainly used in chemical industry to synthesize ammonia, methanol, and produce PVC, in combination with the development of the chlor-alkali industry. Therefore, chemical gas consumption is also affected by coal and oil. Figure 2 shows the mechanism of the influence of oil price on natural gas.

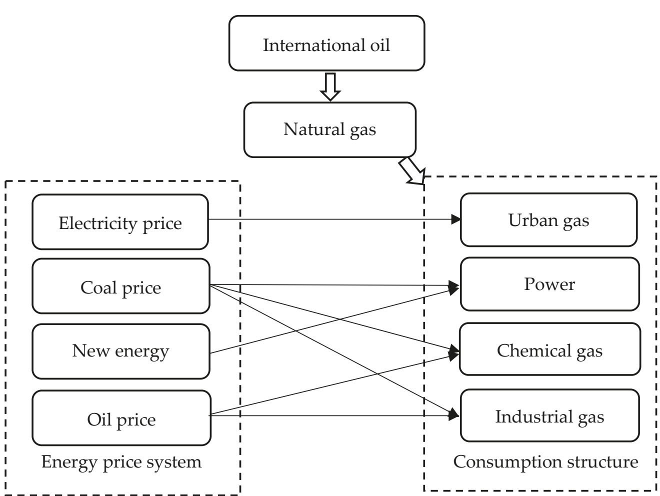


Figure 2. Mechanism of the influence of oil price on natural gas.

4. Data and Models

4.1. Data

Given the leading position of the North American natural gas market in the international energy market, scholars that have studied the relationship between the international natural gas and oil prices have mostly used the West Texas Intermediate (WTI) crude oil price in the United States in the past. However, this paper selects the Brent crude oil price, which is more closely related to China's energy market, in order to study the relationship between China's natural gas consumption and the international oil price in more detail. Moreover, the supply of Brent crude oil is generally stable, less affected by local supply and demand, and more internationally representative. This paper selects the apparent consumption of natural gas as the dependent variable. China's natural gas is mainly used in four fields, namely, urban gas, power generation gas, chemical gas and industrial gas. At the same time, China's oil consumption and natural gas price are selected as control variables here. The price of natural gas is expressed in terms of the Cost Insurance and Freight (CIF) price of propane. Since 2011, China has begun to liberalize the pilot price control of natural gas, so the price data of natural gas starts from 2011. This paper uses the consumption data of natural gas in different industries. Firstly, 50 sub-industries are used, which have been classified according to their actual functions into four categories. The classification results are shown in Table 1. Secondly, according to the monthly apparent consumption data of natural gas, we have determined the monthly weight index of natural gas consumption every year, dividing the four types of natural gas consumption data into monthly data from the annual data.

Table 1. Classification of natural gas consumption types.

Type	Industries
Urban gas	Consumption of living, agriculture, wholesale, retail and accommodation, catering, transportation, storage and postal services, construction, water production and supply, and gas production and supply
Power generation gas	Production and supply of electric power and heat
Chemical gas	Chemical fiber manufacturing, pharmaceutical manufacturing, chemical raw materials, and chemical products manufacturing;
Industrial gas	Communication equipment, computer and other electronic equipment manufacturing, electrical machinery and equipment manufacturing, and transportation equipment manufacturing.

The sample range of this paper is from January 1998 to May 2019. The Brent crude oil price data comes from the website of U.S. Energy Information Administration (EIA) and the apparent consumption of natural gas and consumption by sectors have been based on the Wind database.

4.2. Model Selection

In order to study the dynamic influence of the international oil price on China's total natural gas consumption and structure from the perspective of mutation and gradation, this paper has selected a cointegration test with regime shifts and a state space model.

First of all, considering the long-time span of the research sample, the significant economic events during the sample period may lead to the change of economic structure. However, the traditional Engle-Granger (EG) two-step cointegration test does not consider the situation of structural mutation in the time series data. In order to consider the mutation factors, this paper selects a method proposed by Gregory and Hansen [24]. They considered structural mutation points in a cointegration test. The model mainly includes three types, namely, intercept term change without a time trend (C), intercept term change with a time trend (C/T), and simultaneous intercept term and coefficient term change (C/S). They put forward ADF*, Zt*, and Zα* type tests, the purpose of which is to test the ineffectiveness of non-cointegration and the substitution of cointegration in case of regime shifts. The null hypothesis of the model is that there is no regime shift. If the test statistics obtained reject the null hypothesis, it means that there is cointegration with regime shift. Gregory and Hansen's method can not only accurately test the cointegration relationship between variables, but also determine the location of an endogenous structural change point in a time series. From the perspective of mutation, it can accurately determine the location and the causes of structural change in the relationship between the international oil price and China's total natural gas consumption and analyze the influence of the international oil price on China's natural gas consumption in different periods.

Based on the relationship between the international oil price and China's total natural gas consumption, we have analyzed the dynamic influence of international oil price on four types of natural gas consumption from the perspective of gradual change using a state space model with a time-varying coefficient, judging the dynamic response of China's natural gas consumption structure under the condition of international oil price change.

5. Results and Discussion

5.1. Unit Root Test

Table 2 shows the results of the results of Augmented Dickey–Fuller (ADF) and Philips–Perron tests of the data series, and the specific model type of the unit root test was selected according to Akaike information criterion (AIC) and Schwarz Criterion (SC) criteria. In order to overcome the influence of data series volatility and heteroscedasticity, the logarithm transformation of the data was carried out. The consumption of natural gas in China was recorded as lnCN, the international oil price as lnPO, the consumption of crude oil in China as lnCO, and the price of natural gas as lnPN. It can be seen that the gas and oil prices are integrated by an order of one I (1), while the crude oil consumption and natural gas price are stable sequences. Therefore, we can use Engle-Granger (EG) two-step method to test whether there is cointegration relationship between the gas and oil prices.

Table 2. Results of unit root test.

Variables	ADF		PP		Result
	Level	1st Difference	Level	1st Difference	
lnCN	−0.17	−10.09 ***	−1.35	−43.30 ***	I (1)
lnPO	−2.12	−12.86 ***	−1.96	−12.87 ***	I (1)
lnCO	−4.93 ***		−13.47 ***		I (0)
lnPN	−3.51 **		−3.01 *		I (0)

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

According to the unit root with the break test, the consumption of natural gas in China (lnCN) and the international oil price (lnPO) both represent non-stationary time series, occurring in August 2008 and February 2004, respectively. The results are shown in Table 3.

Table 3. Results of unit root with break test.

Variables	ADF	Break Date
lnCN	−2.83	August 2008
lnPO	−3.24	February 2004

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

5.2. Cointegration Test

5.2.1. EG Two-Step Cointegration Test

As the data of natural gas consumption and the international oil price are stationary regarding the first-order differences, they meet the conditions of the cointegration test. First, the long-term relationship between natural gas consumption and international oil price was analyzed by using the two-step cointegration test proposed by Engle and Grange. It uses the least square method for the first step regression, and the estimated results are shown in Table 4.

Table 4. First step regression results.

C	lnPO	$\overline{R}^2$
0.178	1.011 ***	0.518

* Significant at 10% level; ** significant at 5% level; *** significant at 1% level.

In the second step, the unit root test was carried out for the fitting residual sequence ε_t, and the ADF and PP test methods were selected. The results are shown in Table 5. It can be seen that both test methods show that the residual is non-stationary, that is, there is no long-term stable cointegration relationship between China's natural gas consumption and international oil prices.

Table 5. EG cointegration test results.

Residual	ADF	PP
$\hat{\varepsilon_t}$ (t)	−1.55	−2.50

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

This result is not consistent with many existing research conclusions. It is generally believed that there is a close substitutional relationship between natural gas and oil in production and consumption. The international oil price has a long-term impact on China's natural gas consumption, so their series has a long-term cointegration relationship in theory. Through comparison, we found that much of the current research sample ranges were from up to the end of 2007. However, global political and economic events, such as the global financial crisis in 2008, the widespread exploitation of shale gas in 2015, and US sanctions against Iran in 2019, may have led to structural changes in the relationship between the two. Traditional cointegration testing methods cannot detect the cointegration relationship with regime shifts. Therefore, the accuracy of the above tests needs to be further verified.

5.2.2. Cointegration Test with Regime Shifts

This section uses the cointegration test method proposed by Gregory and Hansen (1996), considering the possibility of structural changes in the cointegration vector, using the following three models to test the cointegration relationship. Among them, $\ln C_{N,t}$ and $\ln P_{O,t}$ represent China's natural gas consumption and international crude oil price, respectively. Here, "ln" represents the logarithmic processing of the data.

1. Level shift (C):

$$\ln C_{N,t} = \alpha_1 + \alpha_2 D_t(T_B) + \beta \ln P_{O,t} + \varepsilon_t \quad (1)$$

2. Level shift with trend (C/T):

$$\ln C_{N,t} = \alpha_1 + \alpha_2 D_t(T_B) + \gamma t + \beta \ln P_{O,t} + \varepsilon_t \quad (2)$$

3. Regime shift (C/S):

$$\ln C_{N,t} = \alpha_1 + \alpha_2 D_t(T_B) + \beta_1 \ln P_{O,t} + \beta_2 \ln P_{O,t} D_t(T_B) + \varepsilon_t \quad (3)$$

Table 6 shows the test results under the three different models. The null hypothesis is that there is no cointegration relationship. It can be seen that the statistics of the C and C/T models significantly reject the null hypothesis at the level of 1%, and the C/S model rejects the null hypothesis at the level of 5%, which indicates that there is still a cointegration relationship between China's natural gas consumption and crude oil price when considering the endogenous structure breakpoint.

Table 6. Gregory–Hansen cointegration test results.

Regime Shifts	C	C/T	C/S
ADF	−5.18 ***	−15.91 ***	−5.52 **
Position	0.805	0.510	0.805
Time	March 2015	November 2008	March 2015

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

By analyzing the location of the structural breakpoint, we have found that the cointegration relationship between natural gas consumption and the oil price has undergone two structural transformations at the end of 2008 and the beginning of 2015. Among them, the global financial crisis broke out in the second half of 2008. In November, the total foreign trade volume of China began to show a negative growth, which fell by 9% year on year. Since November 2008, the global financial crisis has had a substantial impact on China's foreign trade. Taking 2008 as the boundary, the international energy market began to enter the post financial crisis era. At the beginning of 2015, the construction of the "the Belt and Road" stage entered a stage of pragmatic promotion. China's natural gas price consolidation plan was promulgated and implemented, unifying the stock and incremental gas gate station price, comprehensively adjusting the price of natural gas for non-resident users, and attempting to liberalize prices of direct gas for customers. At the same time, the energy market began to form the three pillars of Organization of the Petroleum Exporting Countries (OPEC), the United States, and Russia. The driving mechanism between oil and natural gas has changed such that the market has undergone a structural adjustment. The international energy market has entered a new triangle era. The locations of structural change points determined by the model correspond precisely to the nodes of the changing times of the international energy market. According to the results of the cointegration test, we can infer that the relationship between China's natural gas consumption and international oil price is affected by the global economic performance, the international energy situation, the degree of opening-up strategies, and the market-oriented reform of natural gas price in China.

According to the conclusion of the cointegration test with regime shifts, virtual variables were introduced to fit the above three models, and the results are shown in Table 7.

Table 7. Gregory–Hansen cointegration test equation.

Model	C	Dt (TB)	lnPo	t	lnPo Dt (TB)	$\overline{R^2}$
C	0.150	1.295 ***	0.953 ***			0.859
C/T	2.428 ***	0.183 ***	0.083 ***	0.010 ***		0.964
C/S	0.100	3.348 ***	0.966 ***		−0.512 ***	0.863

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

In order to test the robustness of the model results, the Hatemi-J test of double structure mutation was used in this paper to verify and explain the different structure mutation points of the above three models. The test results are shown in Table 8.

Table 8. Hatemi-J cointegration test results.

ADF	**−8.59 *****	
Position	0.506	0.661
Time	November 2008	January 2012

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

The results of the two methods are November 2008, January 2012, and March 2015. Among them, in January 2012, Guangdong Province and the Guangxi Autonomous Region became the pilots of natural gas price reform, adopting the market net return value to price natural gas for the first time. The price of natural gas has become an essential factor affecting the consumption of natural gas. After the two tests, we found that November 2008 was identified as the structural mutation point of the cointegration relationship between natural gas consumption and the crude oil price in China, and January 2012 and November 2015 were the potential structural mutation points.

According to the results of the cointegration test with regime shifts, we determined November 2008 as the structural mutation point, dividing all the samples into two subsamples, and adding control variables for regression. As the time series of variables are not stable, lnCN and lnPO are I (1) sequences, and lnCO are I (0) sequences, and the autoregressive-distributed lag model (ARDL) is used for regression in this paper. The results are shown in Table 9. From 1998 to 2008, China's natural gas consumption, international oil price and China's oil consumption had a cointegration relationship, but after the structural change in 2008, the cointegration relationship was not significant, given that the natural gas price reform made the natural gas price become an essential factor that affects natural gas consumption since January 2012. The natural gas price (lnPN) was added into the model as a control variable to test the data after 2012. The results are shown in Table 10. The inspection results are shown in Table 11.

Table 9. ARDL long run form of the subsample.

January 1998 to October 2008							
C	lnCN(−1)	lnCO	lnPO(−1)	D(lnCN(−1))	D(lnCN(−2))	D(lnPO)	D(lnPO(−1))
−4.9 ***	0.60 ***	0.88 ***	0.08	−0.34 ***	−0.31 ***	−0.21	−0.49 **
November 2008 to May 2019							
C	lnCN(−1)	lnCO	lnPO(−1)	DlnCN(−1))	D(lnCN(−2))	D(lnPO)	D(lnPO(−1))
0.08	−0.09 **	0.07	−0.05	−0.13 *		−0.37 ***	

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

Table 10. ARDL long run form with the control variable.

January 2012 to May 2019					
C	lnCn(−1)	D(lnCN(−1))	lnCO(−1)	D(lnCO)	D(lnCO(−1))
−8.68 ***	0.55 ***	0.10 ***	1.24 ***	−0.71 ***	−0.20 ***
D(lnCO(−1))	lnPN	lnPO(−1)	D(lnPO)	D(lnPO(−1))	
−0.20 ***	0.30 ***	−0.21 ***	−0.44 ***	0.10	

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

Table 11. F-bounds test.

January 1998 to October 2008	November 2008 to May 2019	January 2012 to May 2019
5.77 ***	1.74	9.16 ***

* Significant at a 10% level; ** significant at a 5% level; *** significant at a 1% level.

Before the structural change in 2008, the main effect of the international oil price on natural gas consumption was a substitution effect, that is to say, oil is the alternative energy of natural gas, and the rise of the international oil price will promote the consumption of natural gas. However, after the structural change in 2008, the long-term impact of the international oil price on China's natural gas consumption is not significant. After 2012, the long-term impact of international oil price on China's natural gas consumption changed from a positive impact to a negative impact. China's natural gas consumption is greatly influenced by oil consumption and the natural gas price, while the international oil price has little influence on China's natural gas consumption. The impact of other factors on the natural gas market has increased, while the impact of the international crude oil market has significantly weakened.

5.2.3. State Space Model

It can be seen from the results in the previous section, the relationship between China's natural gas consumption and international oil prices is unfixed. Moreover, China's natural gas consumption structure is becoming increasingly diversified. Therefore, this section focuses on the dynamic relationship between China's natural gas consumption structure and international oil prices using a state space model, which can be expressed in the following forms:

$$y_{it} = \alpha + \beta_t x_t + \varepsilon_t \tag{4}$$

$$\beta_t = \varphi\beta_{t-1} + \mu_t \tag{5}$$

where y is the consumption of natural gas, x is the international oil price, i stands for types, and t denotes time. Equation (4) is the measurement equation and Equation (5) is the state equation.

The consumption data of the four kinds of natural gas, i.e., urban gas, power generation gas, chemical gas and industrial fuel, and the international oil price data are respectively recorded as lncity, lnelectricity, lnchemistry, lnindustry, and LNP. First of all, the state space equations of the four kinds of natural gas consumption and international oil price were established to study the time-varying dynamic relationship and the structural characteristics between them. Then, the results were normalized to analyze the impact of the international oil price on China's natural gas consumption structure.

1. Time-varying elasticity coefficient of natural gas consumption to oil price:

Figure 3 shows that the time-varying dynamic relationship between various types of natural gas consumption in China and the international oil price is similar. Nevertheless, different types have their own unique characteristics. From 1998 to 2017, the elasticity of the four types of natural gas consumption to international oil prices decreased first, then increased during the global financial crisis in 2008, where the influence of the international oil price on the four types changed significantly and the elasticity of them fell suddenly and then rebounded rapidly. This feature is consistent with the time of the structural breakpoint detected. As new forms of natural gas consumption, urban gas and power generation gas are greatly affected by the change of oil price, among which the most massive change was found for power generation gas. Figure 4 shows that the time-varying elasticity of generation gas and urban gas.

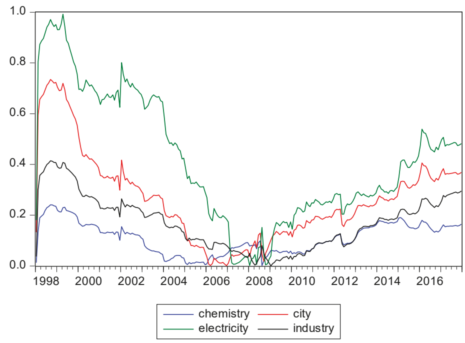
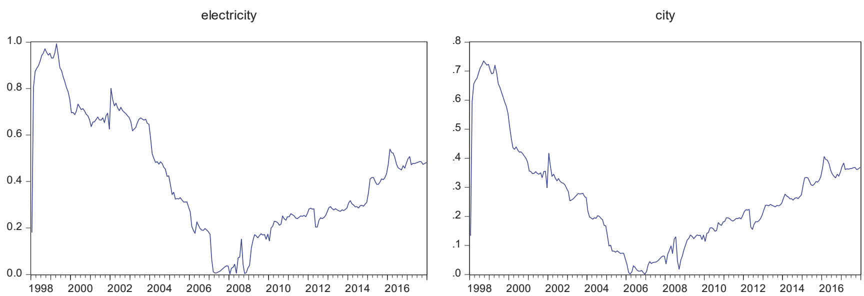


Figure 3. Time-varying elasticity of the four types of gas usage.



(**a**) (**b**)

Figure 4. (**a**) The elasticity of generation gas. (**b**) The elasticity of urban gas.

From 1998 to 2017, the elasticity of power generation gas to oil price experienced a tortuous process. China began to vigorously develop natural gas power generation in 2004. From 2004 to 2005, 60 sets of gas-steam combined cycle power generation projects were tendered successively in China. The increase of demand for natural gas in the power generation industry led to producers being more sensitive to the substitution relationship between oil and gas, and the impact of oil price on power generation gas increased. Therefore, the elasticity of power generation gas to oil price continued to increase from 2006 to 2008. After 2014, with nuclear power, wind power, solar energy, and other new energy power generation methods gradually coming into the public view, the growth rate of China's gas-fired power generation installed capacity continued to decrease, and the increasing trend of the elasticity slowed down from then onwards.

The elasticity of urban gas to oil price has gradually decreased since 1998. After China began to import LNG in 2006, the absolute value of urban gas elasticity was lower than 0.03 from February 2006 to February 2007, during which the change of international oil price had little impact on the consumption of urban gas. While, the long-term LNG trade agreement entered into the "window period", so that there was a limited supply phenomenon in China in 2016, and the elasticity of the urban gas to oil price started to increase. Residential gas and LNG vehicle gas are the main components of China's urban gas. Demand for residential gas is rigid, while the LNG vehicle gas demand has large elasticity, which is easily affected by the changes in international oil prices. It is quite common to use natural gas as vehicle fuel in developed countries. As a vehicle fuel, LNG has significant economic and social benefits due to its mature technology, clean emission, and low fuel cost. However, it also has disadvantages, such as the high purchase cost and difficulty of fuel supply. In the period of tight natural gas supply, consumers are sensitive to the substitution relationship between oil and gas, and the guiding ability of oil price to natural gas is further strengthened. While in the case of the excess supply of natural gas, restricted by conversion technology, it is difficult for natural gas to replace the consumption of oil products further. At this time, the impact of oil price changes on urban gas is significantly weakened.

Industrial gas consumption is greatly affected by environmental protection policies, while chemical gas consumption is mainly influenced by coal and other alternative energy prices. As the main consumption form of natural gas, they are less affected by the change of oil price.

2. The influence of oil price on the consumption structure of natural gas:

According to Figure 5, we can see that the change of oil price has the most significant impact on China's power generation gas and urban gas consumption, and the contribution of them to the change of China's natural gas consumption is the highest. Among the changes in natural gas consumption caused by international oil prices, the total proportion of power generation gas and urban gas can reach 70%. It is worth noting that the proportion of power generation gas exceeded 40% before 2006, although it has declined and continued to be less than 40% after 2008, where it still ranks first among the four types of natural gas consumption. The contribution of industrial gas and chemical gas to the change of China's natural gas consumption is relatively low, which accounts for about 30% of the change caused by the international oil price. The consumption of these two types of natural gas is more stable and less affected by the change in oil price.

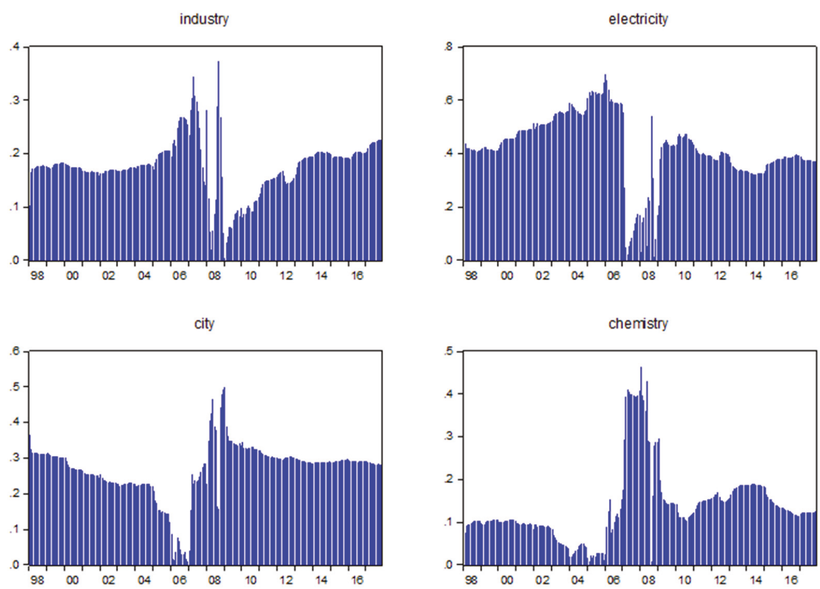


Figure 5. Impact of oil price changes on the natural gas consumption structure.

6. Conclusions and Policy Discussion

This paper has analyzed the dynamic relationship between China's natural gas consumption and international oil price through a cointegration test with regime shifts and has used a state space model to estimate the influence of the international price of oil on China's natural gas consumption structure in different periods. Based on the empirical analysis, this paper has found that:

1. The global financial crisis and China's significant strategic economic policies are the external drivers of structural changes in the relationship between China's natural gas consumption and the international crude oil market. The traditional cointegration test cannot test the structural

change of the relationship between natural gas consumption and crude oil price adequately, while the cointegration test with regime shifts has better testability and can identify the location of breakpoints endogenously. Although there is a cointegration relationship between natural gas and crude oil prices, structural changes took place in November 2008, and uncertain structural changes took place in January 2012 and March 2015. The breakpoints can correspond to the outbreak of the global financial crisis in the second half of 2008, and when Guangdong Province and Guangxi Autonomous Region became the pilots of natural gas price reform in 2012 and the early part of 2015, which is in line with the natural gas price combination plan in China.

2. The influence intensity of the international oil price on natural gas consumption is not fixed and varies in different periods. In periods of tight supply, the guiding ability of the crude oil price to the natural gas price is relatively stable, and the tendency of natural gas consumption to follow oil prices is pronounced. However, the impact of the international oil price on China's natural gas consumption has been weakening since 2008, and the two have a trend of separation.
3. Urban gas and power generation gas are new forms of natural gas consumption and they are greatly affected by changes in oil prices. The influence of oil prices on power generation gas increases as the demand for natural gas in the power generation industry increases. With the input and promotion of new energy generation methods, the consumption elasticity growth trend of power generation to oil price slows down. Urban gas has the same characteristics. During periods of tight natural gas supply, consumers are sensitive to the substitution relationship between oil and gas, such that the guiding ability of the oil price to the natural gas consumption is strong. The impact of oil price changes on urban gas is significantly weakened by the abundance of natural gas. However, as the primary consumption forms of natural gas, industrial gas and chemical gas are less affected by changes in oil prices.

Compared with developed countries, China's natural gas market has two problems, namely, low total consumption and an unreasonable consumption structure. The results of this paper show that different types of natural gas consumption are affected by the international oil price to different degrees. Mindlessly encouraging the development of natural gas and generally carry out energy substitution may achieve little, which will not only increase the burden of the government and enterprises, but also cause the effect of unsatisfactory energy structure optimization. Therefore, in the process of encouraging the development of natural gas, the government should optimize the structure of natural gas consumption on the premise of ensuring the stable and sustainable growth of natural gas consumption. Based on this, this paper puts forward the following suggestions:

1. The results of this paper show that the consumption of gas for power generation is greatly affected by the change of international oil prices and power generation is the most potential field for natural gas development. Combined with the current electricity market situation, we should vigorously develop renewable energy generation to complement and promote natural gas power generation, as to cope with the low trend of natural gas power generation when the oil price is low, thereby maintaining the stability of power generation and ensuring sufficient power supply.
2. From the perspective of urban gas, the development of LNG vehicles should be encouraged to steadily increase the consumption of urban gas and optimize the consumption structure of natural gas. First of all, the government should actively explore ways to improve the competitiveness of natural gas vehicles through financial subsidies, tax incentives, and vehicle purchase differential subsidies. Secondly, in terms of technology, the development of long-distance vehicles, including urban buses and large freight vehicles, should be encouraged to increase the consumption of urban gas.
3. Industrial fuel gas consumption is less affected by changes in international oil prices, so this kind of natural gas consumption is relatively stable, which is essential for the stable development and continuous increase of total natural gas consumption. As an industrial fuel, natural gas is less economical than coal. It is necessary to implement stricter environmental standards and

constraints to increase the use of coal, together with subsidies for natural gas consumption, in order to improve the competitiveness of natural gas under the premise of environmental protection and guarantee the stable development of industrial gas.

4. Due to the rigid demand, the impact of the change of oil prices on the chemical gas is least, where the change of oil prices leads to the rise of natural gas prices, and loss in the chemical sector is the most severe compared to the other sectors. As an irreplaceable raw material, natural gas is widely used in the chemical sector. Based on this, two suggestions are put forward in this paper. Firstly, in terms of technology, we should improve the utilization efficiency of natural gas and reduce the cost and economic loss caused by changes in oil prices. Secondly, in terms of the industrial chain, we should subsidize the downstream industries, such as agriculture and medicine industries, in order to improve the economy of chemical gas.

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Analyzing Oil Price Shocks and Exchange Rates Movements in Korea using Markov Regime-Switching Models

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Abstract: Korea imports all of its crude oil, and is the world's fifth largest oil importing country. We analyze the effects of oil prices, interest rates, consumer price indexes (*CPI*s), and industrial production indexes (*IPI*s) on the regime shift behavior of the Korean exchange rates against the USA from January 1991 to March 2019. We use the Markov regime switching model (MRSM) to detect the regime shift behavior of the movements of Korean exchange rates. In order to select the optimal MRSM, we fit a total of 30 models considering four explanatory variables. The selected model based on Akaike information criteria (*AIC*) and maximum log likelihood (*MLL*) includes the log-differentials of oil prices, the log-differentials of *CPI*s compared to those of the US, and its own auto-regressive terms. Based on the selected MRSM model, throughout all markets, we find evidence to support the existence of two distinct regimes: a stable regime with low-volatility, and an unstable regime with high-volatility. The regime with high-volatility includes the Asian financial crisis of 1997 and the global financial crisis of 2008–2009 in the Korean exchange rates market. In the regime with low-volatility, the Korean exchange rates are not significantly influenced by any of the explanatory variables, except for its own auto-regressive terms. In the regime with high-volatility, the Korean exchange rates are significantly influenced by the *CPI*s and oil prices. The transition probability from the regime with low-volatility to the regime with high-volatility is about ten times that of the opposite case.

Keywords: oil prices; exchange rate; Markov regime switching model

1. Introduction

Oil prices have fluctuated over the last 30 years. Oil prices per barrel have risen to over $140 and dropped to below $20. Although energy dependence on oil has declined in the past, oil is still one of the most important sources of energy. Thus, rising oil prices have a huge impact on the economies of countries, which is especially true in those countries that mostly export or import oil. The greater the energy dependence on oil, the greater the impact oil has on the economy. In particular, Korea imports all of its oil and is the one of the world's top 10 oil importers. As a result, oil price fluctuations have a large impact on the trade balance and also on the supply and demand of dollars in the foreign exchange market. This seems to have further led to fluctuations in exchange rates. Thus, analyzing how oil prices affect the exchange rates has been one of the major concerns of economists. Previous studies which have analyzed the relationship between oil prices and exchange rates are Amano and Van Norden [1], Amano and Van Norden [2], Chaudhuri and Daniel [3], Chen and Chen [4], Lizardo and Mollick [5], Basher et al. [6], Aloui et al. [7], Chen et al. [8], Volkov and Yuhn [9], Chen et al. [10], Basher et al. [11], Yang et al. [12], and so on (see Table 1).

Most of these studies not only analyzed the direct relationship between oil prices and the exchange rates, but also analyzed the relationships with other macroeconomic variables, using the macroeconomic model. Most of the analyses focused on developed countries, including the US, and oil-exporting countries, such as Brazil, Canada, Mexico, Norway, Russia, and the United Kingdom. Basher et al. [11] and Yang et al. [12] included Korea in their analyses; however, there have been no studies that have analyzed only Korea in-depth.

The methodologies used by most of the studies vary from the error correction model (ECM), the vector error correction model (VECM), structural vector auto-regression (SVAR), generalized auto-regressive conditional heteroscedasticity (GARCH), and generalized auto-regressive conditional heteroscedasticity M (GARCH-M). Recently, methodologies such as the Markov regime switching model (Basher et al., [11]) and wavelet coherence analyses (Yang et al., [12]) have been introduced. The methodologies introduced so far are presented in Table 1.

Table 1. Previous studies on the dynamics of oil prices and exchange rates.

Authors	Countries	Periods	Methods	Main Results
Amano and Van Norden [1]	Germany, Japan, USA	1973.01–1993.06	Cointegration, granger causality, FMOLS	Oil shocks could be the most important factor determining real exchange rates in the long run
Amano and Van Norden [2]	USA	1972.02–1993.01	ECM (error correction model), Granger causality	Oil prices may have been the dominant source of persistent real shocks
Chaudhuri and Daniel [3]	16 OECD countries	1973.01–1996.02	ECM (error correction model), Granger causality	US dollar real exchange rates are due to the non-stationarity in the real price of oil.
Chen and Chen [4]	G7 countries	1972.01–2005.10	Panel cointegration, FMOLS, DOLS, and PMG	The real oil prices may have been the dominant source of real exchange rate movements
Lizardo and Mollick [5]	USA	1970s–2008	VECM	Oil price is significant in the movements of the exchange rate
Basher et al. [6]	Emerging economics	1988.01–2008.12	Structural VAR	A positive oil price shock leads to an immediate drop in the exchange rate
Aloui et al. [7]	European union, Canada, UK, Swiss, Japan	2000–2011	copula-GARCH	Evidence of significant and symmetric dependence for almost all the oil-exchange rate pairs. Increases in crude oil prices were found to coincide with a depreciation of the dollar
Chen et al. [8]	USA	1992.08–2011.12 (weekly)	GARCH, CARR, CARR-MIDAS	Crude oil returns are more negatively associated with US dollar returns when the US dollar depreciates, as compared to when it appreciates
Volkov and Yuhn [9]	Russia, Brazil, Mexico, Canada, Norway	1998.02–2012.08	GARCH-M, VECM	Oil price is significant on exchange rates in Russia, Brazil, and Mexico
Chen et al. [10]	16 OECD countries	1990.01–2014.12	Structural VAR	Oil price shocks can explain about 10–20% of long-term variations in exchange rates
Basher et al. [11]	9 countries [1]	Varies by each country [2]	Markov switching model	The significant exchange rate appreciation pressures in oil exporting economies after oil demand shock
Yang et al. [12]	10 countries [3]	1999.01–2014.12	A wavelet coherence analysis	The degree of co-movement between the crude oil price and the exchange rates deviates over time

[1] Analysis is conducted for a group of oil exporting countries (Brazil, Canada, Mexico, Norway, Russia, and the United Kingdom) and oil importing countries (India, Japan, South Korea). [2] For Canada, Norway, India, Japan, and the United Kingdom, models are estimated over the period February 1976 to February 2014. For the other countries the estimation period is: Brazil (February 1995 to February 2014), Mexico (December 1993 to February 2014), Russia (February 1998 to February 2014), and South Korea (May 1981 to February 2014). [3] Brazil, Canada, Mexico, and Russia are treated as oil-exporting countries, and the EU, India, Japan, and South Korea are treated as oil-importing countries.

This study analyzes how oil prices affect the Korean exchange rates in both stable and unstable regimes using the Markov regime switching model (MRSM), taking into account other factors such as interest rates, economic growth, and price level. This study differs from previous studies in several aspects. First, most studies on the relationship between oil prices and exchange rates except Basher et al. [11] have used econometric methodologies such as ECM, VECM, SVAR, GARCH, and GARCH-M. Often a pooled series consists of a few subgroups or regimes with different variances corresponding to different economic situations. The impact of oil prices on the exchange rates is expected to vary depending on regimes. Therefore, this study looks for underlying regimes using the Markov regime switching model (MSRM), fits a separate model in each regime, and then examines the effect of oil prices along with major macroeconomic explanatory variables on the exchange rates. Since the regimes are expected to explain many errors, the model in each regime tends to be simple.

Second, not only oil prices but also macroeconomic factors such as price levels, income, and interest rates are the major factors that influence the exchange rates. Except for Volkov and Yuhn [9] and Basher et al. [11], most studies have analyzed only the direct relationship between oil prices and exchange rates. This study analyzes the effects of oil prices on exchange rates in each regime under the correlation with these macro-economic variables. In addition to discovering regimes, this MRSM analysis tests the significance of oil prices and various macroeconomic variables in each regime. Since regimes stand for different economic situations, the significance of variables also changes depending on regimes.

Third, this study is limited to Korea. Crude oil is entirely imported in Korea and Korea was one of the world's top 10 oil importers. The 10 countries that imported the highest dollar value worth of crude oil during 2018 are 1. China: US$239.2 billion (20.2% of total crude oil imports), 2. United States: $163.1 billion (13.8%), 3. India: $114.5 billion (9.7%), 4. Japan: $80.6 billion (6.8%), 5. South Korea: $80.4 billion (6.8%), 6. Netherlands: $48.8 billion (4.1%), 7. Germany: $45.1 billion (3.8%), 8. Spain: $34.2 billion (2.9%), 9. Italy: $32.6 billion (2.8%) and 10. France: $28.5 billion (2.4%) (http://www.worldstopexports.com/crude-oil-imports-by-country/). In 2018, Korea was the world's fifth largest oil importer. According to Korean Customs Service statistics, crude oil imports in 2018 were worth 80,393 million dollars. This amount of imported crude oil accounted for 15% of Korea's total imports in 2018. Reflecting this economic situation in Korea, this analysis provides unique results for Korea.

Fourth, this study analyzes the effects of movement of explanatory variables on the movement of exchange rates, while most of previous studies have analyzed the direct relationship between exchange rates and explanatory macroeconomic variables. Throughout this paper, we use the US data as the basis for comparison.

Therefore, we use the MRSMs, developed by Hamilton [13]. This methodology is further developed into Markov switching auto-regressive conditional heteroscedasticity (MS-ARCH, Cai [14]), Markov switching generalized auto-regressive conditional heteroscedasticity (MS-GARCH, Gray [15]), and Markov switching exponential generalized auto-regressive conditional heteroscedasticity (MS-EGARCH, Henry [16]), among others. The MSRM used in this study was also used in Kim et al. [17] and Kim et al. [18].

We examine the regime shift behavior of exchange rates associated with oil prices, interest rates, consumer price indices, and industrial production indices in the Korean foreign exchange market. For this, we apply the two-regime MRSM (Hamilton, [13]) using monthly data from January 1991 to March 2019.

The remainder of this paper is organized as follows. In Section 2, the data and the MSRM are explained in detail. In Section 3, the model selection is performed and empirical estimation results are presented based on the selected MRSM, and Section 4 discusses the statistical validity of our model and assumptions. Finally, the conclusions drawn from this study are presented in Section 5.

2. Data and Methods

All monthly data, except for the oil prices, used in this paper are from the OECD (Organization for Economic Cooperation and development) data set (OECD.stat) from January 1991 to March 2019. The monthly Korean exchange rates are expressed as the won value needed to purchase one US dollar. The monthly short-run interest rates measured in % are from the monthly monetary and financial statistics data set of the OECD. The monthly consumer price indices (with the index of 2015 being 100) are from the consumer price indices (*CPI*s) complete database of the OECD, and the monthly industrial production indices (with the index of 2015 being 100) are from the production and sales data set of the OECD. The monthly oil prices which are the CIF (Cost Insurance and Freight) oil importing prices of Asia measured in US dollars are from KESIS (Korea Energy Statistics Information System) of the Korea Energy Economics Institute.

The primary purpose of this study is to analyze how the movement of oil prices affects the movement of the Korean exchange rates in each regime in terms of regime shift behavior. Our research is based on the monetary model of exchange rates determination which has lead emergence of the dominant exchange rates model in early 1970s and henceforward remained as an important exchange rate paradigm (Frenkel [19], Mussa [20–22], Bilson [23]). Following the monetary model, the exchange rates are determined by the relative supply and demand of money between two given countries. The money demand is determined by price level, income, interest rates, and other factors including oil prices. Meese and Rogoff [24,25] conducted the seminal work using monetary models to forecast exchange rates. They regressed the log of exchange rates on various combinations of relative macroeconomic variables which were typically included in the monetary model of exchange rates determination.

Recently, Volkov and Yuhn [9] identified some relevant factors that affect the exchange rates between the United States and the corresponding countries on the basis of the monetary model of exchange rates determination. The fundamental factors include interest rates differentials, income (or production) differentials, and inflation rates differentials between two countries. They excluded the money supply variable from the exchange rates determination model to avoid any possible multicollinearity between the money supply and the determining variables of the exchange rates. Since they use monthly data for the analysis of exchange rates movements, and since monthly GDP figures are not available, industrial production is used as a proxy for income.

We consider some relevant variables that affect the exchange rates between Korea and the USA as in Volkov and Yuhn [9]. Oil prices are added to the fundamental factors including interest rates differentials, production differentials, and inflation rates differentials between the two countries. Here, industrial production index (IPI) and consumer price index (CPI) are set as indices representing production and inflation, respectively.

The two-regime Markov switching model by Hamilton [1] is an adequate approach to analyze the impact of these factors (oil prices, interest rates differentials, *CPI*s differentials, and *IPI*s differentials) on the movements of Korean exchange rates. In terms of methodology, the auto-regressive terms are considered as in the Hamilton models [1]. The MRSM following Hamilton [1] assumes that there are two regimes with different volatilities, and that the processes switch between the two regimes according to the transition probabilities of the Markov process. Regime 1 consists of low-volatility periods and regime 2 consists of high-volatility periods. Regime 2 is used to identify unstable economic situations.

In this paper, we assume that the logarithms of exchange rates follow a normal distribution as the logarithms of return rates in equity markets follow a Brownian motion (Osborne, [26]). Often in economic data, the log-transformation reinforces the normality assumption and using differentials reinforces stationarity of the process. At time t, let LE_t be the logarithm of the monthly changes in exchange rates compared to the ones from the previous month as follows (Ayodeji [27]):

$$LE_t = \log\left(\frac{Exchange\ Rate_t}{Exchange\ Rate_{t-1}}\right), \tag{1}$$

LE_t lies in one of the two regimes S_t, where S_t is 1 or 2. LE_t is $\Delta \log(Exchange\ Rate_t)$ in the interval $[t-1,\ t)$, which is the change of $\log(Exchange\ Rate_t)$. If we consider the time change as $\Delta t = t-(t-1) = 1$, then LE_t is the change rate in $[t-1,\ t)$. Assuming that the series is an infinite continuous process, LE_t is an approximate derivative of $\log(Exchange\ Rate_t)$ at $(t-1)$. That is, LE_t is the slope of the tangent line to $\log(Exchange\ Rate_t)$ which means instantaneous change rate of $\log(Exchange\ Rate_t)$ at $(t-1)$. Now let us call LE_t log-differential of exchange rates. Since regime shift behaviors of $(Exchange\ Rate_t)$ and LE_t should match, we investigate regimes of exchange rates using LE_t. Note that LE_t stands for changes of exchange rates.

Similarly, we transform the four explanatory variables. First, $RINT_{\mathrm{t}}$, $RCPI_{\mathrm{t}}$, and $RIPI_{\mathrm{t}}$ are the ratios of short-run interest rates, the ratio of consumer price indices and ratio of industrial production indices between Korea and the USA, respectively. Then, the log-differentials of these ratios of macroeconomic variables are obtained as $LOIL_t$, $LRINT_t$, $LRCPI_t$, and $LRIPI_t$. The relative differences of these fundamental variables between the two countries are expected to affect US exchange rates in Korea, as confirmed by Volkov and Yuhn [9]. However, this study regards the variable ratio between the two countries, instead of their direct differences like the study of Volkov and Yuhn [9], because the Korean exchange rates are expressed as ratios with the US dollars as its denominator. The similar form of log-differentials of variables provides the same intrinsic explanation as before.

$$LOIL_t = \log\left(\frac{Oil\ Price_t}{Oil\ Price_{t-1}}\right), \tag{2}$$

$$LRINT_t = \log\left(\frac{RINT_t}{RINT_{t-1}}\right), \text{where } RINT_{\mathrm{t}} = \frac{Interest\ rate\ of\ Korea\ at\ t}{Interest\ rate\ of\ USA\ at\ t}, \tag{3}$$

$$LRCPI_t = \log\left(\frac{RCPI_t}{RCPI_{t-1}}\right), \text{where } RCPI_{\mathrm{t}} = \frac{Consumer\ price\ index\ of\ Korea\ at\ t}{Consumer\ price\ index\ of\ USA\ at\ t}, \tag{4}$$

$$LRIPI_t = \log\left(\frac{RIPI_t}{RIPI_{t-1}}\right), \text{where } RIPI_{\mathrm{t}} = \frac{Industrial\ production\ index\ of\ Korea\ at\ t}{Industrial\ production\ index\ of\ USA\ at\ t}, \tag{5}$$

Note that there are two ratios in Equations (3)–(5). First, the ratio between Korea and the USA is evaluated. Secondly, the ratio between time t and time $(t-1)$ is evaluated. Finally, log-transformation is applied. The *LR* in front of the variable name stands for log-transformation of the ratio of the ratio. Therefore, we indirectly observe changes in movements of exchange rates through its log-differentials. In each regime, the standard deviation is that of the log-differentials of exchange rates.

The MRSM with the four explanatory variables we consider can be written as follows:

$$LE_t|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t|s_t, \tag{6}$$

where $\varepsilon_t|s_t \sim N\left(0, \sigma^2_{s_t}\right)$. Our model assumes that the exchange rates switch between the two regimes based on the Markov transition probabilities which are denoted by

$$p_{ij} = Pr[s_{t+1} = j|s_t = i],\ \ i = 1,\ 2,\ \ j = 1,\ 2, \tag{7}$$

where, p_{ij} is the transition probability from state i to state j, $p_{i1} + p_{i2} = 1$, for $i = 1, 2$. The oil prices, the interest rates, the *CPI*s and the *IPI*s do not switch. We assume that $\sigma_1^2 < \sigma_2^2$. The parameter space Θ is as follows

$$\Theta = \left\{\beta_{0s_t},\ \beta_{1s_t}, \beta_{2s_t},\ \beta_{3s_t}, \beta_{4s_t}, \beta_{5s_t}\ \sigma^2_{s_t},\ p_{12,\ },\ p_{21}\right\},\ \ s_t = 1 \text{ or } 2. \tag{8}$$

The filtered probabilities of s_t are defined as $P(s_t = i\ |Z_t;\ \Theta)$ for $i = 1, 2$, where Z_t stands for all observations up to time t. In our empirical studies, the process at time t is said to be in regime 1 (with low-volatility) if its estimated filtered probability of regime 1 is greater than that of regime 2. Otherwise, the process at time t is said to be in regime 2 (Sanchez-Espigares and Jose [28], Kuan [29]).

For model selection, we first fit the full model. Secondly, based on stepwise selection method, we select the most appropriate model using Akaike information criterion (*AIC*) criterion. Third, the Wilks test is performed based on the maximum log-likelihood (*MLL*) to select the final model based on Maximum Likelihood Estimator (*MLE*). If the sample size is large, the $(-2MLL)$ difference between the general model and restricted model is asymptotically a chi-squared distribution, with the degrees of freedom as the dimension difference of the two parameter spaces when the restricted model is correct.

The restricted model is assumed under the null hypothesis and the general model is used under the alternative hypothesis. If MLL_r and MLL_g are the *MLL* of the restricted model and the *MLL* of the more general model, respectively, and d_i is the number of parameters to be estimated in model i, then the difference in *MLL* asymptotically follows a chi-squared distribution for a large sample:

$$\Delta(-2MLL) = (-2MLL_r) - \left(-2MLL_g\right) \rightarrow \chi^2\left(d_g - d_r\right), \quad (9)$$

If the difference in *MLL* between any two selected models is significant, then the general model is selected. In addition to the *MLL*, we use the *AIC* which considers a penalty to increment of dimension of the model.

$$AIC = -2MLL + 2n_{par} \quad (10)$$

where n_{par} is the number of parameters to be estimated in the model. "The model with smaller *AIC* is better." (Akaike [30]; Akaike [31]; Pinheiro and Bates, [32]; Rice [33]). The *AIC* is now one of the most popular model selection criteria in machine learning. Starting from the full model in Equation (6), the variables will be first selected based on *AIC*, and then significance of each variable in the selected model is tested based on $\Delta(-2MLL)$ in Equation (9). We use the msmFit function (Sanchez-Espigares and Jose, [28]) and the stepAIC function (Venables and Ripley, [34]) in R 3.3.1. Throughout the paper, p-values less than 0.10 are considered to be statistically significant.

3. Results

The plots of Figure 1 show time series from January 1991 to March 2019 in the Korean exchange rates market: (1) *LE* (exchange rates), (2) *LOIL* (oil prices) (3) *LRINT* (interest rates between Korea and the USA.), (4) *LRCPI* (*CPI*s between Korea and USA), and (5) *LRIPI* (*IPI*s between Korea and the USA.). Co-movements of high peaks and low valleys are observed in these processes during the Asian financial crisis of 1997 and the global financial crisis of 2008–2009.

With exchange rates as the response variable, we fit the following thirty two-regime switching models, as shown in Table A1 in Appendix A: (1) eight models with one explanatory variable (from 1 (1) to 1 (4p)); (2) twelve models with two explanatory variables (from 2 (1) to 2 (6p)); (3) eight models with three explanatory variables (from 3 (1) to 3 (4p)); and (4) two models with all four explanatory variables (from 4 (1) and 4 (1p)). For each model, p stands for the model with the auto-regressive terms of the exchange rates.

We consider the two model selection criteria: *MLL* and *AIC*. We first fit the full model in Equation (6). Then, the model with smallest *AIC* is selected based on the stepwise selection method. In order to reach the final model, significance of each variable in the selected model is further tested one-by-one based on $\Delta(-2MLL)$ in Equation (9) and the backward selection method. Note that the degrees of freedom is 2 since we test one variable at a time which corresponds to the two coefficients, one for the low-volatility period and the other for the high-volatility period. At the significance level 0.1, if $\Delta(-2MLL) > \chi^2_{0.10}(2) = 4.61$, the variable is said to be significant and remain in the model. Otherwise, it is removed.

For the use of MLL in model selection for MRSM, Hardy [17] mentioned that "even where models are not embedded, the likelihood ratio test can be used for model selection, although the χ^2 distribution is in this case only an approximation".

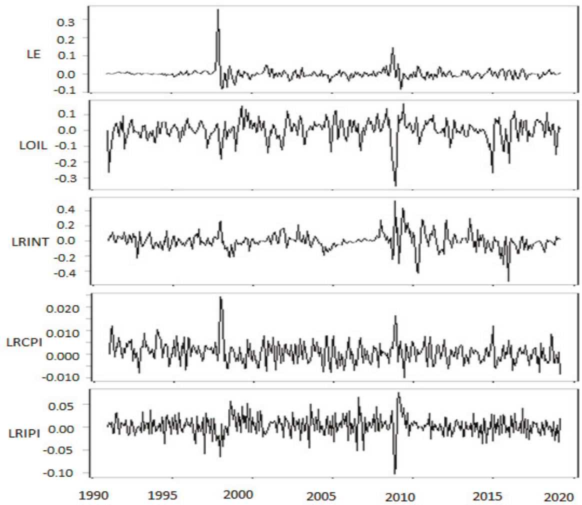


Figure 1. The log differences of exchange rates, oil prices, interest rates, consumer price indexes (*CPI*s), and industrial production indexes (*IPI* s) compared to those of the USA from January 1991 to March 2019 in the Korean financial market.

Starting from the full model with all the explanatory variables in this study, the following model 3(1p) was selected based on *AIC*.

$$3(1\text{p})\ LE_t\big|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\big|s_t \quad (11)$$

We further applied a backward selection method with criteria MLL and examined whether each of the three explanatory variables *LOIL*, *LRINT*, and *LRCPI* were significant. To be more specific, the following three models were compared with 3(1p):

$$\begin{aligned} &2(1\text{p})\ LE_t\big|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \varepsilon_t\big|s_t \\ &2(2\text{p})\ LE_t\big|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\big|s_t \\ &2(4\text{p})\ LE_t\big|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\big|s_t \end{aligned} \quad (12)$$

Their corresponding parameter spaces in Equation (8) are as follows:

$$\begin{aligned} &3(1\text{p})\ \Theta_{3(1p)} = \left\{\beta_{0s_t},\ \beta_{1s_t}, \beta_{2s_t},\ \beta_{3s_t}, \beta_{4s_t},\ \sigma^2_{s_t},\ p_{12,}\ ,\ p_{21}\right\},\ \ s_t = 1 \text{ or } 2. \\ &2(1\text{p})\ \Theta_{2(1p)} = \left\{\beta_{0s_t},\ \beta_{1s_t}, \beta_{2s_t},\ \beta_{3s_t},\ \sigma^2_{s_t},\ p_{12,}\ ,\ p_{21}\right\},\ \ s_t = 1 \text{ or } 2. \\ &2(2\text{p})\ \Theta_{2(2p)} = \left\{\beta_{0s_t},\ \beta_{1s_t}, \beta_{2s_t}, \beta_{4s_t},\ \sigma^2_{s_t},\ p_{12,}\ ,\ p_{21}\right\},\ \ s_t = 1 \text{ or } 2. \\ &2(4\text{p})\ \Theta_{2(4p)} = \left\{\beta_{0s_t},\ \beta_{1s_t},\ \beta_{3s_t}, \beta_{4s_t},\ \sigma^2_{s_t},\ p_{12,}\ ,\ p_{21}\right\},\ \ s_t = 1 \text{ or } 2. \end{aligned} \quad (13)$$

The variable *LRCPI* should remain, since $\Delta(-2MLL)$ between model 3(1p) and model 2(1p) was 2(887.68–881.37) = 12.62, which is greater than 4.61. In other words, the difference between the two models was significant, so the model 3(1p) cannot be reduced to 2(1p) and, thus, the variable *LRCPI* could not be removed. The variable *LOIL* should remain, since $\Delta(-2MLL)$ between model 3(1p) and model 2(4p) was 5.54, which is greater than 4.61. The model 3(1p) could not be reduced to 2(4p) and, thus, the variable *LOIL* was also non-removable. On the other hand, the variable *LRINT* should be removed from the model 3(1p), since $\Delta(-2MLL)$ between model 3(1p) and model 2(2p) was 4.34, which is less than 4.61. Therefore, model 2(2p) was finally selected.

We, again, examined whether it was possible to further reduce the selected model 2(2p). The $\Delta(-2MLL)$ values of models 1(1p), 1(3p), and 2(2) were calculated, but all values were greater than 4.61. It means that all variables were significant and, thus, the model 2(2p) could not be reduced any further. Therefore, model 2(2p) was chosen as the final best model (Table 2).

Table 2. Model selection criteria for the Markov regime switching models (MRSM) for *LE*.

Variable	Model No	p	Criteria		Regime (H)		Regime (L)		Best
			AIC	*MLL*	R^2	*sd*	R^2	*sd*	
LOIL	1(1)	0	−1725.19	866.59	0.010	0.089	0.020	0.015	
	1(1p)	1	−1746.94	879.47	0.264	0.076	0.101	0.015	
LRINT	1(2)	0	−1724.43	866.21	0.029	0.084	0.016	0.015	
	1(2p)	1	−1747.89	879.95	0.242	0.075	0.109	0.015	
LRCPI	1(3)	0	−1739.26	873.63	0.436	0.062	0.004	0.015	
	1(3p)	1	−1753.23	882.61	0.445	0.066	0.094	0.015	
LRIPI	1(4)	0	−1721.82	864.91	0.031	0.086	0.005	0.015	
	1(4p)	1	−1745.15	878.57	0.250	0.077	0.095	0.015	
LOIL, LRINT	2(1)	0	−1725.28	868.64	0.035	0.082	0.037	0.015	
	2(1p)	1	−1746.73	881.37	0.261	0.075	0.116	0.015	
LOIL, LRCPI	2(2)	0	−1743.42	877.71	0.490	0.058	0.023	0.015	
	2(2p)	1	−1755.02	885.51	0.503	0.061	0.103	0.015	*MLL*
LOIL, LRIPI	2(3)	0	−1723.34	867.67	0.029	0.087	0.025	0.015	
	2(3p)	1	−1744.54	880.27	0.264	0.076	0.104	0.015	
LRINT, LRCPI	2(4)	0	−1740.35	876.17	0.445	0.061	0.021	0.015	
	2(4p)	1	−1753.83	884.91	0.441	0.064	0.111	0.015	
LRINT, LRIPI	2(5)	0	−1722.76	867.38	0.042	0.083	0.023	0.015	
	2(5p)	1	−1745.84	880.92	0.244	0.074	0.114	0.015	
LRCPI, LRIPI	2(6)	0	−1737.69	874.84	0.452	0.061	0.009	0.015	
	2(6p)	1	−1751.60	883.80	0.462	0.064	0.097	0.015	
LOIL, LRINT LRCPI	3(1)	0	−1744.77	880.38	0.491	0.056	0.045	0.014	
	3(1p)	1	−1755.36	887.68	0.500	0.060	0.118	0.015	*AIC*
LOIL, LRINT LRIPI	3(2)	0	−1723.76	869.88	0.043	0.081	0.045	0.015	
	3(2p)	1	−1744.60	882.30	0.259	0.074	0.121	0.015	
LOIL, LRCPI, LRIPI	3(3)	0	−1741.31	878.65	0.487	0.058	0.029	0.015	
	3(3p)	1	−1752.67	886.33	0.502	0.061	0.106	0.015	
LRINT, LRCPI, LRIPI	3(4)	0	−1738.86	877.43	0.455	0.060	0.027	0.015	
	3(4p)	1	−1752.56	886.28	0.449	0.062	0.117	0.014	
LOIL LRINT, LRCPI, LRIPI	4(1)	0	−1743.02	881.51	0.491	0.056	0.052	0.014	
	4(1p)	1	−1753.40	888.71	0.495	0.059	0.123	0.014	

Note: R^2 is the coefficient of determination. *sd* is standard deviation. The response variable is exchange rates. Regime 1 consists of low-volatility periods and regime 2 consists of high-volatility periods. $\Delta(-2MLL)$ is the difference of $(-2MLL)$ when the variable is removed from the model with the smallest *AIC*, according to the backward selection method. 'p' in the model names means that the model includes auto-regressive terms, AR(1).

Each time point is grouped into one of the two regimes depending on its estimated filtered probability. At each time point t, the two filtered probabilities sum to 1. Figure 2a shows estimated probabilities of regimes. The upper plot presents the estimated probabilities of being in the regime 1 with low-volatility. The lower plot presents the estimated probabilities of being in the regime 2 with high-volatility, which consists of two periods. The first period lasted for 15 months from October 1997 to January 1999. The second period showed up for 11 months, once in April 2008 and then from August 2008 to May 2009.

Figure 2b,c shows volatilities of the raw data with grey area indicating regime 1 and regime 2, respectively, which are estimated based on the MRSM. Estimated high-volatility periods match the peaks around the Asian financial crisis in 1997 and the global financial crisis in 2008. Korean exchange rates markets suffered great instability during both periods.

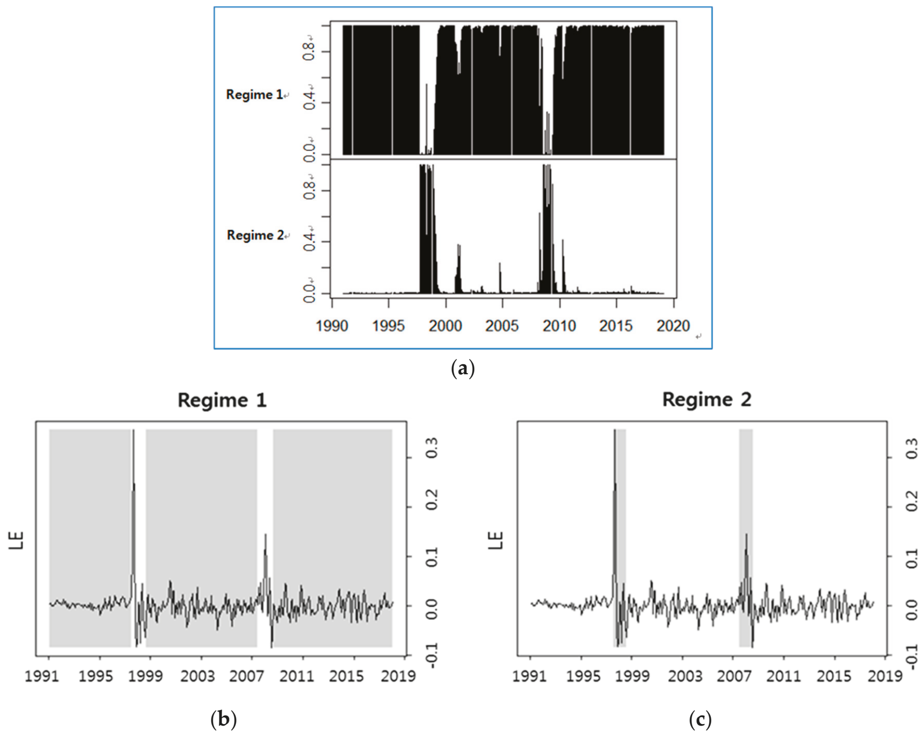


Figure 2. (**a**) The filtered probabilities of being in regime 1 and regime 2, estimated from the MRSM for the exchange rates along with both oil prices and *CPI*s. The upper plot corresponds to the regime 1 with low-volatility, and the lower plot corresponds to the regime 2 with high-volatility. (**b**) Volatility plot of regime 1. (**c**) Volatility plot of regime 2.

We also examine how the explanatory variables influence the exchange rates in each regime, based on the selected best model 2(2p). Table 3 presents the parameter estimates for both regimes. The volatility of regime 2 with high-volatility ($\sigma_2 = 0.0610$) was about four times that of regime 1 with low-volatility ($\sigma_1 = 0.0148$). In regime 1 with low-volatility, Korean exchange rates were not significantly influenced by any of the explanatory variables, but had positive dependence on their auto-regressive term ($p < 0.001$). In regime 2 with high-volatility, the variable *LOIL* positively influenced the exchange rates ($p < 0.05$) and the variable *LRCPI* positively influenced the exchange rates to a much greater extent ($p < 0.001$). This shows that the exchange rates increase as oil prices or *CPI*s increase when the exchange rates markets are highly volatile. We observe that, in a highly volatile market, the exchange rates are significantly influenced by *CPI*s and oil prices but have no significant relationship with their auto-regressive terms. In a low-volatility market, only the auto-regressive terms are significant.

Table 3. Parameter estimates of the selected Markov two-regime switching model.

Regime	Parameters	Estimates	Standard Error
Regime 1 with low-volatility	Intercept (β_{01})	−0.0001	0.0004
	LE_{t-1} (β_{11})	0.2740	0.0563 ***
	$LOIL_t$ (β_{21})	−0.0230	0.0148
	$LRCPI_t$ (β_{41})	0.1058	0.2242
	Residual standard error	0.0148	
	Multiple R^2	0.1028	
Regime 2 with high-volatility	Intercept (β_{02})	0.0005	0.0108
	LE_{t-1} (β_{12})	−0.0462	0.2092
	$LOIL_t$ (β_{22})	0.2181	0.1084 *
	$LRCPI_t$ (β_{42})	9.4279	2.2969 ***
	Residual standard error Multiple R^2	0.0610 0.5025	
Transition probabilities	p_{12}	0.0811	
	p_{21}	0.0081	

Note: The response variable is exchange rate. The explanatory variables are oil prices and *CPI*. β_{01} and β_{02} are intercepts for regime 1 (low-volatility) and regime 2 (high-volatility). β_{11} and β_{12} are the coefficients of oil prices, β_{21} and β_{22} are the coefficients of *CPI*'s, β_{p1} and β_{p2} are the coefficients of (*t*-1) exchange rates, and σ_1 and σ_2 are the standard deviations of the two regimes. ***: significant at the 0.001 level. *: significant at the 0.05 level.

The each transition probabilities are $p_{11} = 0.9189$, $p_{12} = 0.0811$, $p_{21} = 0.0081$, and $p_{22} = 0.9919$. The transition probability from the regime with low-volatility to the regime with high-volatility is about ten times that of the opposite case. The regime with low-volatility can much more easily transit to the regime with high-volatility when the explanatory variables change. This indicates that the Korean exchange rates market is, thus, vulnerable to external shocks.

Let us take a look at how much log-differentials of each explanatory variable can explain among the whole volatility of log-differentials of the exchange rates using the simple regression. The coefficient of determination R^2 in Table 2 shows the proportion of explained volatility compared to the total volatility of log-differentials of the exchange rates. In the regime with high-volatility of the model 1(3), we can see that the *CPI*s alone explains 43.6% of the exchange rates (R^2 = 0.436).

We extend this to the models with two explanatory variables. In the regime with high-volatility with model 2(2), the *CPI*s and oil prices together explain 49.0% of the exchange rates, a 5.4% increase in R^2. In addition, if the exchange rates auto-regressive term is added, as in model 2(2p), the R^2 value increases to 50.3%, an additional increase of 1.3%. All the coefficients of determination in the regime with low-volatility were quite small. Our model explains regimes with high-volatility much better than regimes with low-volatility. One interesting point is that the volatilities estimated in regimes with low-volatility, for all 30 of the models, were around 0.015.

4. Discussion

Let us compare the results with others which used the regime switching model. The previous regime switching model for oil prices and exchange rates of Korea includes Basher et al. [11]. In their findings, oil shocks had a statistically significant impact on exchange rates of Korea in the high-volatility regime, which is the same as ours. Their model assumed that exchange rates could be influenced not only by oil prices, but also by oil supply and global economic demand. Our model differs from theirs in that exchange rates are affected by price level, income, and interest rates as well as oil prices which are based on the monetary model of exchange rates determination. Nonetheless, the same conclusion was drawn that exchange rates are affected by oil prices in a high-volatility regime.

In Table 4, the auto-regression model without regime switching is also fitted for comparison. R^2 in the model is 0.247, which is much less than 0.503 in the high-volatility regime. *LRCPI* is significant ($p < 0.01$) but oil prices are not ($p > 0.1$). In the absence of regime switching, only *LRCPI* and auto-regressive terms affect the Korean exchange rates. In other words, oil prices do not appear to affect the exchange rates, which is different from the results with MRSM. In the presence of Markov regime switching, oil prices significantly affect the exchange rates in the unstable regime. Thus, in models without Markov regime switching, the behavior in the stable regime overwhelms the behavior in the unstable regime. Korea has experienced two major economic crises, the Asian financial crisis and the global financial crisis, which are precisely detected by the MRSM. Therefore, it can be seen from this study that stable management of oil prices is essential for stabilizing exchange rates in these economic crises.

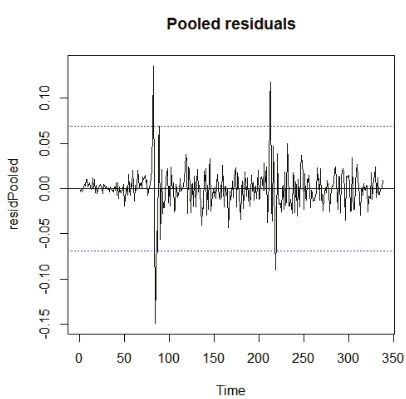
Table 4. Parameter estimates without the regime switching model.

Parameters	Estimates	Standard Error
Intercept (β_{01})	−0.0003	0.0015
$LE_{t-1}(\beta_{11})$	0.3969	0.0535 ***
$LOIL_t$ (β_{21})	0.0225	0.0226
$LRCPI_t$ (β_{41})	0.3442	0.3649 ***
Residual standard error	0.0266	
Multiple R^2	0.2475	

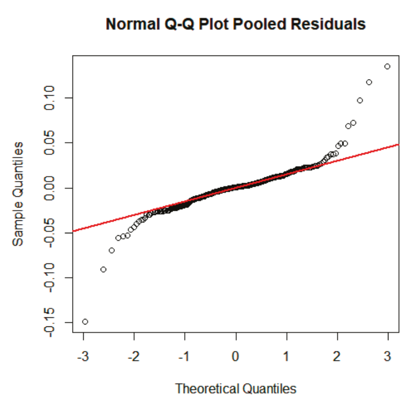
Note: ***: significant at the 0.001 level.

A long period time series data in this research often contains more than two different trends throughout the whole time period. We fit the two-regime MRSM, which estimates separate auto-regression models with AR (1) in each regime and the volatility state at each time point can switch between the two regimes according to the behavior of a Markov process.

Now, we check the assumptions of the errors, normality, and stationarity. The normality can be observed in the four residual plots in Figure 3. Plot (a) represents pooled residuals, where two distinctive high-volatile periods are observed, one around 1997–1998 and the other around 2008–2009. Plot (b) shows the normal quantile-quantile (QQ) plot of pooled residuals with $p = 0.7998$ from the Shapiro test. Separate QQ plots in the two regimes, plots (c) and (d), reveal more distinctive normality based on the Shapiro test ($p = 0.0708$ for regime 1 and $p = 0.6241$ for regime 2). The residuals in each regime show clear normal distribution, while pooled residuals seem to have outliers at both tails.

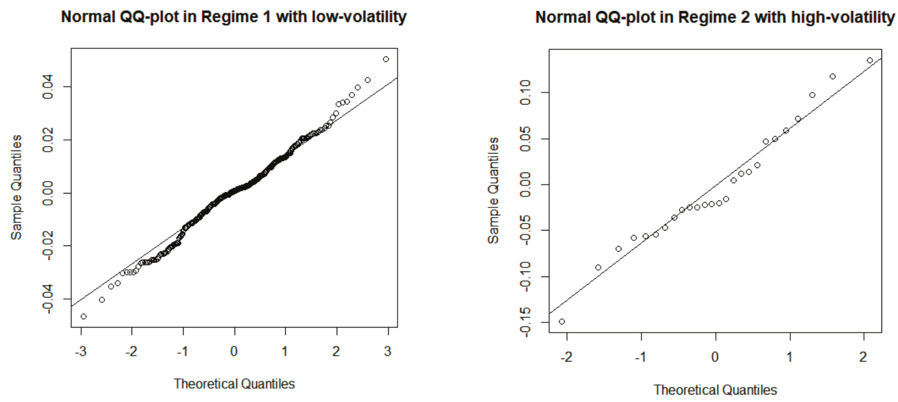


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. These figures show the following four plots of residuals: (**a**) pooled residuals over time order; (**b**) normal quantile-quantile (QQ) plot of pooled residuals; (**c**) normal QQ plot of residuals in regime 1 with low-volatility; (**d**) normal QQ plot of residuals in regime 2 with high-volatility.

The stationarity can be observed by the autocorrelation function (ACF) and the partial autocorrelation function (PACF) of the residuals in Figure 4. Both ACFs and PACFs go to 0 as lag increases, which means stationarity of the residuals. Based on the Dickey–Fuller unit root test, the series LE_t is stationary (p = 0.0100), but the raw *Exchange Rate*$_t$ before the transformation is not stationary (p = 0.4369). The adequacy of the selected model 2(2p) is confirmed by the normality based on QQ-plots and the Shapiro tests, and by the stationarity based on the Dickey–Fuller unit root test. All these goodness-of-fit results ensure relevance of selected explanatory variables in the model.

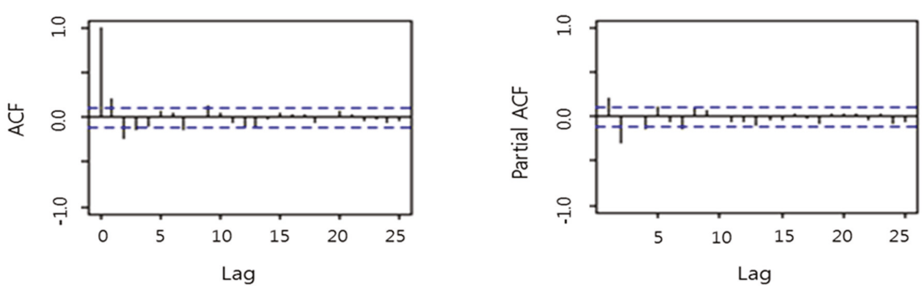


Figure 4. Plots of the autocorrelation function (ACF) and the partial autocorrelation function (PACF) of residuals.

The parameter estimates for the MRSM were consistent in this study, even though they were known to be slightly inconsistent in each run as pointed out in the studies of Campbell [35], Kim, et al. [36], and Yuan [37]: "The unfiltered two-state Markov-switching model suffers estimation instability while the filtered model turns out to be temporally consistent" or "the Maximum Likelihood Estimator is inconsistent for regime-switching models in general".

5. Conclusions

We analyzed the effects of oil prices, interest rates, *CPI*s, and *IPI*s on the regime shift behavior of the Korean exchange rates (against the USA.). This was the first attempt to study these issues, as far as we know. As a result of the MRSM, we detected regime shift behavior in the exchange rates, along with oil prices and major macroeconomic explanatory variables.

For this, we first set up a total of 30 models in consideration of the four variables to select the optimal MRSM, based on the *AIC* and *MLL*. Finally, we selected the model that includes oil price, the difference of *CPI*s between the two countries (Korea and the USA), and the autoregressive term of the exchange rates.

Under the selected MRSM model, we found evidence to support the existence of two distinct regimes for all markets, one regime (1) with low-volatility and another regime (2) with high-volatility. The stable periods of regime 1 are much longer than the unstable periods of regime 2. The most unstable periods lasted for about two to three years. Regime 2, with high-volatility, occurred during the Asian financial crisis of 1997 and the global financial crisis of 2008–2009 in the Korean exchange rates market.

During the stable periods in the regime 1 with low-volatility, the Korean exchange rates were not significantly influenced by any of the explanatory variables, but had positive dependence on their auto-regressive terms at the 1% significance level. This implies that movements of changes of exchange rates are explained by their own previous movements, not by external variables during the stable periods. In the regime 2 with high-volatility, Korean exchange rates were significantly influenced by *CPI*s and oil prices, while their auto-regressive terms had no significant effect on the exchange rates. In other words, Korean exchange rates are more affected by external shocks than by their previous exchange rates during high volatile periods. As far as the exchange rates are concerned in the Korean market, *IPI*s and interest rates are not significant.

This result has very important implications about estimating the movements of changes of Korean exchange rates. Changes in oil prices significantly affect the prediction of Korean exchange rates during unstable periods. On the other hand, the consumer price level (compared to that of the US) has a much greater impact on the changes of exchange rates, compared to oil prices, in the Korean market. In other words, when the consumer price levels in Korea rise higher than those in the US, the movements of the changes of Korean exchange rates accordingly increase. Thus, maintaining stable consumer price levels in Korea contributes to the stabilization of Korean exchange rates.

When the major macroeconomic explanatory variables change, the regime with low-volatility could transit to the regime with high-volatility with 10 times higher transition probability than that of the opposite direction (i.e., from high to low). Thus, the Korean exchange rates market is vulnerable to external shock.

This study has the following limitations. Exchange rates are affected by both *CPI*s and *IPI*s, but both *CPI*s and *IPI*s can be also affected by exchange rates. However, this study does not consider this backward possibility. In other words, we only studied one-way analysis of *CPI*s and *IPI*s affecting exchange rates. In the future, this study can be extended to other countries which import and export oils to a great extent. New explanatory variables can be also added in future researches. Our results will provide valuable insights for Korean policy makers, about how to prepare for external shock, and also to Korean foreign exchange dealers, when they make decisions on foreign exchange speculation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The Markov Regime Switching Models for exchange rates along with oil prices, interest rates, CPI's and IPI's.

Model Number	Equation
1(1)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \varepsilon_t\|s_t$
1(1p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \varepsilon_t\|s_t$
1(2)	$LE_t\|s_t = \beta_{0s_t} + \beta_{3s_t}LRINT_t + \varepsilon_t\|s_t$
1(2p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{3s_t}LRINT_t + \varepsilon_t\|s_t$
1(3)	$LE_t\|s_t = \beta_{0s_t} + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
1(3p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
1(4)	$LE_t\|s_t = \beta_{0s_t} + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
1(4p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(1)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \varepsilon_t\|s_t$
2(1p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \varepsilon_t\|s_t$
2(2)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
2(2p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
2(3)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(3p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(4)	$LE_t\|s_t = \beta_{0s_t} + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
2(4p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
2(5)	$LE_t\|s_t = \beta_{0s_t} + \beta_{3s_t}LRINT_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(5p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{3s_t}LRINT_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(6)	$LE_t\|s_t = \beta_{0s_t} + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
2(6p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(1)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
3(1p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \varepsilon_t\|s_t$
3(2)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(2p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(3)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(3p)	$LE_t\|s_t = \beta_{0s_t}e + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(4)	$LE_t\|s_t = \beta_{0s_t} + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
3(4p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
4(1)	$LE_t\|s_t = \beta_{0s_t} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$
4(1p)	$LE_t\|s_t = \beta_{0s_t} + \beta_{1s_t}LE_{t-1} + \beta_{2s_t}LOIL_t + \beta_{3s_t}LRINT_t + \beta_{4s_t}LRCPI_t + \beta_{5s_t}LRIPI_t + \varepsilon_t\|s_t$

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Article

Causality Relationship Between Electricity Supply and Economic Growth: Evidence from Pakistan

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Abstract: The long-term anticipation of electricity supply (ELS) and demand has supposed substantial prominence in the elementary investigation to offer sustainable resolutions to electricity matters. In this editorial, an outline of the organization of the electricity segment of Pakistan and analysis of historical supply and demand statistics, an up-to-date position of the contrary set of energy plans is presented. The intention of this analysis is to explore the Granger causality relationship between electricity supply and economic growth (EG) by using a multivariate context with time series statistics covering 1990 to 2015 in Pakistan. Augmented dickey-fuller (ADF) and Philips-Perron (PP) unit root tests indicate that variables are non-stationary and integrated in a similar order (1). Our findings also reveal that variables economic growths (GDP), electricity supply (ELS), investment (INV), and export (EX) are co-integrated. The study also finds the Granger causality runs from EG to ELS deprived of any feedback effect. Therefore, the policy implications from our findings indicate that electricity preservation strategies may be implemented without any economic adverse impacts.

Keywords: electricity supply; economic growth; relationship; Pakistan

1. Introduction

The energy performs an overriding part in the economic growth (EG) of every economy and is also a definitive constituent for its prosperity because numerous production and consumption activities implicate energy as an elementary input. In addition to investment and labor, it is deliberated as a third imperative production element in economic models [1]. It associates with ELS, EG and societal steadiness. Electricity is an imperative form of energy and is regarded as the foundation of energy that assists each phase of any economy [2–5]. From a natural point of observation, the usage of electricity motivates monetary efficiency and industrial evolution and is very significant for the operation of every contemporary economy [6]. The significance of the electricity supply was recognized in the beginning of the 20th century. It was the time when the data on supply and demand of electricity became widely accessible. During the industrialization era of the last century, electricity use enhanced briskly and its demand almost doubled. The slight decline in EC (electricity consumption) was noted during the subsequent war retrieval era. The similar trends of an empirical assessment of EG and EC were recorded for the USA. It was this opinion which attained consideration of academics to explore this liaison between EC and EG in order to demonstrate the causal correlation of its nature.

The link between EC and EG is significant and pertinent—even in an industrializing economy. Imperative factors that may affect the relationship between ES and EG could cause oscillations in energy prices, climate variations, energy security and environmental issues. It is also significant to note what type of energy origins are being applied for power generation. If non-renewable sources, e.g., coal, are vigorously utilized, a possible outcome may be great intensities of carbon discharges into the environment. In contrast, in a situation of the inadequate yield of energy raw resources, there could be issued a confirming permanency of reproduction progression, which would affect the speed of financial development. This condition is relatively correlated with emerging economies. Nowadays, several developing economies have power scarcity issues. A suitable and sustainable ES may perhaps be one of the utmost critical elements, which supports economic development in evolving nations [7]. For instance, South Africa produced 92% of its electricity from coal, which caused 42% of emissions across the continent [8]. This has caused an imbalance between demand and ELS. This has resulted in turmoil in the industrial sector in the country and therefore EG [9].

Pakistan, a South Asian economy, is passing through a severe power crisis due to policy failures in the energy sector, which leads to the miserable monetary conduct of the republic. The demand of electricity is driven by populace evolution along with additional dynamics such as tariffs, migration to metropolises and weather. Nevertheless, the major cause of electricity scarcity and this crisis is mainly instigated by larceny, exploitation, and unnecessary wastage of electricity, irrationally instigating massive line losses, maladministration, corruption, institutional weakness, and political involvement [10]. The population of the country is on a rise, which in turn increases the electricity demand [11]. The electricity supply has not been consistent with population growth and electricity demand, which has resulted in frequent unscheduled outages. These circumstances have caused problems for industries and have hindered FDI in the country [12–15].

Pakistani energy division has been described by scarcity and resource restraints. Total installed capability to produce electricity as by February 2019 stands at 33,836 MW, consisting of 31% natural gas, 29% hydro, 16% coal, 14% furnace oil, 5% renewables (solar and wind), 3% nuclear, and 1% other sources (Bagasse, waste heat recovery, etc.). The total ELS have increased during 1990–2015. Nevertheless, factually it has been established that capability extension continuously remains short behind of the objective. On the consumption side, per capita electricity consumption was 971 kWh annually for the year 2015–2016, which is one of the lowermost in the world.

The connection between EC and EG has experienced broad exploration after oil impediments in the 1970s. The central issue has been if EC stimulates EG, or whether the EG itself is an incitement for EC through the indirect medium of significant cumulative demand, enhanced total efficacy and scientific growth. Brown and Yucel [16] deliver a study of the concept and indication on the macroeconomic influence of energy rates. The association between EC and EG was also determined as well as tariff effects. The level of EC may be considered as an indication of EG and socioeconomic progress of a country. Multiple investigations have attempted to observe the causality link between EC and EG. Some other researchers [17,18] delivered some useful outcomes related to Granger causality between EG and EC for multiple economies. Nevertheless, it has been evident from these studies that the specific role of EC in EG has presented diverse outcomes across countries and time periods. Gosh [19] studied co-integration and Granger casuality for India by applying the Joahnsen and Juselius method. This work was not able to find a cointegration link but established short-run Granger casuality directing from EG to EC lacking any feedback effect.

The liaison between EC and EG was vastly investigated by means of the theory of Granger causality. Granger causality does not suggest that 'X causes Y', as in traditional logic. Rather, as Diebold [20] proposes it, 'X causes Y' in the Granger logic proposes that 'X comprises valuable evidence for forecasting Y'. Until now, there is a deficiency of agreement in the literature. The primary cause for this disagreement could be the omitted variables in the Granger causality investigations.

Enquiries which investigated Granger causality in a bi-variate context are most likely influenced by the exclusion of pertinent variables influencing EC and EG [21]. As a result, few Granger causality inquiries determining the nexus between EC and EG have introduced other related variables such as investment besides labor [22], occupation [23], exports [24], chemical emanations [25], prices [26], or urbanization [27]. Multiple prevailing Granger causality inquiries of energy-GDP correlation, which used a bivariate context, have been unsuccessful to discover indication of co-integration and long-run causation, demonstrating the application of bivariate scheme [28–30]. Taking into consideration these constraints, it is essential to reconsider the link between energy and EG together with related variables in the Granger casuality agenda, specifying its consequences for energy preservation.

A few studies of the energy–GDP link also applied the multivariate context [31–40]. Govindaraju et al., [41], incorporated prices together with EC and EG, Ang [25], used greenhouse gasses emission along with EC and EG, whereas Lean and Smyth [42], used investment, exports and labor besides EC and EG. This work adds more to the literature by determining the link between electricity generation, EG, prices and exports. A four VAR instance includes additional evidence than the bivariate setting, causing casual conclusion drawn further reliable [43–45]. Some studies used electricity generation instead of electricity consumption. Yoo and Kim [45] (for Indonesia) and Ghosh [46] (for India) used this technique in emergent economies as T and D losses are frequently extraordinary. According to WB [47], these losses in evolving republics are two to four times greater when compared to OECD economies [48]. As a consequence, EC statistics are underrated. On the other hand, it is more useful to use electricity production as a suitable representation for electricity. We used investment due to its significance in prompting EC and income.

Including ELS, exports, EG and investment in the lone model efficiently marries the Granger casuality literature with the energy–GDP interconnection and exports–GDP link. This type of methodology was used by Narayan and Smyth [23], who presented a panel statistics enquiry for the Middle East. In this exploration, writers used export elevation approaches to understand the great degree of EG [49]. Lean and Smyth [42] examined the Granger casuality between EG, EC and trades for Malaysia; however, they used EC instead of electricity supply, which is less suitable for an evolving economy, as we have discussed. The main aim of this enquiry was to review the electricity–GDP link in Pakistan, as this study diverges from former studies on the subsequent features:

Firstly, this study applies statistics on ELS in a state such as Pakistan, where there are high R and D losses, primarily due to larceny, corruption, mismanagement, institutional issues and ancient infrastructure. Conversely, apart from these losses, entire electricity generated aids to GDP. This provides a possible motivation for applying ELS as a variable instead of demand. Yoo and Kim, 2006 [45] examined a causative link between ELS and EG for Indonesia by employing a time series approach for the era of 1971–2002.

Secondly, the work applied a multi-variate technique over a bivariate technique due to description bias due to the exclusion of appropriate variables [50–52]. Different from former studies e.g., Chang et al., 2001 [50]; Narayan and Smyth, 2005 [23]: Gosh, 2009 [46], this study includes investment and export along with ELS and GDP.

Thirdly, the sample period for investigation is from 1990–2015. The period for the enquiry has been governed by the accessibility of data, which is available simultaneously for all four variables from 1990 onwards.

2. Hypothesis

The first set of the competing hypothesis is associated with the correlation between ES and GDP. The relationship between ES and GDP can be explained by four hypotheses. They include growth, conservation, feedback and neutrality hypothesis. These hypotheses about the energy-GDP link have imperative strategy insinuations. Provided that there is uni-directional Granger casuality directing from GDP to ES or no Granger causativeness in either way, it could be concluded that energy preservation strategies have a minute or no adversative consequence on EG. In contrast, when uni-directional Granger causativeness directs from ES to GDP, declining ES in the market may perhaps result in a drop in income, while an upsurge in ES contributes toward EG.

The second set of opposing hypothesis is related to the causal link between exports and GDP. The hypotheses have been deliberated in exports-GDP link literature. The export run hypothesis elaborates that Granger casuality directs from exports to GDP. There could be multiple causes of Granger causativeness direct from exports to GDP [53]. Exports escalate GDP as they are constituent of GDP in state accounting. Indirectly, economies with more exports to GDP ratio are more prone to external impacts and produce externalities, e.g., inducement to innovate. These efficacy advantages enhance GDP through enhancing TFP in the Solow-Swan growth accounting context. The contending hypothesis that Granger causativeness directs from GDP to exports is taken in deviations of concepts of trade [53], or contention that growth instruments that are internally created best clarify the evolution of exports [54]. Assuming there is a rise in TFP caused by technical advancements that are autonomous from trade, the proportional price arrangement, such as economy, will possibly develop in a mode that is constant with increasing exports [55].

The third array of the conflicting hypothesis is associated with the connection between exports and ES. If Granger causativeness directs from ES to exports, declining ES could obstruct efforts to increase exports as a source of EG. Conversely, if there is Granger casuality directing from exports to ES or no Granger causality directing in whichever direction, it tracks that energy management programs might be anticipated to have no adversarial consequence on export progression.

The fourth set of hypothesis discusses the connection between investments, ELS, EG, and exports. A rise in investment may result in an enhancement in ES, while an enhancement in ELS may lead to more investment. Ultimately, an increase in investment may result in more exports and raise economic growth.

3. Pakistani Perspective

Pakistan is administrated by a central legislative constitution. It is the sixth outmost populated nation with inhabitants of more than 200,000 million persons and a relatively high populace growth level of 1.5% [56]. It is a quasi-industrialized state with a respectable textile, food processing and agriculture support and a per capita GDP of 1561 USD. Conferring to WB, Pakistan has significant tactical bequests and progress possibilities. It has the 10th biggest labor market internationally and it is 67th among worldwide exporters [57].

Traditionally, Pakistan is one of the biggest oil importers and is largely reliant on fossil fuels. With the upsurge of fossil fuel costs, the price of importing oil is causing a loss for the country's FX reserves. The mounting cost of oil along with the growing demand for continuous electricity supply is building an extra burden on the previously delicate ELS network of Pakistan. Consequently, to meet this mounting demand, the government has allotted a huge investment in their energy expansion portfolio [58–60].

Over the past few decades, the increase in power outages and per capita EC in Pakistan lurched the state into a relentless power calamity, resulting in meager monetary conduct of the country. It has urged the policymakers to look for measures to enhance the electricity supply and to upgrade electricity infrastructure including generation, transmission, and distribution. Electricity organization scheduling is jointly associated with the electricity demand and upsurge of GDP—particularly in an emergent republic such as Pakistan. Jamil and Ahmad determined unidirectional causality between EG and EC, which suggests growing electricity demand with greater EG [61]. The electricity demand increase is remarkably owed to a steady 6% GDP growth annually from 2002 to 2007 and with no structure development in electricity division, economy encountered huge power outages, which led to a 2.5% damage to GDP, 0.535 million job cuts and damage to exports of value $1.3 billion in 2010 [62].

Energy plays a governing part in economic development and also is an essential element of every state's economy. It associated with energy safety, EG and social permanence. Energy economics is a systematic investigation of assigning sources for ELS to a civilization. It is severely dependent on strategies and demand and supply interaction of the energy market, which is the primary cause of ambiguity for energy managers, which generally emphasizes providing an atmosphere for resource ventures in energy division [63].

Evidently, forthcoming energy strategy coordination is generally founded on various economic factors along with political and environmental parameters that decide the expertise to be used to approach impending energy demand. The power sector in Pakistan has been disastrous due to insufficient maintenance of power plants, exploitation of subventions in power charges and defective anticipating of the energy mix that could lead to a non-coverable deficit of electricity [64], and accumulation of huge circular debt [65,66]. Moreover, there are numerous problems in Pakistan related to energy security and infrastructure expansion for a consistent supply of electricity that will also stimulus forthcoming policy implications.

The installed capacity to produce electricity of Pakistan is almost 33,836 MW by February 2019, which was approximately 23,337 MW in 2015, indicating the progression of 45% in five years. This capacity was almost 21,036 MW in 2011 [67,68]. Electricity production sources mainly comprise of thermal energy (oil and gas) hydropower and nuclear power. Presently, Coal and RE are performing a minor part; however, they are anticipated to be increased in imminent years [69]. The recognized renewable energy sources are generally wind energy, solar energy and biomass. Thermal, hydropower and nuclear power plants are the constituents of the hybrid electric industry in Pakistan [70] (Figure 1). Additionally, Table 1 compares electricity sources as the percentage of total electricity generated by emerging economies. It is obvious from this comparison that emerging countries such as India, China, Brazil, and South Africa have steadily enhanced their energy sources, differentiating into cleaner and effective energy sources. Amongst all these countries, only Pakistan has constantly persisted on similar energy sources for the period of years deliberated.

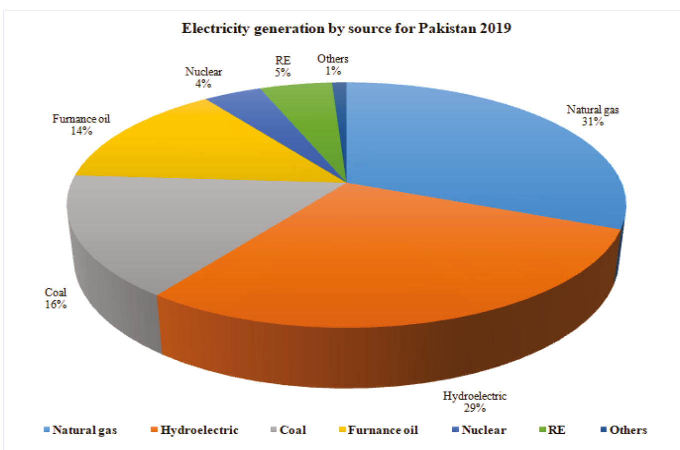


Figure 1. Electricity generation by source for Pakistan 2019 (Source: Ministry of finanace, Pakistan).

Table 1. Electricity sources as the percentage of total electricity generated.

Year	Countries	Coal	Oil	Natural Gas	Hydro	Nuclear	RE
1990	Pakistan	0.101	20.56	33.62	44.92	0.77	0
2010		0.93	35.16	27.41	33.7	3.62	0
2015		0.137	37.22	25.72	30.67	4.78	0.75
1990	China	71.03	8.1	0.44	20.39	0	0.01
2010		77.18	0.35	1.86	16.07	1.76	1.67
2015		70.3	0.16	2.48	19.07	2.33	4.85
1990	India	65.46	4.54	3.4	24.47	2.09	0.01
2010		67.17	2.49	11.56	12.56	2.68	3.47
2015		75.3	1.66	4.92	9.98	2.79	5.36
1990	Korea	16.76	17.89	9.11	99.84	50.19	0.01
2010		44.14	3.81	20.77	0.74	29.91	0.54
2015		43.07	2.27	22.36	0.39	29.99	1.5
1990	Japan	13.49	21.81	19.55	9.95	23.18	1.29
2010		27.15	6.86	27.94	7.21	25.28	3.32
2015		33.15	7.51	39.58	8.22	0.91	7.75

Collected by the investigator from WDI of WB.

The electricity supply of Pakistan has steadily preserved an ascending inclination. Pakistan displays a slower rate of progress in electricity supply, as shown in Figure 2. This discloses that ES may translate into EG and serves as the main factor for the progressing economy of a country. In the same way, per capita economic growth (%) has constantly been escalating. From 2005 to 2010, a decline was noticed and subsequently a gradually rise has been noted. The problem of power losses has been a prime concern for electricity supplying companies in Pakistan (Figure 3). This issue is caused by inefficient and old T and D networks.

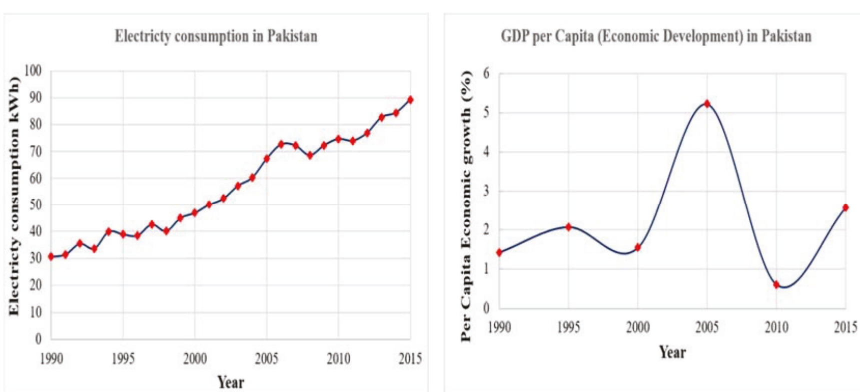


Figure 2. Electricity supply and GDP per capita in Pakistan.

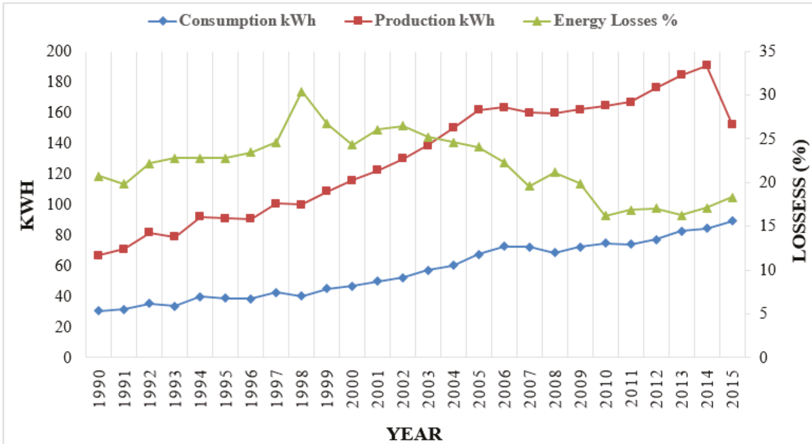


Figure 3. Total electricity generation, consumption and losses (1990–2015).

In the future, the demand for electricity will augment in various segments, together with manufacturing, building, education, farming and significantly, in sustainable growth to lift economic division [71]. Most of this supplied electricity is coming from thermal sources [72], which are also causing huge damage to the environment. The demand for electricity in Pakistan is dictated by multiple factors, e.g. rising population, urban influx, economic development, weather and electricity cost. Conversely, an explicit issue faced by the country is electricity scarcity, which was instigated by larceny and extreme consumption of electricity, leading to massive damage to the power grid and misconduct in mega-power ventures [73,74]. Pakistan undergoes energy deficiency due to production and supply.

3.1. Power Segment Arrangement in Pakistan

The administrative arrangement of Pakistan's electricity sector primarily comprised of four major divisions including WAPDA, PEPCO, PPIB, and KESC, the last one go through privatization in 2005, as shown in Figure 4.

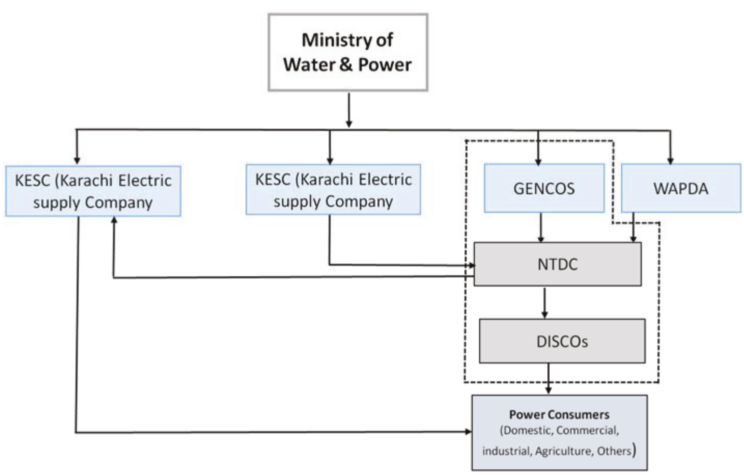


Figure 4. An illustrative outlook of the electric power division of Pakistan.

WAPDA is a semi-sovereign unit with legislative power that was formed in 1958 to manage the organization progress of power and water-related ventures. WAPDA was separated into binary discrete bodies, explicitly, WAPDA and PEPCO. WAPDA is responsible for hydro production and organization expansion. PEPCO comprises of four GENCOs, eight DISCOs, and NTDC, which are allocated the part to restructure, reform and transform these companies into profitable associations. PPIB deals with IPPs, which were brought into the organization as a result of the administration strategy that was presented in 1994 to entice private venture for thermal power production. KESC is solely a perpendicularly unified power corporation responsible for the production and distribution of electricity to metropolitan Karachi [30]. The transmission section of the division is controlled by NTDC. NTDC is a state grid corporation with the independent transmission of electricity throughout Pakistan apart from KESC. Its main aim was to interconnect new power plants to the national grid, the formation of investment policies for transmission systems and grid stations. The distribution subdivision is accomplished by eight community DISCOs, which oblige final customers with an extra charge of electricity tariff retrievals. In recent years, per capita power consumption has enhanced [75]. For that reason, it is essential to propose impeding demand side management of electricity (Figure 5).

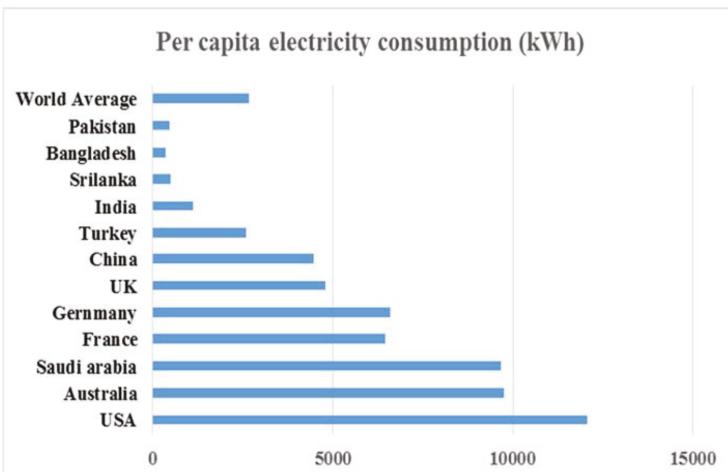


Figure 5. Evaluation of per capita EC for selected nations (Source: BP Statistical review).

3.2. Exploration of Electricity Demand

The final customers are primarily classified as domestic, agriculture, industry and other utilities. The domestic segment covers predominately almost 80% of clients, which is expanding at an average of 3.6% per annum for the past decade, transforming the electricity grid into a complex system leading to enhanced trouble while it arises to forecast the load supervision at peak hours. The admittance to electricity to the population has relatively risen in the last few years [76,77]. The industrial customers are also expanding including textile, cement, and leather industries, which need constant electricity supplies [78]. The commercial sector generally constitutes HT customers and is rising at 2.46% in regards to electricity clients [79]. In the meantime, EC in agriculture sector is expanding 3.02% annually, granting employment to approximately half of the residents of the state [80]. The sector wise exploration of the country indicates that strategies must be executed with the view to supply adequate electricity that is required to increase the production of industrial and service sectors since these segments are associated with electricity requirement than agriculture [81].

3.3. Study of Electricity Supply

An EL in Pakistan is mainly concentrated on non-renewable resources. Fossil fuels supply a major portion of electricity production in the country. Fossil fuels are succeeded by hydropower, which is almost one-third of overall production [82]. The installed capacity of electricity supply has enhanced predominantly in recent years. The difference between electricity generation and demand is basically a result of a circular debit problem in the supply chain system of electricity division.

The ELS is generally delivered by WAPDA, GENCOs, IPPs, KESC, and PAEC. IPPs, which are essentially oil and gas plants, provide a major installed capacity. Recently, WAPDA maintained 22 hydel power stations with a gross installed capacity of 9389 MW. According to NEPRA, GENCOs ancient state owned units provide the cumulative installed capacity of 6991 MW. According to IAEA, PAEC deals with nuclear power plants, and the country has five operational nuclear plants with an aggregate generating capacity of 1430 MW.

This research is essentially on the electricity supply in a country where there is huge corruption, electric losses, institution mismanagement problems, and old electricity infrastructure. This fuels the need to study the relationship between electriciy supply, GDP, investment and export.

4. Econometric Methodology and Data

Our empirical enquiry employs annual statistics to explore the causal relationship between ELS and GDP by using the multivariate framework for the period 1990 to 2015 in Pakistan. GDP is a dependent variable while ELS, gross capital formation (GCF), investment (INV), and export (EX) are taken as an independent variable. Electricity supply was collected from the International Energy Agency (IEA) and other variables have been collected from the World Bank (WDI), the description of all variables and source of facts are given in Table 2.

Table 2. Variables and their sources of data.

Variables	Symbol	Definition	Unit	Source
Gross Domestic Product	GDP	Per capita GDP real growth	%	World Bank Indicators
Electricity Supply	ELS	Total Electricity Supply	KWH	International Energy Agency
Gross Capital Formation	GCF	Total Capital	%	World Bank Indicators
Investment	INV	Net inflows	%	World Bank Indicators
Export	EX	Total export	%	World Bank Indicators

The liaison between ELS and EG in Pakistan test the hypothesis whether electricity supply cause GDP or whether GDP cause electricity supply. For this, the study uses an econometric model with the following steps. Step 1: before examining the econometrics analysis, we analyze the descriptive statistics. Step 2: first and foremost, it is compulsory to examine the stationarity of every variable and integration of order in the model, the series should be in the same order as below in Equation (2). Step 3: if the series are incorporated in the same order I (1), we use the Johnsen co-integration test to determine the presence or absence of the relationship. To check this assumption, the number of lag length criteria is chosen for subsequent Johnsen co-integration test whether either series have long-run equilibrium relationship or not. Step 4: further, to check the relationship among ELS, GDP, GCF, INVm and EX, the Granger causality test is used. The Granger casuality method is important for studying the trend of a causal relationship between variables, and this direction of causation provides the strategy insinuations for policy makers (Figure 6).

This inquiry applies the neoclassical production function where technology is resolved by the gross capital formation (K). We consider the following functional form and econometric model of this production function as follows:

$$GDP = f(\text{ELS}, \text{GCF}, \text{INV}, \text{EX}), \quad (1)$$

$$GDP_t = \alpha_0 + \alpha_1 ELS_t + \alpha_2 GCF_t + \alpha_3 INV_t + \alpha_4 EX_t + u_t, \quad (2)$$

where GDP_t indicates the Gross Domestic Product, ELS_t, is the Electricity supply (KWH), GCF_t, is the Gross Capital Formation, INV_t, is the total investment, EX_t, is the total export at time t and u_t is an error term. α_0, is a constant, a_1, a_2, a_3&a_4 denote the output elasticitiy of electricity supply, gross capital formation, investment and export, respectively.

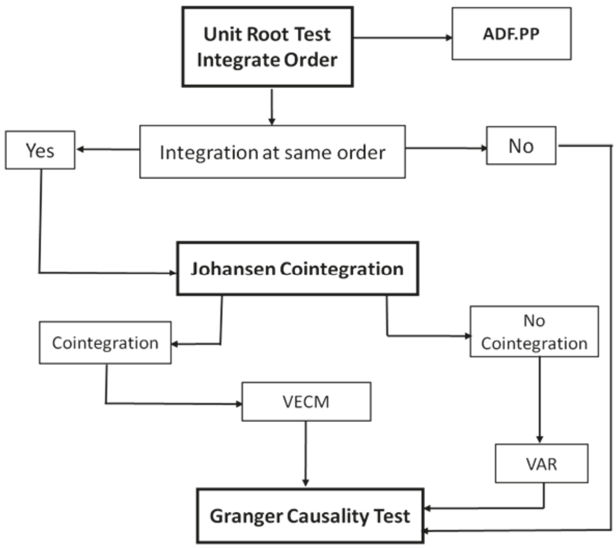


Figure 6. The methodology of the study.

4.1. Unit Root Test

Most macroeconomic time sequence facts contain unit root, integrated of order (1) [83]. A series is integrated of order d as (I (d), if its d'th difference is stationary. If d = 0, then the series will be stationary at level, but if d = 1, the series needs to obtain stationarity at first differencing, then the series will enclose a unit root. The unit root test helps to decide whether the data is stationary or non-stationary, underlying the data generating process of series. If the series has no unit root (stationarity), then it oscillates around a constant mean. On the other hand, if it has a non-constant mean and variance over time, then a series is said to be non-stationary [84]. The study uses the Augmented dickey-fuller (ADF) (1979) and Philips-Perron (PP) (1988) [85] unit root test to explore the stationarity of series, whether the series contains a unit root or not. These tests are broadly used to check the incidence or absence of a unit root test [86]. These unit root tests evacuate the serial correlation by lag selection changes in the residuals of regression [87,88]. The estimation of the ADF test with three models is:

Model 1: without constant and trend:

$$\Delta y_t = \beta y_{t-1} + \sum_{i=1}^{n} a_i \Delta y_{t-i} + u_t. \quad (3)$$

Model 2: with constant:

$$\Delta y_t = \alpha + \beta y_{t-1} + \sum_{i=1}^{n} a_i \Delta y_{t-i} + u_t. \quad (4)$$

Model 3: with constant and trend:

$$\Delta y_t = \alpha + \beta y_{t-1} + \gamma T + \sum_{i=1}^{n} a_i \Delta y_{t-i} + u_t. \quad (5)$$

where α denotes drift (constant), Δ is difference operator; t is a time period, γt is the deterministic trend, n is the optimal lag length, and u_t is an error term. In unit root test, the null hypothesis is the ADF test (H_0: ß = 0, has unit root). The alternate hypothesis is (H_1: ß < 0, has no unit root). The (ADF test statistics) t-value related to the calculated relevant critical values lies on the left side. The null hypothesis is excluded if its t-value is greater than the relevant critical value and has no unit root, which designates that the underlying series is stationary. Contrarily, if it is calculated that the t-value is a less than relevant critical value, then we are unsuccessful to discard the null hypothesis that series are non-stationary. While conversely, the null and substitute hypothesis of PP unit root test are the same as the ADF test. This test is based on the non-parametric statistical method, which removes any serial correlation without lag selection.

4.2. Optimal Lag Length

Most of the time, series statistics is in an autoregressive situation as it can be engaged to residuals, which may create a taint condition into co-integration test results when it is applied. However, the optimal lag length selection is crucial before using the co-integration method. The autoregressive (AR) lag length (p) denote to time series, which shows its current values based on its lagged values of first (p) and are usually indicated by AR (p). The lag length of AR (p) is estimated by lag length selection criteria because it always remains unknown [78]. Numerous criteria are applied for a proper optimal lag length selection in the model such as Schwarz's information criterion (SIC), Akaike's information criterion (AIC), Hannan-Quin information criterion (HQ) and log-likelihood ratio test (LR) criterion. The study uses SIC lag length criterion as follow:

$$\text{SIC} = \text{S ln (â)} + \text{T ln (s)}, \tag{6}$$

where S is the sample size and (â) is an estimated value. The optimal lag lengths of the lowest value of SIC lag length criterions would be chosen for an efficient and accurate model.

4.3. Johansen Co-Integration Test

The Johansen co-integration test is applied to conclude the existence or absence of causlity between variables in time series data. This test is applied when variables are incorporated in similar order and variables are non-stationary at the level. When there is co-integration between series it not only avoids the spurious regression but also discloses that there is equilibrium long-run liaison between series or variable move toghter [89]. In the Johansen co-integration method, two test statistics with the trace statistics and the maximum eigenvalue test information are analyzed. The trace test facts revealed the number of co-integrating vectors and the null and alternative hypothesis of the co-integration test are: H_0: r = 0 against H_1: r > 0 or ≤ 1. Alternatively, the null hypothesis of the maximum eigenvalue is a number of co-integrating vector equal to r and in against alternative hypothesis is r + 1.

H_0: there is no co-integration between series.

H_1: there is co-integration between variables.

$$z_t = \alpha + \lambda_1 z_{t-1} + \ldots + \lambda_p z_{t-p} + u_t, \tag{7}$$

where z_t indicate $(n \times 1)$ vector of variables that are integrated I (1), α denote $(n \times 1)$ vector of intercept, and u_t $(n \times 1)$ is a vector of error terms and λ_1, λ_p are $(n \times n)$ coefficients estimation.

4.4. Granger Causality Test

The Granger casuality is a general method applied to determine the causative relationship between variables reported by Granger, 1969 [90]. Normally, the Granger casuality test, when applied in econometrics analysis, refers to the ability of one variable to forecast the other. According to the

Granger causality test, a variable X Granger causes Y if Y can be projected with enhanced veracity by means of the past values of X variable. The Granger causality test use I (1) to assess the super-consistency possessions if X and Y series are co-integrated in the same order I (1), then causality exists in at least in one direction [36].

$$X_t = a + \sum_{m=1}^{q} \beta_m X_{t-m} + \sum_{n=1}^{q} \varphi_n Y_{t-n} + u_{1_t} \tag{8}$$

$$Y_t = a + \sum_{m=1}^{q} \beta_n Y_{t-n} + \sum_{n=1}^{q} \delta_n X_{t-n} + u_{2_t} \tag{9}$$

Here, X_t and Y_t imply as X and Y measured values at time periods t, q denote the number of lag length used in time series data, $a,\ \beta,\ \varphi \& \delta$ are the estimation of parameters, $u_{1_t},\ u_{2_t}$ is an error term. In Equation (8), Y Granger cause X if the null hypothesis $H_0 = \varphi_1 = \varphi_2 = \ldots = \varphi_k = 0$ is prohibited in favor of the alternative hypothesis H_1: at least one $\varphi_n \neq 0,\ n = 1$. Correspondingly, for Equation (9), X Granger causes Y if the null hypothesis $H_0 = \delta_1 = \delta = \ldots = \delta = 0$ is excluded in favor of the alternative hypothesis H_1: at least one $\delta_n \neq 0,\ n = 1$.

5. Results and Discussions

First, our results are started by statistical exploration; Table 3 shows the descriptive statistics of variables using time series data from 1990–2015. This statistical analysis reveals that the mean value of gross domestic product GDP is 4.063, with a standard deviation (S.D) of 1.86. Electricity supply ELS mean is 64.83, with a standard deviation of 16.05 and the mean of gross capital formation GCF is 21.64, with a standard deviation of 3.51. The variable investment INV mean is 1.18, with standard deviation 0.89 and the average of export EX is 14.91, with standard deviation 1.67.

Table 3. Expressive data analysis of selected variables.

Variables	Mean	Standard Deviation (S.D)	Max	Min
GDP	4.063	1.86	7.70	1.01
ELS	64.83	16.05	106.02	52.06
GCF	21.64	3.51	28.61	16.12
INV	1.18	0.89	3.66	0.38
EX	14.91	1.67	17.35	12.24

To test the hypothesis, the ADF and PP are applied in this investigation to explore the presence of unit root with intercept and intercept and trend. The outcomes of ADF and PP unit root tests are shown in Table 4. From Table 4, the results discovered that the null hypothesis of the unit root may not be prohibited at level but it is strongly excluded at 1% and 5% significance level at first difference. This indicates that the variables are nonstationary and incorporated in the same order I (1).

After establishing the unit root test, we establish that variables are non-stationary and integrated in the order I (1), then, Johnsen co-integration was applied to find long-run liaison between variables. Before using the test, it is obligatory to analyze the lag length criteria. Table 5, represents the lag length assortment criteria. The optimal lag length selection for the model is 1 by using the lowest value of Schwar's information criteria (SIC). The consequences of the Johnsen co-integration test with trace and max eigenvalue test statistics are provided in Table 6. The outcomes indicate that based on the trace test statistic and max Eigen statistic value, the series has three co-integration at a 5% significance level. The trace test statistic 162.2 is greater than 5% critical value of 69.8, so we can discard the null hypothesis of no co-integration (H_0: r = 0). Similarly, the max Eigen test statistics 70.2 is greater than the critical value of 33.8, which is in the favor of the alternative hypothesis that there is a relationship between series.

Table 4. Unit root test outcomes of total variables.

Variables	Augmented Dickey-Fuller (ADF)		Philips-Perron (PP)	
	Intercept	Trend and Intercept	Intercept	Trend and Intercept
GDP	−3.73	−3.58	−3.16	−3.04
ΔGDP	−5.76 *	−5.64 *	−6.21 **	−6.07 *
ELS	−2.22	−0.64	−2.21	−0.61
ΔES	−3.64 **	−4.66 **	−3.64 **	−4.90 **
GCF	−1.72	−2.80	−1.50	−1.98
ΔGCF	−3.26 *	−3.21	−3.29 *	−3.24
INVS	−2.37	−2.87	−1.82	−2.01
ΔINVS	−3.04 **	−2.97	−3.04 **	−2.97
EX	−1.06	−3.30	−1.06	−3.43
ΔEX	−5.15 *	−5.034 **	−5.17 *	−5.04 *

*,** Indicates significance at 1% and 5% significance levels respectively. Δ First difference operator.

Table 5. Selection of lag length.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−644.4104	NA	2.42×10^{19}	53.14788	53.29665	53.18292
1	−574.2939	101.987 *	2.01×10^{18} *	50.64792 *	51.24303 *	50.78811 *
2	−5487010	25.59286	2.81×10^{18}	50.92554	51.96699	51.17088
3	−4873949	33.43969	3.62×10^{18}	51.03223	52.52002	51.38271

* Indicate lag order nominated by criterion, LR: sequential modified LR test statistic (each test at 5% level), FPE: final perdition error, AIC: Akaike evidence criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion.

Table 6. Johansen co-integration test results using trace indicator and maximum eigenvalue trace data.

Hypothesized Number of CE (s)	Eigenvalue	Trace Statistic	5% Critical Value	Prob **
None *	0.958911	162.2678	69.81889	0.0000
At most 1 *	0.915588	92.04344	47.85613	0.0000
At most 2 *	0.746188	37.65832	29.79707	0.0051
At most 3	0.288565	7.492748	15.49471	0.5211
At most 4	0.000108	0.002386	3.841466	0.9589
		Max—Eigenvalue Statistic.		
None *	0.958911	70.22433	33.87687	0.0000
At most 1 *	0.915588	54.38512	27.58434	0.0000
At most 2 *	0.746188	30.16557	21.13162	0.0021
At most 3	0.288565	7.490362	14.26460	0.4329
At most 4	0.000108	0.002386	3.841466	0.9589

* Indicates the rejection of the hypothesis at the 0.05 level, ** Mackinnon-Huag-Michelis (1999) *p*-values.

The Johannsen co-integration determines only the endurance of a long run relationship among variables, but it does not designate the course of causation. This existence of long run link means that the Granger causality must be existing at least in one direction in series [46]. Thus, when the series are co-integrated by using the vector error correction model (VECM) we can analyze the Granger casuality test to explore the direction of causativeness between variables. In the ganger causality test, we want to analyse whether the presence of this long run equilibrium relationship caused the variables, and if ELS lead to the EG or EG lead to the ELS, or if they have a reciprocal causation condition.

Table 7 shows the findings of Granger causality base on the VECM Equations (8) and (9). The results show that causation directs from EG to ELS (GDP to ELS ($p < 0.05$). The finding of this study is reliable with the previous studies [42], but different from [46], who fail to discover the causation between ELS and EG. Thus, an enduring increase in Pakistan's GDP may cause an increase in electricity supply and this long-term increase can have a significant impact on electricity supply. The causality also runs from gross capital formation and investment to GDP, but not vice versa. This shows that a growth in investment and capital that resulted in a higher EG of Pakistan. Thus, enhancing GDP is more crucial and has a broad impact on Pakistan's development. Moreover, bidirectional causality runs from electricity supply and export. This indicates that promoting export can enhance the electricity supply in this country. In other words, we can say that a large amount of electricity is required to produce exported products. Electricity productions play a significant role in Pakistan's export, unidirectional causality electricity supply to gross capital formation, and no causality found export and GDP. It can be concluded that economic growth causes electricity supply, so conservation policies have no adversative impact on EG.

Table 7. Results from the pairwise Granger causality test.

Null-Hypothesis	Observation	F-Statistics	*p*-Value	Decisions	Results
GDP does not Granger Cause ELS	24	5.50268	0.0289 **	Rejected	Uni-directional causality
ELS does not Granger cause GDP		0.84639	0.368	Not rejected	
EX does not Granger Cause GDP	24	1.24186	0.2777	Not rejected	Neutral causality
GDP does not Granger Cause Ex		1.80285	0.1937	Not rejected	Neutral causality
GCF does not Granger Cause GDP	24	0.69985	0.5097	Not rejected	
GDP does not Granger Cause GCF		6.84995	0.0061 *	rejected	Uni-directional causality
INV does not Granger Cause GDP		4.43353	0.0272 **	Rejected	Uni-directional causality
GDP does not Granger Cause INV		0.93643	0.4103	Not rejected	
EX does not Granger Cause ELS	24	15.3146	0.0008 *	Rejected	Bi-directional causality
ELS does not Granger Cause EX		109075	0.0003 *	Rejected	
GCF does not Granger Cause ELS	24	1.70014	0.2071	Not rejected	
ELS does not Granger cause GCF		6.03195	0.0060 *	Rejected	Uni-directional Causality
INV does not Granger Cause GCF	24	1.68197	0.2087	Not rejected	
GCF does not Granger Cause INV		14.8799	0.0009 *	Rejected	Uni-directional causality
INV does not Granger Cause EX	24	2.37094	0.1385	Not Rejected	Neutral causality
EX does not Granger Cause INV		1.89876	0.1827	Not Rejected	Neutral causality

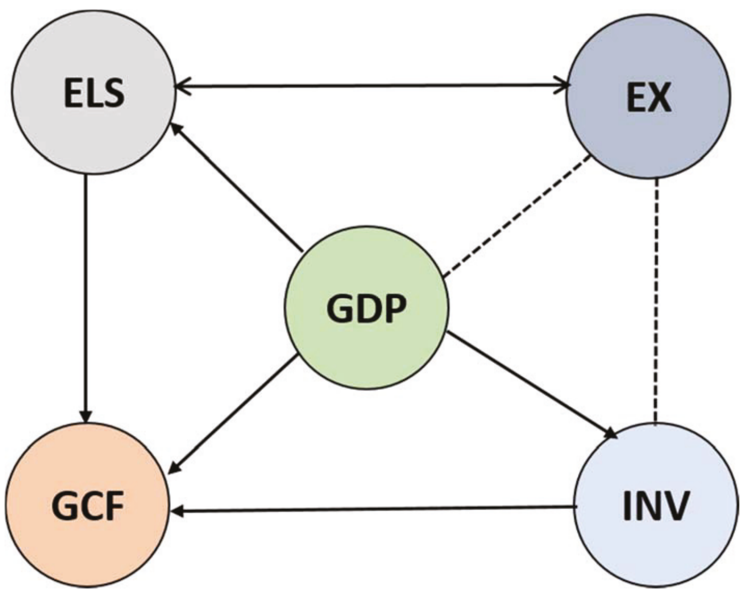
*,** Represent the rejection of the null hypothesis at 1% and 5% significance level.

6. Conclusions

This work attempted to explore the causal relationship between ELS and EG by including investment, gross capital formation and export in Pakistan from 1990–2015. Many researchers have debated on energy-growth nexus but electricity supply and growth nexus is still underexplored. Time series data was used in this study by applying ADF and PP unit root to conclude the order of integration.

This study used the Johnsen co-integration test to determine long run causlity among series. Finally, we applied the Granger casuality test to discover the direction of causal relationship.

The result implies that variables gross domestic product (GDP), electricity supply (ELS), investment (INV), gross capital formation (GCF) and export (EX) are co-integrated. In other words, from our findings we can say that variables have long run relationships, thus they can travel together in the long run or they have the same tendency of crusade in the long run. The outcomes of the Granger casuality concede that unilateral casuality directs from GDP to other variables, e.g., ELS, GCF and also one-way causality between GDP and investment. Furthermore, electricity supply and export are interdependent from each other. Finally, no Granger causality was found from GDP to export and export to investment. In developing countries, if unidirectional causality exists between electricity and growth then it has a negative impact on GDP—but in Pakistan this is not the case. According to our findings, unidirectional causation is flowing from GDP to ELS. Thus, the policy implication is that electricity is not a limiting factor for Pakistan's economic growth. So, according to our findings, Pakistan's GDP is culpable for enhance the electricity supply (Figure 7).



←Unidirectional Granger causality↔Bidirectional Granger Causality----Neutrality Granger Causality

Figure 7. Causality among electricity supply, economic growth (GDP), export, investment and gross capital formation.

EG originates in the growth of commercial and industrial segments where ELS has been applied as a primary energy input due to its efficient and clean nature. ELS in the transport and agricultural sector will help to speed up EG of the country. Hence, it could be anticipated that EG augments the electricity supply in Pakistan.

The electricity supply network in Pakistan has been passing through an era of prolonged supply scarcity, extraordinary T and D losses primarily because of high auxiliary consumption, electricity theft, and environmental issues linked with thermal power plants. The electricity sector of Pakistan is also suffering due to poor operative and monetary performances of electric supply distribution companies. Lower electricity tariffs due to subsidy by the government in the domestic sector inspire the customers for extravagant usage of electricity.

The demand for electricity in Pakistan is rising due to its high population in the coming years. The government of Pakistan (GOP) has already initiated electricity sector reforms such as energy preservation and efficiency enhancement program as a portion of continuing restructuring practice because of the great energy saving perspective in Pakistan.

Nevertheless, in various Asian economies, electricity conservation strategies may have adverse effects on EG due to unidirectional causativeness from EC to GDP, this is not the instance for Pakistan. The causality directs from GDP to EC in the long run according to our outcomes. Consequently, electricity is not a limiting factor for Pakistan's EG. Enhancing electricity tariffs could be a good prospect for the Pakistani economy to stimulate substitution and technical improvement. Meanwhile, high levels of EG has contributed to mounting electricity demand, and the government may endorse environmentally friendly protection by permitting charges to react to market forces. A competitive energy market would signify a stride headed to allocate the country's valuable resources proficiently.

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List of Abbreviations

ES/ELS	Electricity supply
EG	Economic growth
EC	Electricity consumption
INV	Investment
EX	Export
GDP	Gross domestic product
FDI	Foreign direct investment
T and D losses	Transmission and distribution losses
WB	World bank
OECD	Organization for economic co-operation and development
TFP	Total factor productivity
MW	Megawat
USA	United States of America
USD	United States Dollar
WAPDA	Water and Power Development Authority
PEPCO	Pakistan Electric Power Company
PPIB	Private Power and Infrastructure Board
KESC	Karachi Electric Supply Company
GENCOs	Generation Companies
GCF	Gross Capital Formation
DISCOs	Distribution Companies
NTDC	National Transmission and Dispatch Company
IPPs	Independent Power Producers
KES	Karachi Electric Supply Company
IAEA	International Atomic Energy Agency
PAEC	Pakistan Atomic Energy Commission
IEA	International Energy Agency
WDI	World development indicators
GCF	Gross Capital Formation
ADF	Augmented dickey-fuller

PP	Philips-Perron
AR	Autoregressive
SIC	Schwarz's information criterion
AIC	Akaike's information criterion
HQ	Hannan-Quin information criterion
LR criterion	Log-likelihood ratio test criterion
VECM	Vector error correction model
GOP	Government of Pakistan
FX	Foreign Exchange reserves
RE	Renewable energy

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energies

Article

Do Real Output and Renewable Energy Consumption Affect CO_2 Emissions? Evidence for Selected BRICS Countries

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Abstract: Climate change is one of the most important global problems faced by the international community. It is generally believed that increasing the consumption of renewable energy is an effective measure to promote CO_2 emissions reduction. Therefore, renewable energy consumption has become one of the best alternative strategies for sustainable development. Based on this, this paper employs the 3SLS model to conduct an empirical study on the relations among real output, renewable energy consumption, and CO_2 emissions of BRICS countries (except Russia) in 1999–2014. The empirical results support, for BRICS group, the complete tri-variate relationships (energy-output-emission nexus), and renewable energy had a significant positive impact on the real output, and vice versa. Besides, compared with other countries, Brazil also has the same tri-variate relationships as BRICS group. However, China has no relationship from real output to renewable energy consumption and from real output to CO_2 emissions; India does not have the relationship from real output to renewable energy consumption and the bilateral relationship between real output and CO_2 emissions; the relationship between variables in South Africa only occurs in the energy output chain. Finally, according to the estimation results of the simultaneous equation, the BRICs governments should consider the importance of human capital level and financial development when controlling the real output level and pollution. In addition, it should be noted that effective energy policies help to reduce carbon dioxide emissions without compromising real output.

Keywords: renewable energy consumption; real output; CO_2 emissions; BRICS countries

1. Introduction

As we all know, global climate change caused by carbon dioxide emissions is endangering the sustainable development of the world, and has become a hot topic in international political, economic, and diplomatic discourse debate [1]. The rising total CO_2 emissions are not only a threat to the health of the biophysical ecosystem but also has a profound impact on human society. CO_2 emissions, which are closely related to climate change, have always been described as a "super wicked problem" [2] that has an impact on human welfare. Therefore, how to formulate a policy of economic, energy, social inclusion, and environmental sustainability is a serious challenge for all countries in the world.

With economic globalization, developing countries are staying in the key economic development period. Especially, developing countries must show a rapid pace of economy growth in order to fight against poverty and improve industrial structure and infrastructure. In recent years, the concept of BRICS is becoming more and more popular in public media and academia. As a typical kind of the developing countries, BRICS countries have significant common characteristics, such as large population, underdeveloped economy but rapid growth, and the willingness to embrace the global market [3]. In the past 60 years, the BRICS economy has become increasingly prosperous [4]. The research of Goldman Sachs [5] found that in less than 40 years, the BRICS may play a more and more important role in the world economy than G6 (United States, Japan, Germany, France, Italy, and United Kingdom), and the size of BRICS economies may account for more than half of G6 by 2025. Especially according to the latest research of Pao and Tsai [6], the gross domestic product (GDP) of BRICS countries is expected to exceed than that of the group of seven (seven developed economies, namely United States, Canada, the United Kingdom, Germany, France, Italy, and Japan) by 2050. More concretely, in 2018, the nominal GDP of BRICS countries was the US $18.6 trillion, accounting for more than 23% of global output [7]. As shown in Figure 1, the GDP per capita of BRICS countries increased from $2140.98 in 1960 (unchanged in 2010) to $7081.32 in 2018, with an average annual growth rate of 2.11%. Its contribution to world economic growth should not be underestimated. With the rapid economic growth, the relationship between economic growth and air pollution in BRICS countries is a widely debated issue. Especially BRICS countries' economic growth and industrialization level rely heavily on high energy-consuming industries such as construction, mining, and manufacturing [8], which also lead to a sharp rise in CO_2 emissions in BRICS countries. As shown in Table 1, BRICS countries occupy an important seat in the list of major carbon emitters in the world. In 2014, the CO_2 emissions of the whole BRICS countries accounted for three-eighths of the world's total, and of the first three seats, BRICs hold two. It can also be seen from Figure 2 that the per capita CO_2 emissions are also rising rapidly with economic development. The deteriorating environment also makes us aware of the consequent excessive CO_2 emissions, which play a major role in the global greenhouse effect and the world economic development [9]. During the fifth BRICS summit in 2013, BRICS countries sealed a "multilateral agreement on climate cooperation and the green economy" to ensure the financial support and the technical exchange to cope with the negative effect of climate change on developing countries [8]. BRICS economies are currently located downstream of the global value chain, which means that their environmental costs are high [7], and it is unsustainable to sacrifice environmental quality to maintain economic growth [10].

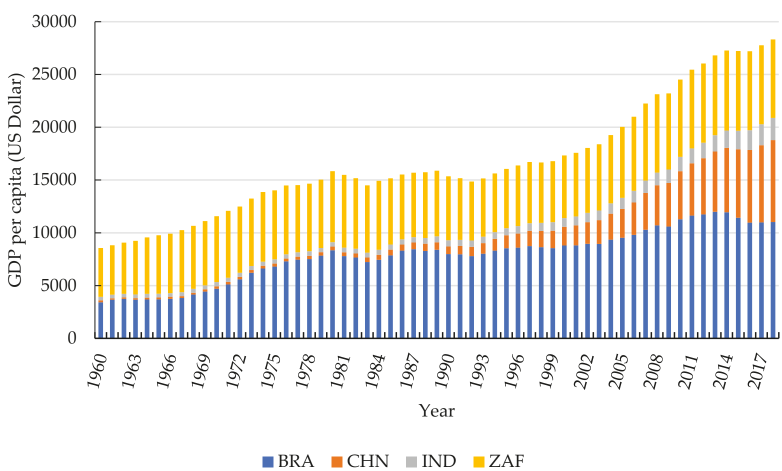

Figure 1. Per capita gross domestic product (GDP) trends of the BRICS countries from 1960 to 2018. (Source: World Bank. BRA stands for Brazil, CHN stands for China, IND stands for India, ZAF stands for South Africa.)

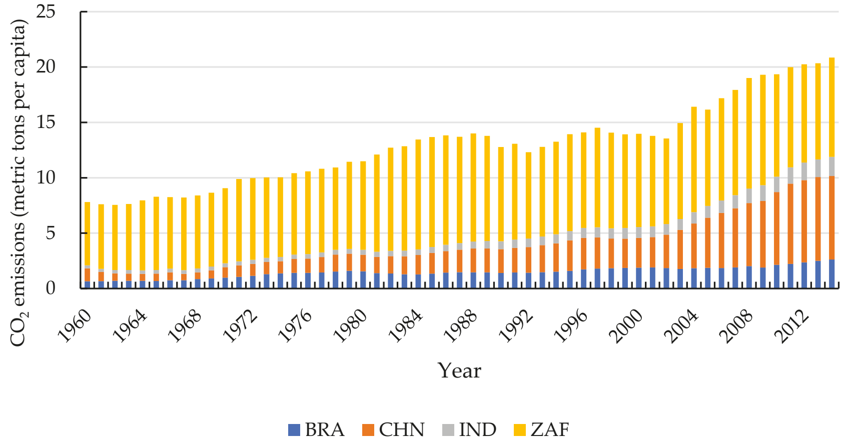

Figure 2. Per capita CO_2 trends of the BRICS countries from 1960 to 2014. (Source: World Bank. BRA stands for Brazil, CHN stands for China, IND stands for India, ZAF stands for South Africa.)

Table 1. CO_2 emissions of the BRICS countries in 2014.

Region	Annual CO_2 Emissions (kt)	% of World Emissions	Rank in the World
Brazil	529,808.16	1.47	13
China	10,291,926.88	28.48	1
India	2,238,377.14	6.19	3
South Africa	489,771.85	1.36	14
World	36,138,285	100	

Source: World Bank.

Under the double challenges of the global climate crisis and economic growth pressure, the concept of low-carbon development and green energy transformation is now essential for the international community [11]. The main energy used by BRICS countries is fossil energy [12], and their dependence on fossil energy has provoked alarm about fossil energy limited supply, energy security, and environmental degradation [13]. The use of fossil energy is identified as a main factor in increasing greenhouse gas emissions, which are the culprit of climate change and global warming [14]. Renewable energy is considered to be the most effective way to reduce carbon dioxide emissions [15]. In order to achieve the goal of sustainable development and protect the environment, renewable energy is promoted to replace the fossil energy. Meanwhile, the use of renewable energy will not only increase environmental benefits, but also help economies increase employment and reduce their dependence on foreign resources [16]. Besides, renewable energy is the fastest-growing energy form. Therefore, as concerns about environmental degradation and energy security grow, the search for and use of renewable energy is considered as a solution for the sustainable development of BRICS countries. The per capita consumption of renewable energy in the BRICS countries has not grown rapidly with the development of the economy, as shown in Figure 3, so renewable energy has a bright future in the BRICS countries. In 2013, four BRICS countries (China, Brazil, India, and South Africa) were among the top 10 renewable energy investment countries [17]. Concern has been raised about the social and environmental sustainability in BRICS countries. It is a top priority for BRICS countries to coordinate the relationship between the economy and environment and mitigate the global greenhouse effect, which is of great significance to the global sustainable development [9,18].

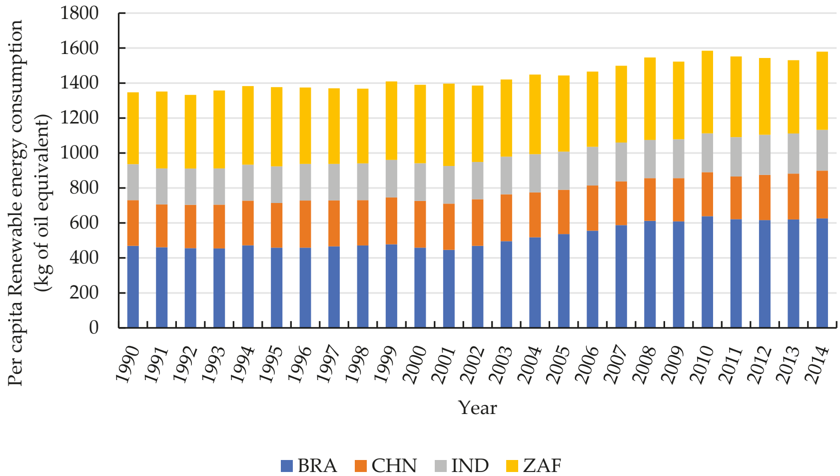

Figure 3. Per capita renewable energy consumption trends of the BRICS countries from 1990 to 2014. (Source: World Bank. BRA stands for Brazil, CHN stands for China, IND stands for India, ZAF stands for South Africa.)

Given that carbon dioxide emissions and sustainable development are the main concerns of policymakers and energy environmentalists, we will take BRICS countries (except Russia) as the research objects based on the 3SLS model and carry out panel analysis on the relationship between real output, renewable energy consumption, and CO_2 emissions. To study the nexus between real output and renewable energy consumption and carbon dioxide emissions, and how to adjust the relationship, we will provide strong suggestions for climate change mitigation policies. In order to study this hot issue, we analyzed the existing literature and adopted appropriate methods. Through unit root test, cointegration test, model setting test, and 3SLS regression estimation we have studied the real output, renewable energy consumption, and CO_2 emissions of BRICS countries, providing a reference for global sustainable development.

The main contributions of this paper to the existing research are as follows: (1) Although there is a lot of literature on the relationship between per capita GDP (or real output) and energy consumption, the literature on renewable energy consumption in BRICs countries, for example, is very scarce, and the results are uneven [19]. As a potential variable, the consumption of renewable energy is added to the relationship between real output and CO_2 emissions. However, the contribution of renewable energy to reducing CO_2 emissions without damaging the actual output is ignored in the literature. As the results of previous studies are not clear, further studies on the relationship between real output, renewable energy consumption, and environmental degradation are needed as different comparative opinions. (2) We study the relationship between real output, energy consumption, and CO_2 emissions through the energy output emission system, rather than using a simple single econometric model to describe the relationship between them. Moreover, simultaneous equation technology can also effectively avoid some econometric problems (such as endogenous problems and residual simultaneous correlation problems). (3) In addition to real output and renewable energy consumption, financial development, human capital level, physical capital, urban population, and trade openness are also included in the research system to overcome regulatory deviation. It is generally believed that taking more factors related to CO_2 emissions into account in the model can ensure the accuracy of the calculation results [20]. (4) To find out the role of renewable energy consumption in real output and CO_2 emissions is of great significance to the sustainable development of developing countries, especially BRICs countries. It not only helps policy-makers and governments to reduce carbon dioxide emissions, but also promotes the growth of the renewable energy industry.

The rest of the paper is arranged as follows: Section 2 states a literature review. Section 3 presents an introduction to the research framework and model. Data description, empirical results, and discussion are described in Section 4. Section 5 introduces the conclusions, policy implications, and study limitations.

2. Literature Review

Because of the incentive effect of CO_2 emissions reduction policies, in recent years, more and more empirical studies are devoted to the study of the relationship between various factors (such as real output, urbanization, and energy consumption) and CO_2 emissions, as well as the impact of these factors on CO_2 emissions. This paper reviews the existing literature from the following three aspects.

2.1. Real Output and CO_2 Emissions

In the past decades, scholars in economics and environmental science have been focusing on the carbon dioxide emissions caused by real output, which is considered to be the main cause of global warming and climate change. Therefore, there is a large number of literatures extensively discussing the relationship between real output and CO_2 emissions. There are two main views on the relationship between real output and CO_2 emissions. One is to support the opinion of Grossman and Krueger [21], that is, in the initial stage of economic growth, CO_2 emissions will go up, but later, with the increase of income, CO_2 emissions will go down in the light of the environmental Kuznets curve (EKC) [22–24]. For example, using a panel vector error correction model, Apergis and Payne [22] studied the relationship between carbon dioxide emissions, energy consumption, and output for six Central American countries from 1971 to 2004. The results show that there is an inverted U-shaped relationship between real output and CO_2 emissions in long-run equilibrium. Another view is that there is a causal relationship between real output and carbon dioxide emissions [25–27]. For example, Apergis and Payne [27] pointed out that long term elasticity estimates are positively correlated with real GDP per capita, CO_2 emissions per capita, and real oil prices in 11 South American countries from 1980 to 2010.

2.2. Renewable Energy Consumption and CO_2 Emissions

Inspired by the ecological challenges and theoretical debates, a large number of studies have empirically studied renewable energy consumption, one of the determinants of carbon dioxide emissions [28–34]. For example, Menyah and Wolde-Rufael [28] explored the relations between CO_2 emissions, renewable energy and nuclear energy consumption, and real GDP in the United States from 1960 to 2007 through the modified Granger causality test. It is found that the one-way causal relationship from nuclear energy consumption to CO_2 emissions has no feedback, however, there is no causal relationship between renewable energy and carbon dioxide emissions. Based on the data of OECD member countries from 1980 to 2011, Shafiei and Salim [29] tried to explore the factors affecting CO_2 emissions through the STIRPAT model. The results confirm that nonrenewable energy consumption causes the increase of CO_2 emissions, while renewable energy consumption causes the decrease of CO_2 emissions. Apergis et al. [34] studied the causality between carbon dioxide emissions, nuclear energy consumption, renewable energy consumption, and economic growth in a group of 19 developed and developing countries from 1984 to 2007. The empirical results show that there is a short-term two-way causal relationship between economic growth and renewable energy and nuclear energy consumption, which supports the feedback hypothesis.

2.3. CO_2 Emissions' Factors and CO_2 Emissions in BRICS Countries

A large number of studies use statistical tools and regression models to study the impact factors of CO_2 emissions in BRICS countries. For example, Wang and Zhang [10] used the least square method to conduct empirical research on R&D investment and CO_2 emissions of BRICS countries in 1996–2014. Their results show that increasing R&D investment has a positive impact on the decoupling of economic growth and environmental pressure. Wang and Kubota [18] tried to make an empirical study on the relationship between urbanization and CO_2 emissions in BRICS countries over the period 1985 to 2014. The results bored out that there is a long-term equilibrium cointegration relationship between urbanization and CO_2 emissions. Table 2 is a summary of empirical research on the relationship between various influencing factors and CO_2 emissions in BRICS countries. In general, the findings of the existing literature show that few studies attempt to explore the relationship between the renewable energy consumption and CO_2 emissions of BRICS countries (Dong et al. [9]), and the research results are uncertain and mixed. It is necessary to further explore the causality between real output, renewable energy consumption, and CO_2 in the BRICS context. As a developing country with a large emerging economy, BRICS countries are concerned about the relationship between these variables, both in policy and academic circles. In order to understand this knowledge gap and contribute to the existing literature, given this motivation, our experience in this area will try to provide profound policy insights to help policymakers develop sustainable energy policies to support efficient or optimal growth paths in BRICS countries.

Table 2. Summary of the relevant literature of BRICS.

Authors	Period	Method/Model	Results
Wang and Zhang [10]	1996–2014	FMOLS	R&D→CO_2↓
Wang et al. [18]	1985–2014	PGC	URB→CO_2↑
Adedoyin et al. [35]	1990–2014	ARDL	CR→CO_2↓
Baloch and Wang [36]	1996–2017	WPC, DKSEPR, PMG, and DOLS	Governance→CO_2↓
Sinha et al. [37]	1990–2017	GMM	Corruption→CO_2↑
Dong et al. [9]	1985–2016	AMG	NGC→CO_2↓REC→CO_2↓
Wu et al. [38]	2004–2010	NMVGM	EG→CO_2↓ in Brazil and Russia, EG→CO_2↑ in China and South Africa
Mahalik et al. [39]	1980–2013	ARDL and VECM	II→CO_2↑ in Brazil, India and China, II→CO_2↓ in South Africa
Khattak et al. [40]	1980–2016	CCEMG and AMG	IC↔CO_2↑ in Russia, India, China, and South AfricaREC↔CO_2↓in Russia, India, and China
Liu, et al. [41]	1992–2013	VECM	PO→CO_2↓, PREC→CO_2↓, PNREC→CO_2↑, PAE→CO_2↑
Pao and Tsai [42]	1992–2007	ECM, OLS and VECM	FDI↔CO_2
Haseeb et al. [43]	1990–2014	FMOLS	URB→CO_2↑ (except Russia); GDP→CO_2↓ in Brazil, Russia, and South Africa, GDP→CO_2↑ in India and China; EC→CO_2↑ in Brazil, India, and China, EC→CO_2↓ in Russia
Dai et al. [44]	1995–2014	LMDI	EI→CO_2↓
Balsalobre et al. [45]	1990–2014	DOLS and FMOLS	AO→CO_2↑, TO→CO_2↑, ELC→CO_2↑
Adewuyi et al. [46]	1980–2010	3SLS	BIO↔CO_2, GDP↔CO_2 in West Africa

Note: "↑": positive effect, "↓": negative effect, "↔": bidirectional causality effect. Variables: Research and development (R&D), urbanization rate (URB), coal rents (CR), natural gas consumption (NGC), renewable energy consumption (REC), economic growth (EG), income inequality (II), innovation activities (IC), per capita output (PO), per capita renewable energy consumption (PREC), per capita nonrenewable energy consumption (PNREC), per capita agriculture exert (PAE), foreign direct investment (FDI), energy consumption (EC), per capita gross domestic product (GDP), energy intensity (EI), agriculture output (AO), trade openness (TO), biomass consumption per capita (BIO), electricity consumption (ELC). Methods: Fully modified OLS (FMOLS), Panel Granger causality (PGC), additional autoregressive distributed lag (ARDL), Westerlund panel cointegration (WPC), Driscoll-Kraay standard error panel regression (DKSEPR), pooled mean group (PMG), dynamic ordinary least square (DOLS), generalized method of moments (GMM), augmented mean group (AMG), novel multi-variable grey model (NMVGM), vector error correction model (VECM), Common correlated effect mean group (CCEMG), error-correction model (ECM), ordinary least squares (OLS), log mean Divisia index (LMDI), three-stage least squares (3SLS).

3. Theoretical Framework and Methodology

3.1. Theoretical Framework

Capital, labor, and energy are essential resources for economic growth and social development of an economy. However, since the industrial revolution, human society has not only promoted economic growth and social prosperity by consuming a lot of energy but also triggered the emergence of global climate change. Therefore, energy input must be used in an environmentally friendly way to achieve sustainable development. The current research mainly focuses on the relationship between overall energy consumption and real output. There are a few kinds of literature on the relationship between renewable energy consumption and real output. Therefore, it is necessary to study the relationship between energy consumption, real output, and ecological environment. We construct an enhanced endogenous growth model that explores in detail the link between renewable energy consumption growth, real output, and CO_2 emissions. The endogenous growth model emphasizes the role of human capital and physical capital in economic growth. Since energy plays a vital role in the key inputs of labor and capital, energy should be regarded as an important input in the production process. In this study, an enhanced endogenous growth model [46] is used to describe the role of physical capital (K), the labor force (L), human capital (H), energy (E), and system efficiency (A). System efficiency is the ability to improve environmental quality by reducing CO_2 emissions in some ways. Therefore, the specific model is as follows:

$$Y_t = \mathrm{K}_t L_t H_t E_t \mathrm{CO}_{2t} \quad (1)$$

where $A_t = A(\mathrm{CO}_{2t})$.

In the literature on the relationship between renewable energy consumption and real output, energy consumption has both direct and indirect effects on real output. On the one hand, energy is the main input of the production process and commercial activities. As a result, the increased demand for energy may lead to huge investment by local and foreign investors in the energy sector, which promotes the technical efficiency of renewable energy that needs a higher level of technology and also contribute to the real output in the process. The cost of renewable energy is relatively high, such as wind power and nuclear power. The cost of both is more than twice that of thermal power. However, because of environmental protection and the rapid growth of energy demand, the high demand for renewable energy creates employment opportunities for those directly engaged in green energy production and supply. More importantly, the long industrial chain of the renewable energy industry can drive the increase in employment in all sectors. The increase of real output will increase the per capita real income. The increase of per capita income will make the improvement of people's quality of life and the requirements of environmental quality will also increase. Green energy has become an alternative to reduce CO_2 emissions without reducing the actual output. The demand for renewable energy will rise. On the other hand, for those economies that rely on resource exports, real output may reduce local energy consumption because of social governance and other reasons. Asafu [47] believes that there is a two-way causal relationship between energy consumption and economic growth. The complementary relationship between energy consumption and economic growth, unfortunately, the research results of some countries show that the impact of energy consumption on real output is ignored. Therefore, this hypothesis does not consider that there is a causal relationship between energy consumption and real output.

With the rapid real output growth and increasing global energy consumption, CO_2 emissions tend to rise, at least beyond the low-income level (EKC assumption). CO_2 emissions may also have a causal impact on GDP. Under the premise of maintaining real output growth, there are two ways to reduce energy consumption: industrial structure adjustment and substitution between input factors. Therefore, the research of high efficiency, low cost, and environment-friendly renewable energy has become a research hotspot. With the highlight of the greenhouse effect and the frequent occurrence of extreme weather, CO_2 emissions have a great impact on the global climate and environment. Excessive carbon dioxide emissions also have an impact on the weather conditions in an area, especially in terms of human health and the temperature of agricultural products, while having a negative impact on health and labor productivity. The increase in energy consumption may have more and more impact on carbon dioxide emissions. How to achieve energy conservation and emission reduction while ensuring economic development, and achieve sustainable economic development? Renewable energy alternative fossil energy has huge benefits (Reinhardt and Falkenstein [48]).

The production function of CO_2 emissions describes the generation of CO_2 emissions as a function of economic activity level (Y_t), urbanization rate (U), energy consumption (E), and technical efficiency (A_t), because the energy efficiency is improved by obtaining foreign investment through economic and trade opening (T).

$$CO_{2t} = A_t Y_t U_t E_t \quad (2)$$

where $A_{tt} = A(T_t)$.

Therefore,

$$CO_{2t} = Y_t E_t U_t T_t \quad (3)$$

The production function of CO_2 emission conforms to the EKC hypothesis [21]. The production of CO_2 emissions mainly depends on the level of output (Y). The growth of output needs a lot of energy, followed by the growth of CO_2 emissions. Besides, the level of urbanization is usually closely related to the level of CO_2 emissions [18,43]. The cross-regional flow of goods and services brought about by economic opening up also has an important impact on the CO_2 emissions level of a specific economy.

Energy demand (E^{d}) is closely related to economic and social factors. Household energy demand (E^{hd}) is mainly affected by per capita income level (Y), energy price (P), and urbanization rate (U). The energy demand (E^{fd}) of enterprises is also affected by income (Y), physical capital (K), labor force (L), human capital development (H), financial development (F), and production system efficiency (A).

$$E^{\mathrm{hd}} = \mathrm{E}(Y_t, P_t, U_t) \quad (4)$$

$$E^{\mathrm{fd}} = \mathrm{E}(A_t, Y_t, K_t, L_t, H_t, F_t) \quad (5)$$

where $\mathrm{A} = \mathrm{A}(CO_{2t},)$.

$$E^{\mathrm{fd}} = \mathrm{E}(Y_t, K_t, L_t, H_t, F_t, CO_{2t},) \quad (6)$$

Therefore, the energy equation can be written as follows:

$$E^{d} = \mathrm{E}(Y_t, P_t, U_t, K_t, L_t, H_t, F_t, CO_{2t},) \quad (7)$$

The demand for energy (such as renewable energy) is a function of income levels, real output, and affordable alternatives. The development of the financial sector can simplify the process of capital accumulation and energy procurement financing, and the use of sufficient funds and advanced technology can make more effective use of energy [49]. As a result of real output growth and social development, a large labor force is transferred from agriculture to urban industry, and urban economic activities are more intensive, resulting in the rapid increase of energy use in urban areas [18,43,49,50]. According to the International Energy Agency (IEA) estimate [51], from the perspective of production, about 70% of global energy-related CO_2 emissions come from urban areas, and by 2030, this proportion is expected to be as high as 76%. As a result, high population growth or urbanization leads to increased energy demand. Urbanization has become an important factor in climate change management and sustainable development for academics and policymakers. Labor and capital are the main inputs of production activities, which have a crucial impact on the development of enterprises. Improving human capital through education will improve labor productivity and reduce the use of energy-intensive technologies or carbon-intensive energy products. The higher the CO_2 emissions of an energy source, the less the demand for it if there are equally affordable alternative energy sources because of the harmful effects of pollution. Therefore, the relationship between energy- output-emission in this paper can be described by a simultaneous equation model based on the combination of Equations (1), (3), and (7), as follows:

$$Y_t = \mathrm{f}(K_t, L_t, H_t, E_t, \mathrm{CO}_{2t}) \quad (8)$$

$$\mathrm{CO}_{2t} = \mathrm{f}(Y_t, E_t, U_t, T_t) \quad (9)$$

$$E_t = \mathrm{f}(Y_t, P_t, U_t, K_t, L_t, H_t, F_t, \mathrm{CO}_{2t},) \quad (10)$$

3.2. Methodology

According to the above analysis framework, the EKC equation, real output equation, and energy demand equation are jointly composed of the following simultaneous equations. Thus, the simultaneous equations can be re-specified in the log-linear form as follows:

$$ln(PGDP_{it}) = \partial_0 + \partial_1 ln(REC_{it}) + \partial_2 ln(K_{it}) + \partial_3 ln(H_{it}) + \partial_4 ln(CO_{2it}) + \mu_{it} \quad (11)$$

$$\begin{aligned} ln(REC_{it}) = \beta_0 + \beta_1 ln(CO_2 i_t) + \beta_2 ln(PGDP_{it}) + \beta_3 ln(H_{it}) + \beta_4 ln(K_{it}) \\ + \beta_5 ln(FD_{it}) + \beta_6 ln(URB_{it}) + \nu_{it} \end{aligned} \quad (12)$$

$$\begin{aligned} ln(CO_{2it}) = \lambda_0 + \lambda_1 ln(REC_{it}) + \lambda_2 ln(URB_{it}) + \lambda_3 ln(PGDP_{it}) \\ + \lambda_4 ln(OPENNESS_{it}) + \theta_{it} \end{aligned} \quad (13)$$

where *PGDP* = *GDP* per capita; *REC* = proportion of renewable energy consumption to total energy consumption.

CO_2 = CO_2 emissions per capita; *K* = physical capital.

H = human capital development; *FD* = financial development.

URB = urbanization rate; *OPENNESS*= trade openness.

μ_{it}, ν_{it}, and θ_{it} = Error terms.

Considering the internal correlation between the explanatory variables and the error term in the specified equation, the simultaneous equation model may be biased if it is estimated by the ordinary least square method (OLS). In this study, the three-stage least square method (3SLS) is used. The 3SLS proposed by Zellner and Theil [52] is a kind of complete information estimation method for estimating the simultaneous equation model. Its basic idea is to construct the statistics of the covariance matrix of random disturbance term of the model by using the estimation error of two-stage least square method, so as to carry out the generalized least square estimation for the whole model. Compared with 2SLS, 3SLS allows the correlation between unobserved interferences between different equations to be used in the analysis and has better asymptotic efficiency. In this paper, R software is used to estimate the equations.

4. Results Analysis

4.1. Preliminary Analysis

4.1.1. Descriptive Statistic

As mentioned earlier, CO_2 emissions are considered to be the main greenhouse gases that contribute to global warming. This paper aims to study the impact of renewable energy consumption and real output on CO_2 emissions of BRICS countries (Brazil, China, India, Russia, South Africa). All data were obtained from the World Bank. Russia' data on financial development are not available before 2014, thus Russia is excluded from the BRICs sample. Because of data availability constraints, the research period was extended from 1999 to 2014. Before conducting the empirical analysis, all the data were converted to the natural logarithm, see Table 3 for details of selected variables.

Table 3. Variable description and data sources.

Variable	Definition	Source
CO_2	Carbon dioxide emissions (metric tons per capita)	World Development Indicators
REC	Renewable energy consumption (% of total final energy consumption)	World Development Indicators
FD	Domestic credit to the private sector (% of GDP)	World Development Indicators
H	School enrollment, primary (% gross)	World Development Indicators
K	Gross fixed capital formation (% of GDP)	World Development Indicators
PGDP	GDP per capita (constant 2010 US$)	World Development Indicators
URB	Urban population (% of the total population)	World Development Indicators
OPENNESS	Trade (% of GDP)	World Development Indicators

Notes: All of the data are annual over the period 1999–2014. Data source: World Development Indicators (https://data.worldbank.org).

CO_2 is measured in metric tons per capita. Real output is measured by GDP per capita (constant 2010 US$), and the renewable energy consumption is measured by the percentage of renewable energy consumption in total energy consumption. As the relationship between CO_2 emissions, real output, and renewable energy consumption may be affected by other factors, according to the theoretical work, traditional experience and previous literature in Section 3.1 [9,18,45], this model includes additional explanatory variable vectors composed of trade openness, financial development level, urbanization, physical capital, and human capital level.

Table 4 shows the descriptive statistics of the variables. The distribution of all variables is skewed. The kurtosis value indicates that the distribution of the eight sequences is more concentrated than the normal distribution with a long tail. At the same time, the correlation matrix in Table 4 shows that all variables are positively correlated with carbon dioxide except for the proportion of renewable energy, physical capital, and human capital. Descriptive statistics do not reveal the causal relationship but need empirical research on the causal relationship between carbon dioxide and the predicted variables in the study.

Table 4. Results of descriptive statistics and correlation matrix.

Variable	$LNCO_2$	LNREC	LNFD	LNH	LNK	LNPGDP	LNURB	LNOPENNESS
Mean	1.160	3.327	4.277	4.711	3.236	8.287	3.925	3.7185
Median	0.968	3.510	4.408	4.674	3.174	8.676	4.013	3.840
Maximum	2.301	3.947	5.076	5.110	3.822	9.392	4.448	4.289
Minimum	−0.042	2.460	3.236	4.528	2.718	6.697	3.312	3.044
Std. Dev.	0.809	0.518	0.6209	0.132	0.356	0.882	0.391	0.362
Skewness	0.087	−0.242	−0.238	1.245	0.215	−0.487	−0.158	−0.407
Kurtosis	1.504	1.385	1.456	3.851	1.575	1.740	1.656	1.691
Jarque-Bera	6.053 **	7.577 **	6.960 **	18.456 ***	5.909 *	6.764 **	5.080 *	6.338 **
Correlation matrix								
$LNCO_2$	1							
LNREC	−0.934	1						
LNFD	0.909	−0.909	1					
LNH	−0.322	0.508	−0.508	1				
LNK	−0.106	−0.221	0.172	−0.476	1			
LNPGDP	0.530	−0.280	0.258	0.510	−0.579	1		
LNURB	0.383	−0.119	0.097	0.626	−0.635	0.983	1	
LNOPENNESS	0.639	−0.746	0.746	−0.622	0.327	−0.159	−0.310	1

Note: *** Statistical significance at the 1% level, ** statistical significance at the 5% level, and * statistical significance at the 10% level.

4.1.2. Test for Cross-Sectional Dependence

We used the Pesaran [53] test to diagnose whether cross-sectional dependencies exist in our panel variables. The zero hypothesis of this test assumes that the cross-section is independent of the other hypothesis of cross-section dependence. Table 5 shows the cross-sectional correlation test results for all variables. All variables are strongly opposed to the zero assumption of cross-sectional independence. We conclude that cross-sectional dependence exists as expected.

Table 5. Cross-section dependence test.

Variable	Breusch-Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM	Pesaran CD
$LNCO_2$	45.015 ***	11.263 ***	11.129 ***	6.072 ***
LNREC	37.518 ***	9.098 ***	8.965 ***	2.083 **
LNPGDP	91.315 ***	24.628 ***	24.495 ***	9.554 ***
LNFD	34.692 ***	8.283 ***	8.149 ***	5.322 ***
LNH	36.331 ***	8.756 ***	8.622 ***	−1.274
LNK	42.545 ***	10.550 ***	10.416 ***	6.404 ***
LNOPENNESS	21.467 ***	4.465 ***	4.332 ***	4.039 ***
LNURB	95.525 ***	25.844 ***	25.710 ***	9.774 ***

Note: The null hypothesis is no cross-section dependence (correlation). **, *** represent 5%, and 10% significant levels respectively.

See Table 6 for panel unit root test results. Four-panel unit root tests [54–56] are used to determine the stability of the series. The results show that the BRICS panel is integrated with the first stage, i.e., I (1).

4.2. Results and Analysis

Based on the analysis and test of the data, this paper uses the 3SLS model to estimate the relationship between the real output, renewable energy consumption, and CO_2 emissions of BRICS countries. The estimation results of the simultaneous equation show that there is a ternary relationship between BRICS group variables (energy—output—emission). We present a detailed analysis of the impact and direction between the specific variables below.

4.2.1. Effects of Renewable Energy Consumption and CO_2 Emission on Real Output

Based on the constructed simultaneous equation model (Equation (9)), this paper uses the three-stage least square method (3SLS) to estimate the BRICS group (except Russia) and individual BRICS countries (Brazil, China, India, and South Africa). Table 7 shows the impact of the proportion of renewable energy consumption (REC) and carbon dioxide emissions (CO_2) on the per capita GDP (PGDP) of the selected BRICS countries. From the perspective of the BRICS group, renewable energy consumption and per capita CO_2 emissions have a significant positive impact on the per capita GDP of BRICS. The share of renewable energy consumption (or per capita CO_2 emissions) increased by 1%, and the per capita GDP increased by 2.194% (or 2.077%). At the same time, the increase of CO_2 emissions will lead to output growth, which may be because BRICS, as the fastest-growing developing country at this stage, mainly relies on the secondary industry to promote its output growth, and the energy currently used is mainly fossil energy. Therefore, it will lead to a large number of CO_2 emissions, to some extent, it is still to sacrifice the environment to promote its rapid output growth. Among the control variables, the impact of physical capital on per capita GDP is not significant, while the impact of the human capital level on per capita GDP is extremely significant. This means that education has a significant effect in promoting the overall output growth of BRICS.

Table 6. Unit root tests results (panel).

Variable	Levin, Lin and Chu t *		Lm, Pesaran, and Shin W-Stat		ADF-Fisher Chi-Square		PP-Fisher Chi-Square		Decision
	Level	First Difference	Level	First Difference	Level	First Difference	Level	First Difference	
LN CO_2	−1.315 *	−5.261 ***	1.941	−3.548 ***	5.780	26.662 ***	2.549	25.337 ***	I(1)
LNREC	−0.836	−2.877 ***	0.661	−1.927 **	4.675	16.083 **	2.987	15.600 **	I(1)
LNPGDP	−1.158	−3.440 ***	1.798	−2.433 ***	3.689	19.955 **	2.723	29.999 ***	I(1)
LNFD	−2.222 **	−4.706 ***	−0.130	−2.187 **	6.705	19.280 **	7.001	35.075 ***	I(1)
LNH	−1.160	−5.103 ***	0.101	−4.089 ***	7.613	30.081 ***	6.105	26.536 ***	I(1)
LNK	−1.609 *	−4.529 ***	0.160	−3.040 ***	5.052	22.695 ***	8.153	22.025 ***	I(1)
LNOPENNESS	−2.131 **	−7.230 ***	−1.248	−4.143 ***	11.838	30.165 ***	13.815 *	39.459 ***	I(1)
LNURB	−38.368 ***	−4.301 ***	−30.394 ***	−10.735 ***	46.387 ***	31.148 ***	20.269 ***	44.984 ***	I(0)

Note: *, **, *** represent 1%, 5% and 10% significant levels respectively.

Table 7. Estimation results of the renewable energy and CO_2 emissions on GDP (3SLS).

Dependent Variable: GDP per Capita (PGDP)					
Variable	**Panel**	**BRA**	**CHN**	**IND**	**ZAF**
(Intercept)	−15.405 ***	5.060 ***	−5.843	5.694 **	19.274 ***
LNREC	2.194 ***	0.990 ***	1.979 ***	−0.829 **	−0.990 ***
LNK	0.070	0.252 **	−0.364	−0.092	0.366 **
LNH	2.919 ***	−0.183 **	1.014	1.016 **	−1.860 **
$LNCO_2$	2.077 ***	0.793 ***	3.128 ***	0.388	−0.023
Adjusted R-Squared	0.803	0.983	0.977	0.982	0.853

Note: **, *** represent 5%, and 10% significant levels respectively.

From the empirical results of individual countries, all variables in Brazil (i.e., REC, K, H, CO_2) have a significant impact on GDP, among which REC, K, and CO_2 have a positive impact on GDP, while H has a negative impact. Consistent with the research results of Fang [57], this paper also confirms that REC and CO_2 in China have a significant positive impact on GDP. REC and H of India and South Africa have a significant impact on GDP. The similarity between both countries is that their REC and GDP change in the opposite direction. The difference is that India's H and GDP change in the same direction, and South Africa's H and GDP change in the opposite direction. In terms of control variables, the impact of physical capital on per capita GDP only has a significant positive impact in Brazil and South Africa. The impact of human capital development on per capita GDP is significant in Brazil (negative), India (positive), and South Africa (negative). This shows that education promotes India's real output, but hinders Brazil's and South Africa's real output. Of course, education also has a positive impact on China's real output, but it is not significant.

4.2.2. Effects of Real Output and CO_2 Emission on Renewable Energy Consumption

Table 8 shows the impact of GDP per capita and CO_2 emissions per capita on the proportion of renewable energy consumption to total energy consumption. In general, from the group's estimates, GDP per capita has a positive and significant influence on the share of renewable energy consumption, while CO_2 per capita has a significant negative impact on the share of renewable energy. The increase in income will require higher environmental quality and increase investment in renewable energy. Of course, the increase in income also increases the consumption of energy. The use of renewable energy and nonrenewable energy together may reduce CO_2 emissions. However, it depends on the availability of alternative energy. Besides, high levels of CO_2 emissions will damage the quality of the environment, thus affecting human health and productivity, and thus GDP. GDP per capita (or CO_2 per capita) increased by 1%, and the proportion of renewable energy increased by 0.158% (or decreased by 0.923%). In terms of control variables, except for physical capital and financial development, the influence of other control variables is not significant. Physical capital has a significant negative impact on the proportion of renewable energy, while financial development has a significant positive effect on the proportion of renewable energy.

At the national level, except that Brazil's per capita GDP has a significant positive impact on Brazil's share of renewable energy consumption, the other three countries are not significant. CO_2 is different. Except for South Africa, it has a significant negative impact on the share of renewable energy consumption in the other three countries. As far as other variables are concerned, physical capital has a significant negative impact only in Brazil and China. The level of human capital only has a significant impact on India (positive) and South Africa (negative). Financial development and urbanization rate only have a positive and significant impact in China. Therefore, compared with other BRICS countries, China has obvious advantages in the effective use of energy by obtaining funds through financial sector development.

Table 8. Estimation results of GDP and CO_2 emissions on renewable energy consumption (3SLS).

Dependent Variable: Renewable Energy Consumption (REC)					
Variable	**Panel**	**BRA**	**CHN**	**IND**	**ZAF**
(Intercept)	3.604 ***	−0.276	3.621 **	4.024	13.998 ***
$LNCO_2$	−0.923 ***	−0.837 ***	−0.879 ***	−0.402 ***	−0.324
LNPGDP	0.158 **	0.984 ***	−0.320	−0.240	−0.414
LNH	−0.006	0.080	−0.169	0.381 **	−1.216 *
LNK	−0.470 ***	−0.200 *	−0.554 **	−0.035	0.147
LNFD	0.326 ***	0.037	0.365 **	−0.022	0.024
LNURB	−0.092	−0.985	1.133 *	−0.008	−0.413
Adjusted R-Squared	0.994	0.900	0.998	0.982	0.735

Note: *, **, *** represent 1%, 5% and 10% significant levels respectively.

4.2.3. Effects of Real Output and Renewable Energy Consumption on CO_2 Emission

The impact of per capita real GDP and renewable energy consumption on per capita carbon dioxide emissions are shown in Table 9. From the perspective of the BRICS group as a whole, GDP per capita and the proportion of renewable energy have a significant impact on per capita CO_2 emissions. The proportion of renewable energy increased by 1%, per capita CO_2 emissions decreased by 1.144%, while per capita GDP increased by 1%, per capita CO_2 emissions increased by 0.696%. This is also in line with the "priority" expectation that as a group of developing countries, the use of energy-intensive technologies (with low per capita income) will generate high pollution (EKC assumption). The influence of control variables on per capita CO_2 emissions is not significant. The increase in income leads to an increase in energy consumption, which is closely related to CO_2 emissions. The increase in the proportion of renewable energy can significantly reduce per capita CO_2 emissions, so for BRICS countries, the feasible way to solve the energy demand and environmental quality is to vigorously develop renewable energy.

Table 9. Estimation results of GDP and renewable energy consumption on CO_2 emission (3SLS).

Dependent Variable: CO_2 Emissions per Capita (CO_2)					
	Panel	**BRA**	**CHN**	**IND**	**ZAF**
(Intercept)	1.998 **	−0.682	0.795	3.437	2.377
LNREC	−1.144 ***	−1.148 ***	−0.728 ***	−1.240 ***	−0.574
LNPGDP	0.696 **	1.033 ***	0.191	0.261	1.199
LNURB	−0.827	−0.821	0.336	−0.075	−2.026
LNOPENNESS	0.119	−0.045	0.010	−0.029	−0.208
Adjusted R-Squared	0.952	0.976	0.997	0.983	0.632

Note: **, *** represent 5% and 10% significant levels respectively.

From the results of individual countries, although the per capita GDP of BRICS countries has a positive impact on per capita CO_2 emissions, only Brazil's results are significant. Compared with the per capita CO_2 emissions, the proportion of renewable energy in all countries has a negative impact on per capita CO_2 emissions. Except for South Africa, the impact of the other three countries is very significant. As a control variable, urbanization rate and trade openness have no significant impact on per capita CO_2 emissions.

4.2.4. The Relationship between Renewable Energy, Real Output, and CO_2 Emissions in BRICS Countries

Table 10 is a summary of the results of the relationship between the three core variables, renewable energy, real output, and CO_2 emissions. The BRICS and Brazil variables have a completely significant interaction (simultaneous) effect (energy output emissions). There is an incomplete link between China (no output emission relationship) and India (no output emission relationship) variables. Renewable energy has a positive impact on real output and vice versa, especially in Brazil compared with other countries. For South Africa, only a binary link between energy and output has been found. The rising incomes will require higher environmental quality and increase investment in renewable energy. Of course, the income grew also increases the consumption of energy. The use of renewable energy and nonrenewable energy together may reduce CO_2 emissions. However, it depends on the availability of alternative energy. Also, high levels of CO_2 emissions will damage the quality of the environment, thus affecting human health and productivity, and thus GDP.

Table 10. Summary of results of the relationship between real output, renewable energy consumption and CO_2 emission.

Country	REC→PGDP	PGDP→REC	CO_2→PGDP	PGDP→CO_2	CO_2→REC	REC→CO_2
Panel	+	+	+	+	-	-
BRA	+	+	+	+	-	-
CHN	+	×	+	×	-	-
IND	-	×	×	×	-	-
ZAF	-	×	×	×	×	×

Note: + Signifies positive relationship exists; - signifies negative relationship exists. × signifies no relationship exists.

5. Conclusions

This paper studies the relationship between real output, renewable energy consumption, and CO_2 emissions in BRICS countries from 1999 to 2014. Through the energy output emission relationship, a simultaneous equation model is established. On this basis, this paper estimates the simultaneous equation model by three-stage least square method (3SLS) and makes an empirical analysis of the results of the BRICS group and individual countries. The empirical results show that for BRICS, there is a complete ternary relationship between BRICS variables (energy—output—emission), and renewable energy has a significant positive impact on real output, and vice versa. Compared with other countries, this result is particularly significant in Brazil. There is an incomplete link (no output emission relationship) between China and India variables. However, the correlation between variables in South Africa mainly occurs in the energy output chain (renewable energy GDP per capita). In addition, financial development plays a significant role in promoting the development of renewable energy. Financial development can simplify the process of capital accumulation and energy procurement financing, contribute to more investment in renewable energy, and enable BRICS countries to benefit from the transfer of "green technology."

The results show that the relationship among real output, renewable energy consumption, and CO_2 emissions is different in different countries. There are also imbalances in the internal development of BRICS countries, so each country should also adapt its energy policies to local conditions. For India and South Africa, increasing renewable energy consumption can reduce CO_2 emissions at the expense of real output. For economies such as India and South Africa in urgent need of development, encouraging renewable energy consumption is not necessarily an effective way to reduce CO_2 emissions. How to achieve sustainable development is crucial for South Africa and India. In order to make per capita GDP reach the turning point of Kuznets curve, it is necessary to improve citizen consciousness, industrial structure reform, and human capital level. The increase in income will have higher requirements for environmental quality, which will eventually lead to increased investment in renewable energy in India and South Africa. For China and Brazil, how to achieve low-carbon growth by increasing investment in renewable energy and adjusting energy consumption structure without reducing real output. In addition, the positive role of financial development in promoting renewable energy consumption should not be ignored, so it is suggested that BRICS countries can improve the renewable energy financing network and reduce the financing cost of renewable energy. As a group of developing countries with rapid development, sustainable development is the most important, and environmental pollution is the obstacle to sustainable development. Therefore, effective measures must be taken to adapt to local conditions. Finally, BRICS countries should act together, strengthen cooperation, jointly promote the development of renewable energy and energy conservation and emission reduction technologies, and meet the growing energy demand by finding alternative clean energy.

The relationship between real output, renewable energy consumption, and CO_2 emissions of BRICS countries is studied in this paper. This research also has some shortcomings, such as: (1) lack of Russia's data makes the BRICS sample data incomplete. In future studies, enough data samples can be collected for in-depth analysis. Of course, similar groups of countries can repeat this analysis. (2) Although our research focuses on renewable energy, there are many types of renewable energy that were not covered. In future studies, we can analyze the impact of different types of renewable energy on real output and CO_2 emissions.

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Article

The Impact of Economic Growth, FDI and Energy Intensity on China's Manufacturing Industry's CO_2 Emissions: An Empirical Study Based on the Fixed-Effect Panel Quantile Regression Model

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Abstract: Since the reform and opening-up, China's CO_2 emissions have increased dramatically, and it has become the world's largest CO_2 emission and primary energy consumption country. The manufacturing industry is one of the biggest contributors to CO_2 emission, and determining the drivers of CO_2 emissions are essential for effective environmental policy. China is also a vast transition economy with great regional differences. Therefore, based on the data of China's provincial panel from 2000 to 2013 and the improved STIRPAT model, this paper studies the impact of economic growth, foreign direct investment (FDI) and energy intensity on China's manufacturing carbon emissions through the fixed-effect panel quantile regression model. The results show that the effects of economic growth, FDI and energy intensity on carbon emissions of the manufacturing industry are different in different levels and regions, and they have apparent heterogeneity. In particular, economic growth plays a decisive role in the CO_2 emissions of the manufacturing industry. Economic growth has a positive impact on the carbon emissions of the manufacturing industry; specifically, a higher impact on high carbon emission provinces. Besides, FDI has a significant positive effect on the upper emission provinces of the manufacturing industry, which proves that there is a pollution paradise hypothesis in China's manufacturing industry, but no halo effect hypothesis. The reduction of energy intensity does not have a positive effect on the reduction of carbon emissions. The higher impact of the energy intensity of upper emission provinces on carbon emissions from their manufacturing industry, shows that there is an energy rebound effect in China's manufacturing industry. Finally, our study confirms that China's manufacturing industry has considerable space for emission reduction. The results also provide policy recommendations for policymakers.

Keywords: carbon emission; economic growth; energy intensity; FDI; panel quantile regression; China's manufacturing industry

1. Introduction

Global warming caused by carbon emissions has caused severe damage to the world's ecological environment [1]. China's carbon emissions have exceeded that of the United States in 2007, and has become the world's largest CO_2 emission emitter [2]. With the rapid development of China's economy and increasing improvement of people's living standards, a large amount of energy will inevitably be consumed, resulting in a large number of carbon emissions [3]. China has made a lot of efforts to reduce carbon emissions. The Chinese government has committed that by 2030, China's carbon emission intensity will be reduced by 60%–65% compared with 2005 [4], and the proportion of non-fossil fuels in primary energy consumption will be increased to 20% [5], striving to reach peak carbon emission by 2030 [6]. Therefore, China's carbon emission actions are increasingly concerned by the world [7]. Moreover, China will still be in the process of industrialization for a long time in the future [8], and the industrial sector is the main source of China's energy consumption and carbon dioxide emissions. Therefore, it is of great significance to understand the driving factors of carbon dioxide emission in China's major industries.

As the engine of China's industrialization and the pillar of China's national economy, the manufacturing industry has maintained rapid development since the 1990s. It is an industry with high energy consumption and emissions, and one of the largest contributors to the growth of China's CO_2 emission [9]. Especially with the further development of China's reform and opening-up, China is becoming a "world factory" [10], and the sales revenue of manufacturing industry has increased from 459 billion yuan in 1990 to 98,793.9 billion yuan in 2015, with an average annual growth of 24% [11]. However, the rapid development of China's manufacturing industry has also accelerated environmental damage, especially coal will continue to be China's primary energy source for a long time in the future. Due to the backward technology level, the energy consumption of China's manufacturing industry accounts for about 60% of China's total energy consumption and more than 50% of its total CO_2 emission [12]. China's manufacturing industry will continue to expand, which will also lead to an increase in carbon dioxide emissions of China's manufacturing industry [13]. Therefore, it is of great significance to explore the influencing factors of carbon emission in China's major manufacturing industries.

The three most important and discussed variables related to carbon emissions are economic growth, foreign direct investment and energy efficiency [14–17]. Due to different analysis samples, different selection variables and different estimation methods, although a large number of studies have discussed the relationship between economic growth and carbon emissions, the existing research has not found consistent evidence about the impact of economic growth on CO_2 emission. The main reason is that the heterogeneity of distribution has been neglected in the past [18].

With the increasing importance of foreign direct investment (FDI), many researchers believe that only better practice and excellent knowledge can make transnational corporations gain a competitive advantage in foreign land, which is the reason for the productivity spillover and environmental spillover of FDI [19]. Many studies focused on the relationship between economic growth, environmental pollution and FDI inflows, but few studies discussed the relationship between CO_2 emission and FDI inflows [20], especially in China's manufacturing industry. Economic growth depends on more FDI inflows, which in turn may lead to increased CO_2 emissions. In fact, will increasing FDI investment from developing countries have an impact on the environment [21]? Who should be responsible for greenhouse gas emissions, the producer or consumer? These problems have aroused broad and intense debate all over the world. Furthermore, to attract a large number of foreign investments, developing countries often neglect environmental issues through loose regulatory mechanisms, which leads to the emergence of the pollution avoidance hypothesis. In particular, the relaxation of environmental regulations and standards may promote CO_2 emission caused by foreign direct investment [22]. However, when advanced technology and management concepts are introduced by foreign capital, or foreign capital flows to the tertiary industry, the overall carbon emissions will decrease, which leads to the emergence of the halo effect hypothesis. Therefore, it is necessary to study the impact of FDI on China's manufacturing carbon emissions.

Moreover, compared with total carbon emissions and per capita carbon emissions, energy intensity is a better indicator of a country's energy and economic performance, and an important indicator of China's international emission reduction commitment [23]. However, the impact of energy intensity on overall carbon emissions is also controversial. Especially in the context of sustainable development, carbon emission reduction and economic development are significant for China. Therefore, the target of energy intensity reduction means reducing CO_2 emissions without damaging economic growth.

Against this background, many scholars have conducted in-depth investigation and research on the main factors affecting carbon emissions and their relationship from three perspectives: The relationship between carbon emissions and economic development, the relationship between carbon emissions and foreign direct investment and the relationship between carbon emissions and energy intensity.

A large number of studies have explored the relationship between carbon emissions and economic development. The environmental Kuznets curve (EKC) theory and decoupling analysis model are the hot spots of this kind of research [24]. EKC theory reflects the inverted U-shaped relationship between economic growth and income; that is, at the initial stage of economic development, environmental degradation will be stimulated, and then environmental quality will be improved with economic growth. Due to global warming, the existence of EKC theory has attracted great attention from scholars. For example, Narayan and Narayan [25] studied the relationship between economic growth and carbon emissions in 43 developing countries and found that EKC curves do not exist in all countries and regions. Dong et al. [26], based on panel data of carbon emission levels related to natural gas consumption in 30 provinces of China, checked whether the EKC curve exists. Shuai et al. [27] used EKC theory to judge the inflexion point of an EKC curve of 164 countries and regions and proved that the relationship between economic development and carbon emissions of 123 countries conforms to EKC theory. Decoupling analysis is another method to study the relationship between carbon emissions and economic growth, which originates from physics and is defined by the OECD as the relationship between economic growth and environmental degradation [28]. Compared with EKC theory, decoupling analysis has the advantages of simple calculation [29], easier understanding and operation [30], as well as effective identification of the real-time dynamic relationship between economic development and environmental degradation [31]. Many studies explored the relationship between carbon emissions and economic growth through decoupling analysis [32–34], especially the research on China's industrial sub-industries [35–37]. For example, Hardt et al. [34] conducted a study on the economic growth and carbon emissions of the UK's production sector from 1997 to 2013 using decoupling analysis, proving that the UK's economic growth and carbon emissions have been successfully decoupled.

For the relationship between carbon emission and foreign direct investment, from previous studies, FDI has a two-way impact on carbon emissions; that is, the pollution haven hypothesis and halo effect hypothesis [18,38–40]. For example, Ren et al. [38] tested the impact of FDI, trade opening, export, import and per capita income on CO_2 emissions through a GMM method based on industrial panel data, and the results proved the existence of the pollution paradise hypothesis. Hao and Liu [39] used a two-equation model to explore the relationship between FDI, foreign trade and China's CO_2 emission. The results confirmed the existence of the halo effect hypothesis.

From the perspective of the relationship between carbon emissions and energy efficiency, the International Energy Agency (IEA), the United Nations Intergovernmental Panel on Climate Change (IPCC), some countries and many scholars believe that energy efficiency is an effective strategy to reduce energy consumption and carbon emissions [41], while other scholars believe that the improvement of energy efficiency will lead to the increase of CO_2 emissions, which is the rebound effect of energy efficiency. The improvement of energy efficiency reduces the effective price of energy use and services, which may increase the demand for energy and its services, leading to an increase in total emissions [42]. For example, Wang and Wei [15] evaluated China's energy and emission efficiency based on the DEA method and measured its energy conservation and emission reduction potential. Yao et al. [43] discussed carbon emission efficiency, energy efficiency and emission reduction potential from a regional perspective, and found that there was significant group heterogeneity between carbon emission efficiency and energy efficiency in various regions of China. Lin and Zhao [44], based on the Morishima alternative elasticity (MES) model, through asymmetric energy price, cross logarithmic cost function and other methods, established a research framework to measure the rebound effect of China's textile industry. The results show that improving energy efficiency is not the only way for China's textile industry to achieve energy conservation and emission reduction. Zhang et al. [42], based on the annual data of 1994–2012, studied the energy rebound effect of the industrial sector through an index decomposition model and panel data model. The results show that the energy rebound effect does exist in China's industrial industry, and the energy rebound effect of industrial industry and manufacturing industry shows an overall downward trend over time.

Although the above research has a great contribution to understanding the main factors affecting carbon dioxide emissions of China's manufacturing industry, it also has its limitations. First, the mitigation potential of China's total carbon dioxide emissions from manufacturing is still unclear at this stage [45]. Moreover, the analysis of the relationship between China's carbon emissions and economic growth, FDI and energy intensity is still lacking. Given this, it is necessary to clarify the factors that affect the carbon dioxide emissions of China's manufacturing industry, and make an effective and comprehensive analysis of the driving factors of the carbon emissions of China's manufacturing industry, so as to make up for the research gap of the relationship between the carbon emissions of China's manufacturing industry and China's economic development, FDI and energy intensity, and strive to enrich the research results of China's low-carbon economy at the industry level.

Compared with the traditional OLS method, the panel quantile method may provide more complete results, and prove the possible heterogeneity at the same time [46]. Meanwhile, many scholars employ the panel quantile method to study the relationship between carbon emissions and its influencing factors [9,18,46–49]. Besides, each quantile can fully describe the distribution characteristics of the carbon emissions of China's manufacturing industry. That is, the high quantile represents the provinces with high carbon emissions from the manufacturing industry, while the low quantile represents the provinces with low carbon emissions from the manufacturing industry. Therefore, based on the improved STIRPAT model and the panel quantile regression model with a two-way fixed effect, this paper uses the panel data of 2000–2013 to study the impact of FDI, economic growth and energy intensity on China's manufacturing carbon emissions. Each quantile can fully describe the distribution characteristics of carbon emissions of China's manufacturing industry. That is, the high quantile represents the provinces with high carbon emissions from the manufacturing industry, while the low quantile represents the provinces with low carbon emissions from the manufacturing industry. The results show that the impact of economic growth, foreign direct investment and energy intensity on the carbon emissions of the manufacturing industry is different under different levels of carbon emissions from the manufacturing industry and different regions, with obvious heterogeneity, and economic growth plays a decisive role in the carbon emissions of the manufacturing industry. Among them, economic growth has a positive impact on the carbon emissions of the manufacturing industry, and the higher the impact of the economic growth of high emission provinces on the carbon emissions of the manufacturing industry is, the more significant the impact of foreign direct investment is on the carbon emissions of the manufacturing industry and on regional heterogeneity. The impact is also more significant in high emission provinces and supports the hypothesis that there is a pollution paradise in China's manufacturing industry, but there is no halo effect hypothesis. In addition, the reduction of energy intensity does not have a positive effect on the reduction of carbon emissions. The higher the impact of energy intensity on the carbon emissions of the manufacturing industry in high emission provinces, the higher the impact of energy intensity on the carbon emissions of the manufacturing industry, indicating that there is an energy rebound effect in China's manufacturing industry. Finally, we have proven that China's manufacturing industry has considerable space for emission reduction. The novelties of this paper are fourfold: (1) This paper focuses on the carbon emissions of China's manufacturing industry. As reducing manufacturing's carbon emissions plays a crucial role in China's response to climate change, studying the impact of economic development, foreign direct investment and energy efficiency on China's manufacturing carbon emissions will help us better understand the importance of industry emission reduction and provide a new perspective for policymakers to reduce overall carbon emissions. (2) We thoroughly study the determinants of CO_2 emission of the Chinese manufacturing industry with distribution heterogeneity. This is mainly because to effectively achieve reducing manufacturing's emissions will require full consideration of the spatial differences in different regions and the differential effects of various variables in different periods [47,50]. China is currently facing economic transformation, with substantial regional differences. In this context, if cross-regional heterogeneity is not considered, the calculation results of energy and carbon emission variables may be biased. Specifically, China has many provinces, and the level of economic development, natural resources, technology and human capital of each province are different. (3) Fixed-effect panel quantile regression model can provide more information and data, which provides a new perspective on how these factors affect the carbon emissions of China's manufacturing industry, and then helps decision-makers to make more strict environmental protection policies. The regression coefficients of different quantiles are often different; that is, the impact of explanatory variables on carbon emissions of the manufacturing industry in different quantiles is different. The quantile regression model can describe the full conditional distribution of dependent variables. Therefore, it can help us to understand more comprehensively the factors related to China's manufacturing industry's carbon emissions, especially in extreme distribution conditions. (4) Our model contains some related control variables, which can solve the problem of variable deviation ignored in previous studies [51].

2. Methodology and Data

2.1. Fixed-Effect Panel Quantile Regression

This paper discusses the effects of economic growth, foreign direct investment and energy efficiency on China's manufacturing industry's carbon emissions through the fixed-effect panel quantile regression model. Traditional OLS usually leads to the underestimation or overestimation of the correlation coefficient, and even cannot detect its relationship [52]. However, by using panel quantile regression, we can study the determinants of China's manufacturing industry's carbon emissions over the entire conditional distribution, especially those regions with the most and least emissions. The quantile regression method is the extension of the mean regression on other quantiles, which was first proposed by Koenker and Bassett [53]. Based on different quantile points, it makes full use of sample data for regression analysis. The quantile regression model has been widely used in environmental research [18,46,47,49,54]. The conditional quantile y_i for a given x_i is as follows:

$$Q_{y_i}(\tau|x_i) = x_i^T \beta_\tau \tag{1}$$

The traditional quantile regression model is robust to outliers, but the traditional model does not take into account the heterogeneity that cannot be observed in any province. Therefore, to better control the non-observed heterogeneity of individual provinces, this paper uses the panel quantile model with a fixed effect to estimate the conditional heterogeneity covariance effect of carbon emission drivers in China's manufacturing industry, so as to control the non-observed individual heterogeneity [55–57]. The quantile regression model of fixed effect panel is as follows:

$$Q_{y_{it}}(\tau_k|\alpha_i, x_{it}) = \alpha_i + x'_{it}\beta(\tau_k). \tag{2}$$

However, the fixed-effect panel quantile regression model has its disadvantages; that is, the total experience containing a large number of fixed effects (α_i) is affected by the additional parameters [58]. However, if the number of individuals tends to infinity because the number of observations per unit cross-section is fixed, the estimators will be inconsistent. In particular, the method of eliminating the fixed effect that cannot be observed is unfeasible in the quantile regression model. The main reason is that the expectation is a linear operation, but the conditional quantile is not [57]. To solve these problems, Koenker [59] proposed to estimate the covariate effect in different quantiles by taking the fixed effect that cannot be observed as a parameter. A penalty term is introduced in the process of minimizing the benefits of this method, which solves the problem of parameter quality estimation. The calculation method of parameter estimation is as follows:

$$\min_{(\alpha,\beta)} \sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{i=1}^{N} \omega_k \rho_{\tau_k}\left(y_{it} - \alpha_i - x_{it}^T \beta(\tau_k)\right) + \lambda \sum_{i}^{N} |\alpha_i| \quad (3)$$

where $i(i = 1, 2, \cdots, 30)$ is each province, t is the number of observations per province, K is the quantile, x is the explanatory variable matrix, ρ_{τ_k} is the quantile loss function and ω_k is the relative weight of the k-th quantile, which is used to control the contribution of the k-th quantiles to the fixed-effect estimation. The same as Lamarche [60] and Alexander [61], this paper uses the equal weight quantile, namely $\omega_k = 1/K$, and λ is the tuning parameter, which improves β estimation performance by reducing individual effects to zero. If λ is zero, then the penalty term disappears, and we get the usually fixed-effect estimator. On the contrary, when λ becomes infinite, we get an estimate of a model without any individual influence. Consistent with Damette and Delacote [62], this paper sets λ to 1.

2.2. Model Specification

The IPAT equation (Equation (4)) is used to study various factors leading to environmental pollution [63], which is defined as

$$I = P \times A \times T \quad (4)$$

where I represents the emission level of pollutants, P represents the population scale, A represents the richness of a country and T represents technological progress. Then, the IPAT equation cannot directly determine how various factors affect environmental change [64], and the elasticity of the three factors to environmental change is unified, which is contrary to the traditional EKC theory [65]. Therefore, to fully investigate the factors affecting environmental change, the STIRPAT model is as follows [66]:

$$I_t = aP_t^b A_t^c T_t^d e_t \quad (5)$$

where P, A and T have the same meaning as in Equation (4), a represents the intercepted item, and b, c and d represents the elasticity of environmental impact on P, A, T, t is the representative time and e_t is the random interference term. The development of the manufacturing industry is very important for the sustainable development of China's economy and environment. Therefore, it is necessary to study one of the important factors that influence the carbon emissions of the manufacturing industry. Besides, although FDI is regarded as one of the main driving forces of economic growth in many cases, it may also bring harm to the environment. An increase in FDI can not only lead to an increase in the manufacturing industry's carbon emissions through the improvement of technology and systems but also to the decrease of manufacturing's carbon emissions due to the transfer of high emission production lines. Therefore, it is necessary to study the relationship between FDI and manufacturing's carbon emissions. Moreover, energy intensity is also essential for the carbon dioxide emission levels of the iron and steel industry. The energy-saving potential of the manufacturing industry in the future is determined to some extent by energy intensity [67]. Therefore, energy intensity is also very important for the carbon emission level of the manufacturing industry. Furthermore, in order to fully understand the impact of economic growth, foreign direct investment and energy intensity on China's manufacturing industry's carbon emissions, based on the STIRPAT model, we introduce the total population, urbanization rate, foreign trade dependence and energy structure as control variables into the model according to the reality of China's manufacturing industry and relevant previous studies [9,50,68,69].

For the above reasons, based on the extended STIRPAT model (logarithmic form), this paper constructs the fixed-effect panel quantile regression model of China's manufacturing industry and studies the impact of economic growth, FDI and energy efficiency on China's manufacturing industry's carbon emissions. The conditional quantile function of quantile τ is as follows:

$$Q_{CO_{2_{it}}}(\tau|\alpha_i, x_{it}, \xi_t) = \alpha_i + \beta_{1\tau}POP_{it} + \beta_{2\tau}GDP_{it} + \beta_{3\tau}FDI_{it} + \beta_{4\tau}URB_{it} + \beta_{5\tau}FTD_{it} + \beta_{6\tau}ENE_{it} + \beta_{7\tau}ENS_{it} + \xi_t \quad (6)$$

where the introduction of variables is shown in Table 1 and i and t have the same meaning as in Equation (3). All variables are transformed into their natural logarithm forms.

Table 1. Definition of variables.

Variable	Definition	Unit
CO_2	Total carbon emissions from the manufacturing industry	Ten thousand tons
POP	Total population	Ten thousand people
GDP	Per capita GDP	Yuan
FDI	Amount of foreign direct investment	100 million
URB	Urbanization rate	%
FTD	The ratio of dependence on foreign trade	%
ENE	Energy intensity	%
ENS	Energy structure	%

Note: (1) All data are annual data from 2000 to 2013. (2) Due to the lack of data, Tibet is not included. (3) Per capita GDP is based on the year 2000.

2.3. Variable, Data Description and Descriptive Statistic

2.3.1. Variable Description

The purpose of this paper is to explore the impact of economic growth, foreign direct investment and energy efficiency on China's manufacturing industry's carbon emissions using data from 30 provinces (excluding Tibet, Hong Kong and Macao, China) from 2000 to 2013. As the relationship between economic growth, foreign direct investment, energy intensity and manufacturing's carbon emissions may be affected by other relevant factors [18] (thus, in order to further analyze the influencing factors of the manufacturing industry's carbon emissions), based on previous literature, we expanded the STIRPAT model [70–72], which includes population size, urbanization rate, dependence on foreign trade and energy structure. The population scale is the total number of each province; according to the regulations of the National Bureau of Statistics of China, the urbanization rate is defined as the ratio of urban population to total population; the dependence on foreign trade is the ratio of total import and export to GDP. Based on the exchange rate between China and the United States over the years, we calculate the dependence on foreign trade of each province; the energy structure is the coal consumption of manufacturing industry divided by its total energy consumption. All variables were converted to the natural logarithm before empirical analysis. See Table 1 for details of data variables.

2.3.2. Data Description

Table 2 shows the descriptive statistics of all variables. When the data samples have a non-normal distribution, the quantile regression estimation results are more robust than OLS. It can be seen from Table 3 that, based on the results of skewness and kurtosis, we find that the distribution of all variables is skewed, and its distribution is more concentrated than the normal distribution of the long tail. Therefore, compared with OLS, the quantile regression model is more reasonable for empirical analysis, and the estimation of the regression coefficient is more robust.

Table 2. Descriptive statistical analysis.

Variable	CO_2	POP	GDP	FDI	URB	FTD	ENE	ENS
Min.	520.10	516.50	263.70	1.27	0.23	0.00	0.03	0.07
Median	7214.50	3823.50	5442.80	171.45	0.45	0.13	0.6148	0.71
Mean	13,983.50	4344.80	7751.70	331.42	0.48	0.32	0.9027	0.72
Max.	253,302.10	10,644.00	46,522.70	2257.32	0.90	6.77	7.1515	1.87

Table 3. Normal distribution test.

Variable	LCO_2	*L*POP	*L*GDP	*L*FDI	*L*URB	*L*FTD	*L*ENE	*L*ENS
Std. Dev.	21,836.31	2641.90	7522.12	419.33	0.15	0.57	1.03	0.24
Skewness	6.77	0.49	2.14	1.98	1.02	6.84	3.23	1.62
Kurtosis	65.434	2.32	8.60	6.88	3.76	70.89	16.06	10.53
Jarque–Bera	71,422.42	24.79	867.99	538.67	82.71	83,926.19	3712.26	1176.45

3. Empirical Results and Analysis

In this section, we first conduct the panel unit root test on the research samples and then perform the panel unit root test. Finally, the panel quantile model is used to study the impact of economic growth, FDI and energy intensity on China's manufacturing industry's carbon emissions.

3.1. Panel Unit Root Test and Panel Cointegration Results

Because of the complexity of real economic phenomena, the data of the economic variables are usually non-stationary. If we use non-stationary data for regression estimation analysis, it will lead to the emergence of pseudo regression [73]. Therefore, before estimating the panel quantile regression model, we tested whether the variables used in the model are stable. In this paper, four-panel unit root tests were carried out, i.e., the LLC test, IPS test, Fisher ADF test and Fisher PP test. Table 4 shows the results of panel unit root test. These results show that the original hypothesis of unit root can be rejected by all the selected variables. At the 1% level, the unit root zero hypothesis of all variables can be rejected almost completely for the first difference variable. Therefore, all variables can be analyzed directly without a difference.

Table 4. Panel unit root test results.

Variable	CO_2	POP	GDP	FDI	URB	FTD	ENE	ENS
Levels								
LLC	−6.58 ***	−2.22 **	−11.07 ***	−3.45 ***	−5.21 ***	−6.55 ***	9.99	4.96
	(1.85)	(−1.88 **)	(2.22)	(−14.33 ***)	(−5.36 ***)	(−6.25 ***)	(2.05)	(3.52)
IPS	−0.54	5.12	−0.53	1.23	3.23	−2.09 **	7.81	7.34 *
	(2.59)	(1.91)	(2.28)	(−4.32 ***)	(0.72)	(0.01)	(7.02)	(2.79)
Fisher-ADF	77.98 *	36.65	87.38 **	55.32	46.46	81.20 **	16.59	24.66
	(48.178)	(54.43)	(40.36)	(107.87 ***)	(50.06)	(59.01)	(16.03)	(46.70)
Fisher-PP	147.91 ***	66.69	28.97	59.98	207.46 ***	64.49	23.33 **	42.42
	(95.70 ***)	(65.19)	(94.95 ***)	(95.52 ***)	(42.96)	(47.30)	(39.68 **)	(68.16)
First difference								
LLC	0.99	2.27	−2.84 ***	−13.41 ***	−5.51 ***	−10.02 ***	−0.25	−2.82 ***
	(1.16)	(8.44)	(−5.37 ***)	(−9.05 ***)	(−5.18 ***)	(−11.19 ***)	(−0.85)	(−1.11)
IPS	−2.02 **	0.33	−1.96 **	−8.36 ***	−2.90 ***	−6.60 ***	−1.24	−3.86 ***
	(−1.21)	(3.32)	(1.72)	(−4.37 ***)	(−1.58 *)	(−5.47 ***)	()	(−2.34 ***)
Fisher-ADF	82.26 **	63.09	76.61 *	180.51 ***	89.62 ***	149.52 ***	72.31	110.45 ***
	(69.14)	(41.79)	(55.02)	(122.51 ***)	(79.12 **)	(136.52 ***)	(88.32 **)	(90.31 ***)
Fisher-PP	184.96 ***	147.60 ***	78.50 *	265.62 ***	146.01 ***	233.39 ***	240.78 ***	262.04 ***
	(191.37 ***)	(72.59)	(89.54 ***)	(243.24 ***)	(180.17 ***)	(292.67 ***)	(387.93 ***)	(269.53 ***)

Note: (1) LLC (Levin, Lin and Chu) and IPS (Im, Pesaran and Shin W-stat) represent the panel unit root test by Levin et al. [74]. Fisher-ADF (ADF-Fisher Chi-square) and Fisher-PP (PP-Fisher Chi-square) represent the panel unit root test on behalf of Maddala and Wu [73]. (2) Numbers without brackets are individual intercept values. (3) The numbers in brackets are individual intercept and trend values. (4) *** represents statistical significance at the 1% level, ** represents statistical significance at the 5% level, and * represents statistical significance at the 10% level.

The panel cointegration test is employed to judge whether there is a long-term equilibrium relationship among variables. Pedroni's [75,76] panel cointegration test and Kao's [77] panel cointegration test are widely used to test the existence of panel cointegration. On this basis, and thus in order to have comparative analysis, we used the Pedroni panel cointegration test method and Kao panel cointegration test method to verify Equation (6). The Pedroni and Kao tests are both based on the regression residual under the condition of the independent section. It can be seen from Table 5 that there is a cointegration relationship between variables. Therefore, we took all variables directly into the equation for quantile regression.

Table 5. Panel co-integration test results of Pedroni and Kao.

Pedroni Cointegrating Vector Test: Panel Specific			**Kao Residual Cointegration Test**		
Test Value	**Statistic**	***p*-Value**		**t-Statistic**	**Prob.**
Modified Phillips–Perron t	8.77	0.00	ADF	−6.72	0.00
Phillips–Perron t	−14.90	0.00	Residual variance	0.02	
Augmented Dickey–Fuller t	−13.13	0.00	HAC variance	0.02	

3.2. Panel Quantile Regression Results

As each quantile can adequately describe the distribution characteristics of manufacturing's carbon emissions, the quantile regression model directly reveals the marginal effect of explanatory variables on manufacturing carbon emissions at different quantile levels. Besides, China's manufacturing industry has obvious characteristics of massive development, and there are significant differences in different provinces, mainly ignoring the fixed effect of time cycle that may lead to the deviation of estimates in traditional time series research. Therefore, in order to control the heterogeneity of distribution and consider the different effects of different periods, this paper adopts a panel quantile model with bidirectional fixed effects [60] for regression analysis. Table 6 presents the panel quantile regression estimates of the two-way fixed effect (5th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th and 95th quantiles). In general, the influence of various factors and different quantiles on carbon emissions is different. The quantile results show that economic growth (*GDP*), foreign direct investment (*FDI*) and energy intensity (*ENE*) have different effects on manufacturing's carbon emissions under different levels and regions.

Table 6. Panel quantile regression results.

Variable	**Quantile Statistics**									
	5th	**20th**	**30th**	**40th**	**50th**	**60th**	**70th**	**80th**	**90th**	**95th**
Constant	3.45 ***	3.67 ***	3.74 ***	3.69 ***	3.88 ***	3.94 ***	3.91 ***	3.92 ***	3.84 ***	3.56 ***
	(3.31)	(3.81)	(3.89)	(3.89)	(4.11)	(4.17)	(4.03)	(4.02)	(3.81)	(3.48)
POP	0.08	0.08	0.05	0.01	−0.01	−0.05	−0.11	−0.18	−0.24	−0.27
	(0.35)	(0.52)	(0.33)	(0.08)	(−0.02)	(−0.25)	(−0.56)	(−0.90)	(−1.16)	(−1.34)
GDP	0.59 ***	0.57 ***	0.59 ***	0.63 ***	0.64 ***	0.69 ***	0.73 ***	0.79 ***	0.84 ***	0.90 ***
	(2.80)	(4.83)	(4.92)	(5.08)	(4.70)	(4.53)	(4.59)	(4.91)	(5.19)	(5.50)
FDI	0.07	0.08	0.06	0.05	0.03	0.01	0.04	0.05	0.09	0.13 *
	(1.26)	(1.35)	(1.04)	(1.01)	(0.66)	(0.28)	(0.74)	(0.77)	(1.41)	(1.89)
URB	0.65	0.72 **	0.65 *	0.57	0.61	0.62	0.48	0.43	0.25	0.15
	(1.25)	(1.99)	(1.76)	(1.53)	(1.57)	(1.55)	(1.18)	(1.05)	(0.64)	(0.37)
FTD	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.04
	(1.15)	(0.31)	(0.23)	(0.23)	(0.17)	(0.19)	(0.24)	(0.09)	(0.43)	(0.90)
ENE	0.27 ***	0.28 ***	0.28 ***	0.28 ***	0.29 ***	0.29 ***	0.29 ***	0.30 ***	0.42 ***	0.50 ***
	(3.00)	(3.61)	(3.56)	(3.60)	(3.76)	(3.81)	(3.64)	(3.42)	(3.58)	(3.93)

Table 6. *Cont.*

Variable	Quantile Statistics									
	5th	20th	30th	40th	50th	60th	70th	80th	90th	95th
ENS	−0.31 (−1.40)	−0.32 (−1.53)	−0.35 * (−1.75)	−0.38 * (−1.94)	−0.43 ** (−2.19)	−0.46 ** (−2.44)	−0.46 ** (−2.47)	−0.48 ** (−2.42)	−0.57 *** (−2.72)	−0.66 *** (−3.39)

Note: (1) This table shows the results of the panel quantile regression model with carbon emissions of the manufacturing industry in different provinces as dependent variables and FDI, economic growth, energy intensity and control variables as independent variables. (2) The number in brackets are t values. (3) *** represents statistical significance at the 1% level, ** represents statistical significance at the 5% level, and * represents statistical significance at the 10% level.

4. Discussion

According to the above empirical results, there are some interesting phenomena.

In terms of economic growth, we can find that the impact of economic growth on carbon emissions of the manufacturing industry is not heterogeneous. The GDP coefficients of all quantiles are very significant (at the level of 1%), and their coefficients show a trend of decreasing first and then increasing. These results indicate that economic growth has a positive impact on carbon emissions of the manufacturing industry, which is consistent with the research conclusions of Xu et al. [50] and Lin and Xu [9]. The higher the impact of economic growth on the manufacturing industry's carbon emissions of high emission provinces, the stronger the impact of economic growth on manufacturing's carbon emissions of provinces in the 95th quantile than other quantile provinces. The reason may be that, at present, China mainly relies on fixed investment to promote economic growth, and the manufacturing industry, as an essential industry, plays a vital role in fixed investment. At the same time, the manufacturing industry is a high emission industry, and there is a significant demand for many products. The manufacturing industry not only promotes the economy but also produces a lot of emissions. Besides, China's production emissions are greater than its consumption emissions. Under the existing climate policy and international trade rules, carbon leakage occurs [78]. Although foreign trade is one of the power sources of China's economic growth, due to the low level of technology in China at this stage, most of the products exported are energy-intensive products. Therefore, while foreign trade causes economic growth, it also leads to an increase in carbon emissions in the manufacturing industry.

On the contrary, for FDI, we can observe that the FDI coefficient is positive at all quantile points (especially the impact is significantly positive in high emission provinces), but it is not significant at the 10% level except for the high quantile (i.e., 95th quantile, which is significant at 10%). These results support the hypothesis that the manufacturing industry is a pollution heaven in China, but not the halo effect hypothesis. The inflow of FDI will lead to an increase in carbon emissions in big emission provinces, but the impact on the low quantile point is not significant, which means that most FDI investment in small emission provinces may be located in the less-polluting manufacturing industry, and the environmental laws and regulations of low emission provinces may be relatively perfect and strict. Alternatively, with the help of its advanced production technology and management experience, it has a positive impact on the emissions of the manufacturing industry.

Similarly, in terms of energy intensity, we can find that the impact of energy intensity on the carbon emissions of the manufacturing industry is not heterogeneous. The *ENE* coefficient of all quantile points is very significant; that is, it is significant at the 1% level, and its coefficient shows a monotonous increasing trend. Compared with the low emission provinces, the energy intensity of the high emission provinces has a higher impact on the carbon emissions of their manufacturing industries. In particular, the impact of energy intensity on carbon emissions of the 95th quantile provinces is higher than that of other quantile provinces. Consistent with Du et al. [79] and Lin and Xu [9], the reduction of energy intensity does not have a positive effect on the reduction of carbon emissions. The research results show that there is a rebound effect of energy intensity in China's manufacturing industry, and our research results are consistent with the previous empirical study Zhang et al. [42], which also confirms that there is indeed an energy rebound effect in China's manufacturing industry. Through the above studies, we find that for China's manufacturing industry, the current stage is too single to pursue the macro energy intensity goal, while ignoring the overall control of carbon emissions, which directly affects the energy-saving effect of the manufacturing industry, causing damage to the whole environment.

In addition, regardless whether in regions with high carbon emission or low carbon emission, the impact of economic growth on carbon emission of the manufacturing industry is far higher than that of foreign direct investment and energy intensity, which plays a decisive role, followed by energy intensity, because the *ENE* coefficient in each quantile is greater than the *FDI* coefficient. With the gradual improvement of carbon emission levels of the manufacturing industry, the impact of economic growth, foreign direct investment and energy intensity on the carbon emission of the manufacturing industry is gradually increasing. In addition, China's manufacturing industry has a huge space for emission reduction. Because with the gradual improvement of the carbon emission level of the manufacturing industry, economic growth, foreign direct investment and energy intensity increase promote an increase in carbon emissions in the manufacturing industry (especially the sum of coefficients of the 70th, 80th, 90th and 95th percentiles are greater than 1). Therefore, we should adequately deal with the relationship between economic growth and carbon emissions, pay attention to the changes in total carbon emissions while focusing on foreign direct investment and energy intensity improvement, especially making good use of the larger emission reduction space in high emission areas, and reduce the total emissions of China's manufacturing industry through a reasonable combination of economic growth, foreign direct investment and energy intensity.

The empirical results of the control variables included in the model also provide reference information. First, we can observe the impact of urbanization rate on carbon emissions. At the low quantiles (20th and 30th), the coefficient of urbanization rate is significant; at other quantiles, it is not significant. All coefficients of *URB* are positive, which means that higher urbanization rate will lead to higher carbon emissions of the manufacturing industry. In comparison, the impact of urbanization in low emission areas on manufacturing carbon emissions is greater than that in high emission areas, because its coefficient elasticity is greater. The reason may be that the increase in urbanization rate not only causes the increase of urban population, but also leads to the rise in demand for high emission products such as vehicles and real estate, and then causes the increase of carbon emissions in the manufacturing industry. Second, the coefficient of dependence on foreign trade is not significant in all quantiles. All coefficients are positive, but the elasticity is very weak; that is, the dependence on foreign trade will have a positive impact on the carbon emissions of China's manufacturing industry, which shows that China's manufacturing industry has a weak carbon leakage phenomenon. Third, the impact of total population on carbon emissions; we can see that the impact of total population on carbon emissions is obvious heterogeneity. At the 5th, 20th, 30th and 40th quantiles, the pop coefficient was positive, but not significant at the 10% level. In the 50th, 60th, 70th, 80th, 90th and 95th quantiles, the *POP* coefficient was negative, but not significant at the level of 10%. In low emission areas, population size has a positive impact on carbon emissions of manufacturing industry, while in high emission areas, population size hurts carbon emissions of manufacturing industry. This shows that population size is not an important factor affecting carbon emissions of the manufacturing industry in these regions. In addition, in the low quantile (5th and 20th quantiles), the energy structure coefficient is not significant, but the high quantile (30th and 40th quantiles), the 50th, 60th, 70th, and 80th quantiles, are at the level of 5%, whereas at the 90th and 95th quantiles they are significant at the level of 1%; the energy structure coefficient is significant. All these results above proved that it is necessary to further optimize the energy structure for low emission areas.

5. Conclusions and Policy Recommendations

Based on panel data of 30 provinces in China from 2000 to 2013, this paper studied the impact of FDI, economic growth and energy intensity on carbon emissions of China's manufacturing industry by a two-way fixed-effect panel quantile regression model. The results show that the impact of economic growth, foreign direct investment and energy intensity on the carbon emissions of the manufacturing industry is different under different levels of carbon emissions from the manufacturing industry and different regions, with obvious heterogeneity, and economic growth plays a decisive role in the carbon emissions of the manufacturing industry. Among them, economic growth has a positive impact on the carbon emissions of the manufacturing industry, and the higher the impact of economic growth of high emission provinces on the carbon emissions of the manufacturing industry is, the more significant the impact of foreign direct investment on the carbon emissions of the manufacturing industry is regional heterogeneity, and the impact is more significant in high emission provinces and supports the hypothesis that there is a pollution paradise in China's manufacturing industry, but there is no halo effect hypothesis. The reduction of energy intensity also does not have a positive effect on the reduction of carbon emissions. The high impact of energy intensity in high emission provinces on the carbon emissions of their manufacturing industries, indicates that there is energy rebound effect in China's manufacturing industry. Finally, it is confirmed that China's manufacturing industry has a vast space for emission reduction.

According to the above research results, in order to reduce the total carbon emissions of China's manufacturing industry and improve China's environmental quality, the following three policies are recommended.

(1). Based on the hypothesis of pollution heaven and halo effect in different provinces, China should try to assess the impact of foreign direct investment on the environment before the introduction of foreign capital into China's manufacturing industry. Especially in high emission areas, the level of FDI should be improved. Moreover, through financial, tax and industrial policies to limit the inflow of high emission foreign capital, encourage the entry of high-tech and advanced management experience.

(2). The Chinese government should not only consider the energy conservation brought about by technological change but also pay attention to the energy rebound effect, to avoid overestimating the energy conservation brought about by the technological progress of the industry.

(3). China should adopt different carbon emission policies in regions with different carbon emission levels and properly handle the relationship between economic growth and carbon emissions. Based on the different characteristics of economic growth in each province, targeted measures are taken to reduce the CO_2 emission of the manufacturing industry. There is a huge space for China's manufacturing industry to reduce emissions, and we should encourage manufacturing enterprises to join the carbon trading market.

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