ADBI Working Paper Series

UNDERSTANDING GAS PRICING MECHANISMS: IMPLICATIONS FOR THE ASIAN MARKET

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No. 1175
August 2020

Asian Development Bank Institute

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Suggested citation:

Cai, Y. and Y. Wu. 2020. Understanding Gas Pricing Mechanisms: Implications for the Asian Market. ADBI Working Paper 1175. Tokyo: Asian Development Bank Institute. Available: https://www.adb.org/publications/understanding-gas-pricing-mechanisms-implications-asian-market

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The research presented in this paper benefited from a University Postgraduate Award (UPA) and an Australian Government Research Training Program (RTP) scholarship. The authors also acknowledge helpful comments and suggestions from Muhammad Mohsin and participants in a work-in-progress departmental seminar (Economics, UWA, Australia) and a workshop on "Meeting Environmental Objectives through Energy Sector Reforms in Asia and the Pacific: Role of Energy Pricing and Reforms for Emissions Reduction" that ADBI and the CAREC Institute jointly organized on 22–24 June 2020.

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Abstract

This paper aims to understand the gas-pricing mechanism in the major markets and hence draw implications for gas-pricing reform in Asia. It adopts the bootstrap sub-sample rolling-window Granger test to investigate the causality between crude oil and natural gas prices. Unlike the estimations based on full-sample data with the problem of parameter constancy, the rolling-window technique can provide evidence with time-varying properties. The findings in this paper support a coupling relationship between oil and gas prices in Japan before 2013 and a mixed relationship after that. In Europe, the relationship is mixed. Lastly, the study identifies a decoupling relationship in the US. The oil supply and demand, OPEC decisions, and the financial crisis are likely to affect the traditional oil indexation. However, the shale gas revolution tends to affect the deviation between crude oil and gas price changes in the US. The empirical results suggest the necessity to establish trading hubs in Asia and Europe so that gas pricing can fully reflect the fundamentals in gas markets and help to achieve more efficient gas allocation.

Keywords: natural gas pricing, oil indexation, time-varying Granger causality test, rolling-window technique, Asia

JEL Classification: Q31, Q41

Contents

1. INTRODUCTION

The oil price has fluctuated significantly over the past years due to political polarization across the world. Changes in the oil price also affect the price of natural gas, which countries traditionally index to oil prices (so-called oil indexation) (Hartley, Medlock III, and Rosthal 2008; Zhang and Ji 2018). However, oil indexation may reflect the supply and demand of oil but not those of natural gas. Thus, researchers have discussed the idea of an independent natural gas trading system (Shi and Variam 2016). There are emerging studies focusing on the potential decoupling of natural gas and crude oil prices and whether the deviation will be a temporary or permanent process if decoupling does occur (Erdos 2012; Zhang and Ji 2018). This paper adds to the existing literature by examining the gas-pricing mechanisms in major gas markets, particularly the time-varying causal nexus between natural gas and crude oil price changes.

There are essentially three regional gas markets, which cover three continents, namely America, Europe, and Asia. The gas-pricing mechanisms in these markets differ from each other. In recent years, major changes have affected these three markets, such as North America's shale gas revolution, the People's Republic of China's rising energy demand in Asia, and the Ukraine conflict in Europe. The pricing mechanisms and certain events in the three markets may significantly change the relationship between gas and oil pricing. Existing studies have not reached a consistent conclusion in regard to the nexus between oil and natural gas prices.

This study first presents time-varying evidence about the causal nexus between crude oil and natural gas price changes. In fact, the estimations using the whole sample may produce misleading inferences due to the assumption of fixed parameters in the vector autoregressive model (Balcilar, Ozdemir, and Arslanturk 2010). Structural breaks may lead to variation in the parameters in the system. Traditional methods to solve this problem of structural breaks involve the use of dummy variables (Bai and Perron 2003). Another approach is the use of the sample-splitting method, which Balcilar, Ozdemir, and Arslanturk (2010) proposed. This approach can provide more robust inferences about causality as well as evidence of a time-varying relationship through a rolling-window method. Further, the number of periods of the causality can be indexed through the bootstrap rolling-window Granger test and the use of sub-samples.

There are several main findings in this paper. Through the analysis of the full sample, we find unidirectional causality of price changes from the oil market to the natural gas market in Europe, Japan, and the US. No evidence supports the assertion that gas price changes cause oil price changes. When implementing the bootstrap rolling-window technique, we find time-varying bi-directional causality between oil and natural gas price changes in Europe and the US. Differently, gas price changes in Japan cannot cause oil price changes with time-varying properties. These findings are first illustrated by providing time-varying Granger causal evidence. The periods with the rejection of non-Granger causality in Japan and Europe are related to low spare capacity in 2005, the global financial crisis in 2008, and the OPEC production quota change in 2015. In contrast, crude oil price changes cannot cause natural gas price changes in the US before 2010. However, since the shale gas boom in 2010, the interactions between oil and Henry Hub gas price changes have been mixed. Lastly, we consider different factors that may affect the robustness of the estimations, such as the window size and other proxy variables for crude oil price changes. There are no significant variations in the estimations, implying that the results are robust.

The remainder of this paper begins with a literature review in Section 2. Section 3 discusses the dataset. Section 4 introduces the econometric procedures. Section 5 presents the analytical results and robustness checks. Finally, Section 6 makes concluding remarks and discusses the policy implications.

2. LITERATURE REVIEW

Researchers have widely used the cointegration test to investigate the long-run relationship between crude oil and gas prices. For example, Bachmeier and Griffin (2006) investigated the integration of coal, natural gas, and oil markets.[1] The results that these authors obtained show weak integration in the three markets, even without a primary energy market. Furthermore, there is strong evidence of integration between oil and natural gas markets. Villar and Joutz (2006) determined that the West Texas Intermediate (WTI) crude oil and Henry Hub gas prices are cointegrated. Based on their estimation, a 20% temporary WTI price shock will cause a contemporaneous increase in the natural gas price of 5%. Moreover, a 20% permanent WTI price shock will make the Henry Hub price increase by 16%.

Hartley, Medlock III, and Rosthal (2008) first revealed an indirect relationship between natural gas and oil prices as natural gas competes with residual fuel oil, while other authors mainly provided direct evidence. Panagiotidis and Rutledge (2007) demonstrated that the two prices are cointegrated. However, Ramberg and Parsons (2010) suggested a weak relationship between gas and crude oil prices. Their findings supported the idea that the relationship should be a time-varying process and change over time. Erdos (2012) showed that the gas price decouples from the crude oil price in the US market. Atil, Lahiani, and Nguyen (2014) extended the existing studies to explore the non-linear relationship between natural gas and crude oil prices. They showed that a negative oil shock has greater impacts on the natural gas price than a positive oil shock. Asche, Oglend, and Osmundsen (2015) used regime-switching models to avoid erroneous inferences with the linear models and found that the natural gas price in the UK market is cointegrated with the crude oil price for most of their sample period. Lin and Li (2015) supported the cointegration hypothesis in Japan and found a decoupling relationship in the US and Europe. Zhang and Ji (2018) utilized an approach with "long memory" to examine whether oil and natural gas prices decouple by providing time-varying evidence. The empirical results suggested that the oil and natural gas price relationship is non-stationary and decouples over time in the US. However, the European and Asian oil and gas prices only showed evidence of temporary decoupling.

Geng, Ji, and Fan (2016a, 2016b) argued that supply and demand are the main determinants of the US natural gas price while oil plays the key role in the Japanese and European markets. Besides, the US gas market is sensitive to temperature changes in winter. These authors also investigated the impacts of the shale gas explosion in the American and European markets. The dynamics in Henry Hub prices have turned from a slight increase to a sharp decrease. However, the national balancing point (NBP) price has shifted from a sharp increase to a regime between abrupt increases and modest decreases, indicating that the shale gas boom has had little impact on the NBP pricing mechanism.

Wolfe and Rosenman (2014) employed a high-frequency dataset and found bi-directional causality between gas and crude oil prices. The gluts and shortages of crude oil and gas have cross-commodity effects on price volatility. Batten, Ciner, and Lucey (2017)

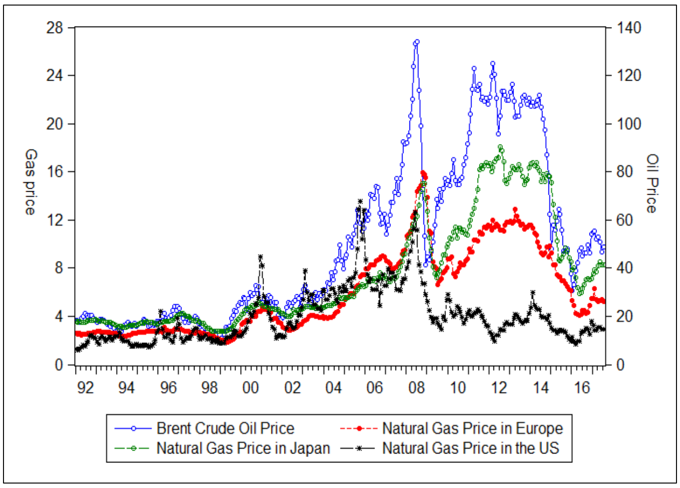
[1] Other examples include Asche, Osmundsen, and Sandsmark (2006), Ramberg and Parsons (2010), Wakamatsu and Aruga (2013), Atil, Lahiani, and Nguyen (2014), Brigida (2014), Asche, Oglend, and Osmundsen (2015), and Zhang and Ji (2018).

investigated the causal nexus between the natural gas and the crude oil market by only considering the gas price in the US. There is little evidence to support the dependency between gas and oil prices. They attributed the decoupling between crude oil and gas to both economic and natural events, such as the earthquake in Tohoku, Hurricane Katrina in the US, the global financial crisis, and technological developments. Jadidzadeh and Serletis (2017) employed the structural vector autoregressive model to explore the effects of crude oil supply and demand shocks on the US natural gas market. The results show that nearly half of the real gas price change is due to shocks in the oil supply and demand in the market. In fact, recent studies have shown consistently that the interactions between natural gas and crude oil prices are time varying (Batten, Ciner, and Lucey 2017; Hou and Nguyen 2018; Zhang and Ji 2018).

3. DATA

The study draws the dataset from the Global Economic Monitor (GEM) commodity price database that the World Bank maintains. It covers the period from 1992M2 to 2017M7. The study employs Brent crude oil prices to represent the performance of the global crude oil market. As mentioned, there are three main natural gas trading markets, namely the European average import border price, the Henry Hub spot price of the US, and the imported liquefied natural gas (LNG) price of Japan. Figure 1 plots all the series. The crude oil and natural gas prices in Japan are clearly consistent over the whole period. Further, there are hysteresis effects in the natural gas price in Japan. However, the relationship between the crude oil price and the natural gas price seems to be weaker in Europe. Especially after the 2008 financial crisis, the two prices move in opposite directions. In contrast, the US natural gas price seems to be uncorrelated with the crude oil price. The reasons for such differences are mainly attributable to the pricing mechanisms in these three markets. As Asche, Oglend, and Osmundsen (2015) and Zhang and Ji (2018) suggested, the natural gas price in the European and Japanese markets still uses oil indexation. In the US, a gas-to-gas competition pricing mechanism has existed for years, with more spikes and fluctuations. The market for crude oil is less likely to have an impact on such a pricing mechanism.

Figure 1: Brent Crude Oil Prices vs Natural Gas Prices

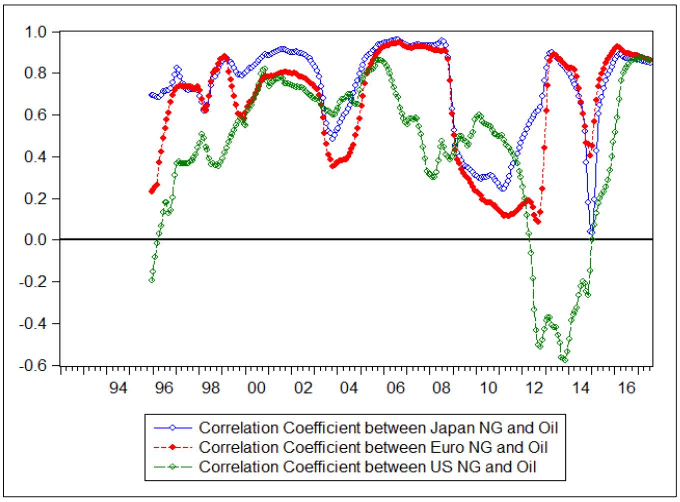


To reveal the time-varying correlation relationship between oil and natural gas prices, the study employs the rolling-window technique to calculate the correlation between oil and gas prices sequentially. Figure 2 contains the results. Specifically, if a rolling window has *l* observations, it is possible to use the full sample to create $T-l$ sub-samples, namely, $\tau-l+1$, $\tau-l+2$, $\cdots$, τ for $\tau=l,l+1,\cdots,T$. The study computes the correlation coefficient for each of the $T-l$ sub-samples, that is,

$$\rho_{Oil,Gas}=\frac{cov(P_{oil},P_{gas})}{\sigma_{oil}\sigma_{gas}} \tag{1}$$

We determine the window size l to be 48, which we also utilize for the sub-sample Granger causality test in the next section for the sake of consistency. Interestingly, the correlation coefficient of natural gas prices in Japan and Europe remains positive over the whole sample period. However, the correlation coefficient in the US is negative in a few months of 1996 and the period from 2012 to 2015. These observations reconfirm that the differences in pricing mechanisms may matter for the price link in the gas and oil markets. To conduct the causality test and ensure the stationarity of the variables, the models use the log-difference of the variables.

Figure 2: Correlation Coefficients between Oil and Gas Prices



4. ANALYTICAL MODELS

4.1 Bootstrap Granger Causality Test Using the Full Sample

We employ a bootstrap Granger causality test to explore the causal relationship between natural gas and oil price changes. It is essentially a residual bootstrap (RB) modified likelihood ratio (LR) test. To accommodate gas and oil price changes in a bivariate vector autoregressive (VAR) model with *p* lags, we can present the specification as follows:

$$y_t=\phi_0+\phi_1 y_{t-1}+\cdots+\phi_p y_{t-p}+\varepsilon_t, t=1,2,\cdots,T \tag{2}$$

where we can select the number of lags p according to the Schwarz information criterion (SIC) and ε_t is the residual with mean zero and covariance matrix $\sum$. We can divide the vector y_t into two sub-vectors $(OIL_{1,t}, NG_{2,t})'$. Accordingly, we can expand equation (2) into the following form:

$$\begin{bmatrix} OIL_t \\ NG_t \end{bmatrix} = \begin{bmatrix} \phi_{1,0} \\ \phi_{2,0} \end{bmatrix} + \begin{bmatrix} \phi_{1,1} & \phi_{1,2} \\ \phi_{2,1} & \phi_{2,2} \end{bmatrix} \begin{bmatrix} OIL_t \\ NG_t \end{bmatrix} + \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix} \tag{3}$$

where OIL_t and NG_t indicate crude oil and gas price changes, which we calculate as the log differences of prices, respectively.[2] $\phi_{i,j}(L) = \sum_{k=1}^{p+1} \phi_{i,j,k} L^k$ with $L^k x_t = x_{t-k}$ $(i, j = 1,2)$. Given equation (3), we impose restrictions on the coefficients to test the non-Granger causality hypothesis. Specifically, we can test the null hypothesis that natural gas price changes do not Granger cause crude oil price changes by imposing $\phi_{1,2,k} = 0$ $(k = 1,2, \cdots, p)$. Likewise, we can test for non-Granger causality from oil price changes to natural gas price changes by restricting $\phi_{2,1,k} = 0$.

As Balcilar and Ozdemir (2013) suggested, parameter non-constancy highly affects the results of causal inference. Specifically, if there are drifts and structural breaks in the full-sample VAR model, the estimates are likely to be biased. To solve this problem, we adopt the $Sup - F$ test statistic that the literature has proposed (Andrews 1993). We can generate the corresponding *p*-values and critical values through a bootstrapping procedure. To perform this test, we trim the sample at both ends by 15% (Andrews 1993). That is, we apply this test to the (0.15, 0.85) segment of the sample. We conduct the $Sup - F$ test for each model and the VAR system.

4.2 Bootstrap Granger Causality Test: Sub-sample

It is possible to extend the traditional RB modified LR causality test by incorporating time-varying properties (Balcilar, Ozdemir, and Arslanturk 2010). Using the rolling-window technique, we divide the full sample into a set of sub-samples, which we test sequentially using the traditional method. Having determined a suitable window size, the rolling-window technique can overcome the biased estimations due to fixed parameters (Balcilar, Ozdemir, and Arslanturk 2010). Specifically, given a sample including *T* observations and a chosen window size *l*, it is possible to use the sample to generate $T - l$ sub-samples, namely, $\tau - l + 1$, $\tau - l + 2$, $\cdots$, T, where $\tau = l, l + 1, \cdots, T$. Then, we conduct the aforementioned modified LR causality test against the null hypothesis for each sub-sample. Balcilar and Ozdemir (2013) provided the details of the construction of this test statistic. By computing the bootstrapping p-values of the derived LR statistic for each sub-sample, we can intuitively observe potential changes in the causal links between oil and gas price changes, respectively.

To provide the magnitude of the dynamic effects, we save the estimated coefficients and calculate the 90% significance bounds. In greater detail, it is possible to compute the effects of gas price changes on oil price changes by taking the average of the entire bootstrap estimations based on $N_b^{-1} \sum_{k=1}^{p} \phi_{1,2,k}^*$, where N_b is the number of repetitions of the bootstrapping estimation. Similarly, we can calculate the effects of oil price changes on gas price changes based on $N_b^{-1} \sum_{k=1}^{p} \phi_{2,1,k}^*$. We also provide the 90% confidence intervals of these estimates. It is notable that the empirical findings may be sensitive to the size *l* of the selected window, though there is no specific selection rule (Balcilar, Ozdemir, and Arslanturk 2010). Pesaran and Timmermann (2005)

[2] Toda and Phillips (1993, 1994) argued that, if the time series variables in the model are non-stationary, the LR statistics are not standard.

suggested that the selection criterion can partially refer to the persistence and size of the breaks. In this study, we determine the fixed window size as 48, which we selected based on previous studies, multiple structural breaks, and the degree of freedom (Balcilar and Ozdemir 2013).

5. EMPIRICAL RESULTS

This section includes three parts. We present the results from the full-sample estimation first. Then we discuss the bootstrap rolling-window test (sub-sample) results. Finally, we conduct a robustness check.

5.1 Full-Sample Estimates

We first conduct the bootstrap causality test by employing the whole sample period. We use 5,000 replications to obtain the p value. Table 1 presents the empirical results under the non-causality null hypothesis. The estimation results of all three markets reject the null hypothesis that OIL does not Granger cause NG. Therefore, in the long run, crude oil price changes cause natural gas price changes, which is consistent with the findings in the existing studies, such as Villar and Joutz (2006), and supports the conclusion that the crude oil market influences the gas market. In contrast, the empirical findings do not reject the null hypothesis that natural gas price changes do not cause oil price changes and imply that natural gas price changes cannot influence oil price changes.

Table 1: Results of the Bootstrap Causality Tests (Using the Full Sample)

	H_0: OIL Does Not Cause NG		H_0: NG Does Not Cause OIL	
	LR stat.	**p-value**	**LR stat.**	**p-value**
Japan	38.647***	0.000	2.719	0.433
Europe	39.838***	0.000	3.023	0.381
US	10.770**	0.012	1.352	0.715

Note: *** and ** indicate significance at the 1% and 5% levels. The tests use bootstrap 5,000 replications.

However, research has suggested that the crude oil and gas price nexus should be a mutually interacting process with time-varying properties (Zhang and Ji 2018). In fact, it has found that the crude oil price affects the natural gas price in Europe and Japan but that there is no relationship in the US (Lin and Li 2015; Zhang and Ji 2018). Thus, the full-sample estimation may not be trustworthy due to parameter non-constancy in the VAR system, as Balcilar and Ozdemir (2013) showed. Besides, as the US government launched the program for shale gas exploitation, the supply and demand in the gas market changed significantly, which may have indirectly affected the nexus between the oil and the gas market.

To check whether parameter instability causes inaccurate estimations of the system, we conduct the $Sup - F$ test for each VAR equation in the system and the system as a whole. Table 2 shows the outcome. Overall, the $Sup - F$ test cannot reject the null hypothesis of parameter constancy for the OIL equation of all three markets. Further, it rejects the $Sup - F$ statistic for the NG equation of the Japanese and European gas markets. As for the whole VAR system, the $Sup - F$ statistic is significant for all the markets. Thus, the estimation of the whole VAR system is not valid in the short run due to parameter non-constancy, which will affect the empirical results in the full-sample estimation.

Table 2: Results of the Parameter Stability Tests

	OIL		**NG**		**System**	
	Sup-F	**p**	**Sup-F**	**p**	**Sup F**	**p**
Oil–Japanese Gas	7.402	0.474	12.749*	0.079	27.494***	0.003
Oil–European Gas	11.194	0.141	14.059**	0.047	24.511***	0.010
Oil–US Gas	10.589	0.175	6.403	0.609	27.494***	0.003

Note: ***, **, and * represent significance at the 1%, 5%, and 10% levels. The null hypothesis *Ho*: constant parameters. The alternative hypothesis *Ha*: one sharp shift in the parameters. *p*: *p*-value.

5.2 Sub-sample Estimates

To deal with the problem of parameter non-constancy and provide more robust estimation with time-varying evidence, we adopt the above-mentioned rolling-window method. The results may be sensitive to the window size selected. A small size can generate more sub-samples and hence more sets of estimates but reduces the estimation precision. In contrast, a large size can avoid the effects of heterogeneity but diminishes the number of sub-samples available. We choose the window size of 48 because the estimation with such a window size is robust, and the results do not change as the window size continuously increases.[3] We determine the optimal number of lags as 3, which is adequate to eliminate the potential serial correlation.

Figure 3 shows the causality testing results for Japan. The null hypothesis is that crude oil price changes do not cause gas price changes, which the test rejects for the majority of the periods. However, crude oil price changes cannot cause gas price changes over a few months in 2005, 2008, 2013, and 2015. As suggested by the Energy Information Administration (EIA), some key geopolitical and economic events occurred during those periods. Specifically, in 2005, the global oil market's status was of low spare capacity. Further, the global financial crisis occurred in 2008. In 2015, the OPEC production quota changed. These findings mean that geopolitical and economic risks easily affect the continuous causal effects of crude oil price changes on Japanese natural gas price changes. The coefficients $\phi^{*}_{12,k}$ always remain positive over time, which implies that oil price changes can cause gas price changes in the same direction. There is, however, no evidence to support causality running from gas price changes to oil price changes. As Zhang and Ji (2018) noted, the natural gas price still uses oil indexation, which only captures the demand and supply conditions of crude oil. Based on the empirical results, we believe that a coupling relationship existed before 2013 and a mixed relationship after that.

[3] The robustness check provides the empirical results with a larger window size.

Figure 3: Rolling-Window Granger Test (Sub-sample): Japan

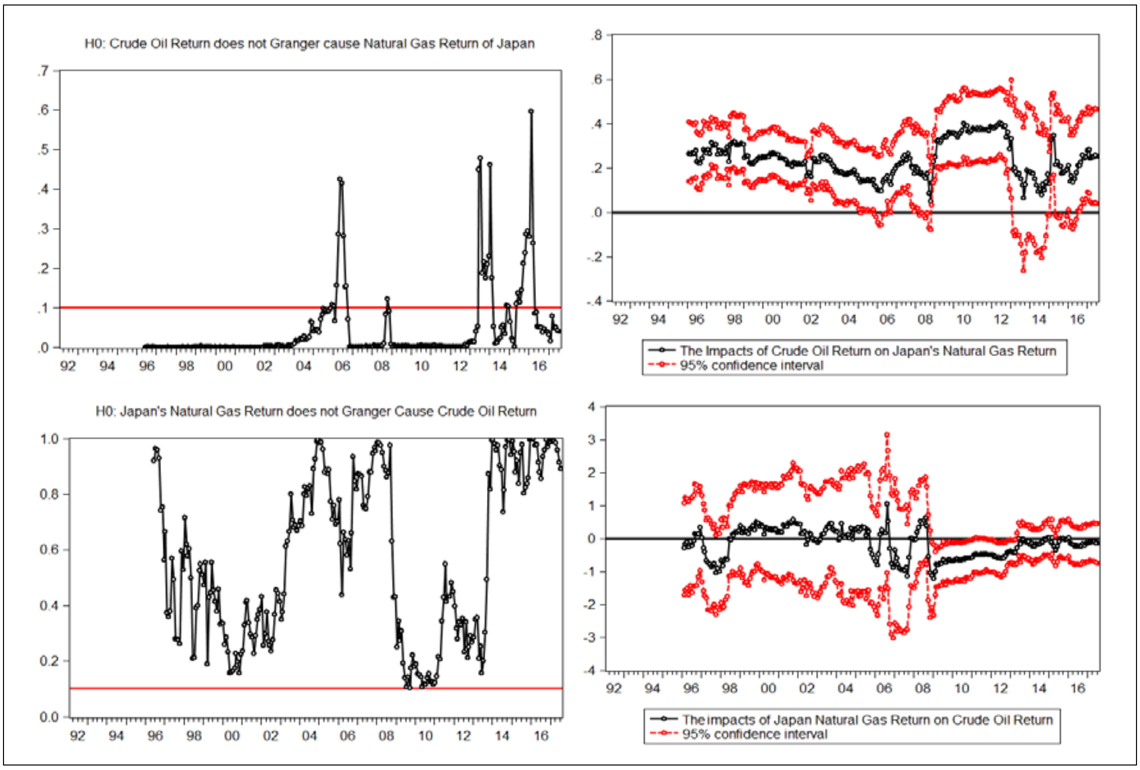


Figure 4 presents the findings about the crude oil and gas price nexus in the European market. Unlike the Japanese market, it is more likely that the null hypothesis of crude oil price changes not Granger causing natural gas price changes will be intermittently rejected. This implies that the European natural gas market is less oil driven. Specifically, the periods without rejection are in a few months of 1995, 1999, 2001, 2008, 2013, 2014, and 2015. In 1999, OPEC cut the production targets to 1.7 mmbpd. The notorious 9/11 terrorist attack occurred in 2001. Besides, the swing decision of OPEC on oil production brought more uncertainties to the crude oil market. The unpredictable future that economic and geopolitical events caused affected the relationship between oil and European natural gas price changes. In terms of the null hypothesis that natural gas price changes do not cause crude oil price changes, the test rejects it over a few months from 2000 to 2001 and from 2015 to 2016. Thus, unlike Japan, we find a mixed relationship over the whole sample period in Europe.

Figure 5 reports the results of examining the crude oil market and US natural gas prices. It shows that crude oil price changes cannot cause US gas price fluctuations in most periods. This is different from the observations in the Japanese and European natural gas markets. Especially before 2010, the rejection only occurs in a few periods during the 9/11 attack and the low spare capacity in 2001. Interestingly, after 2010, it is more likely that the US natural gas price changes are a result of the US crude oil price changes. In fact, the shale gas surge since 2009 considerably affected the energy structure in the US. The coefficients of $\phi^{*}_{12,k}$ remain positive in most periods. The test rejects the null hypothesis that natural gas price changes in the US do not cause crude oil price changes in a few months of 2006 and 2014. In 2005, Hurricane Katrina hit the US and brought about a substantial drop in gas production. In contrast to Japan and Europe, a decoupling relationship is apparent in the US before 2010. Since the shale gas expansion, the relationship between crude oil and gas prices in the US market has been mixed.

Figure 4: Rolling-Window Granger Test (Sub-sample): Europe

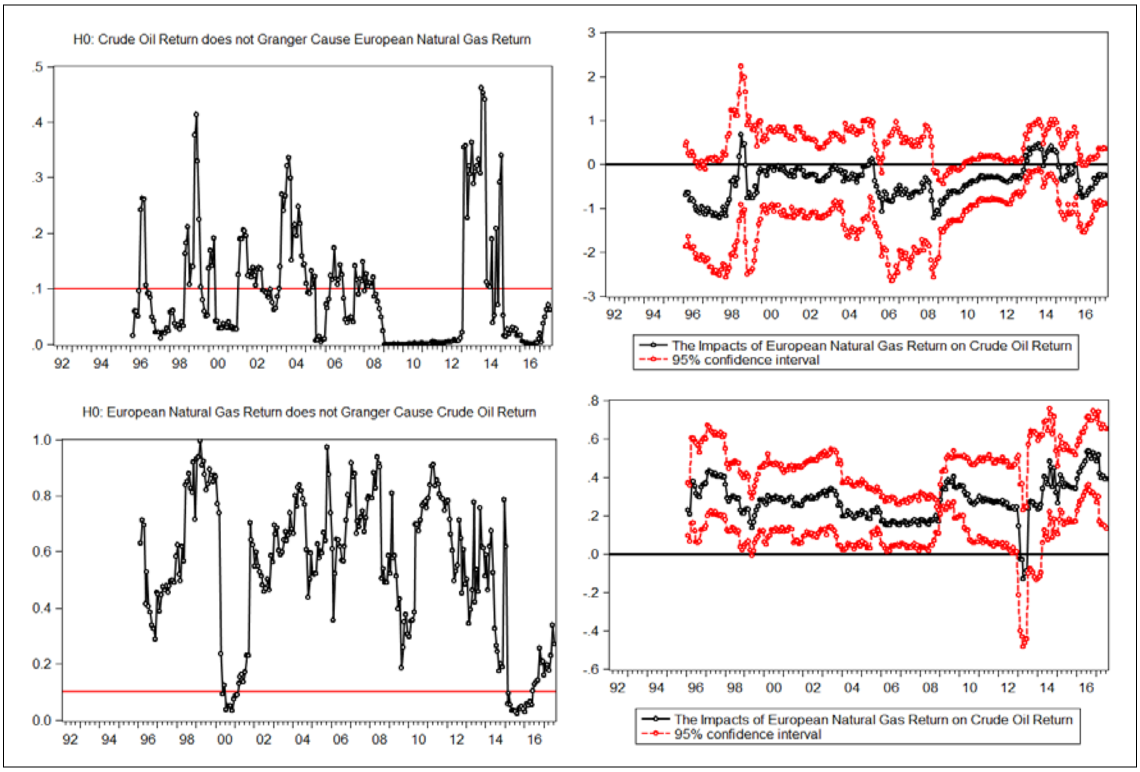


Figure 5: Rolling-Window Granger Test (Sub-sample): US

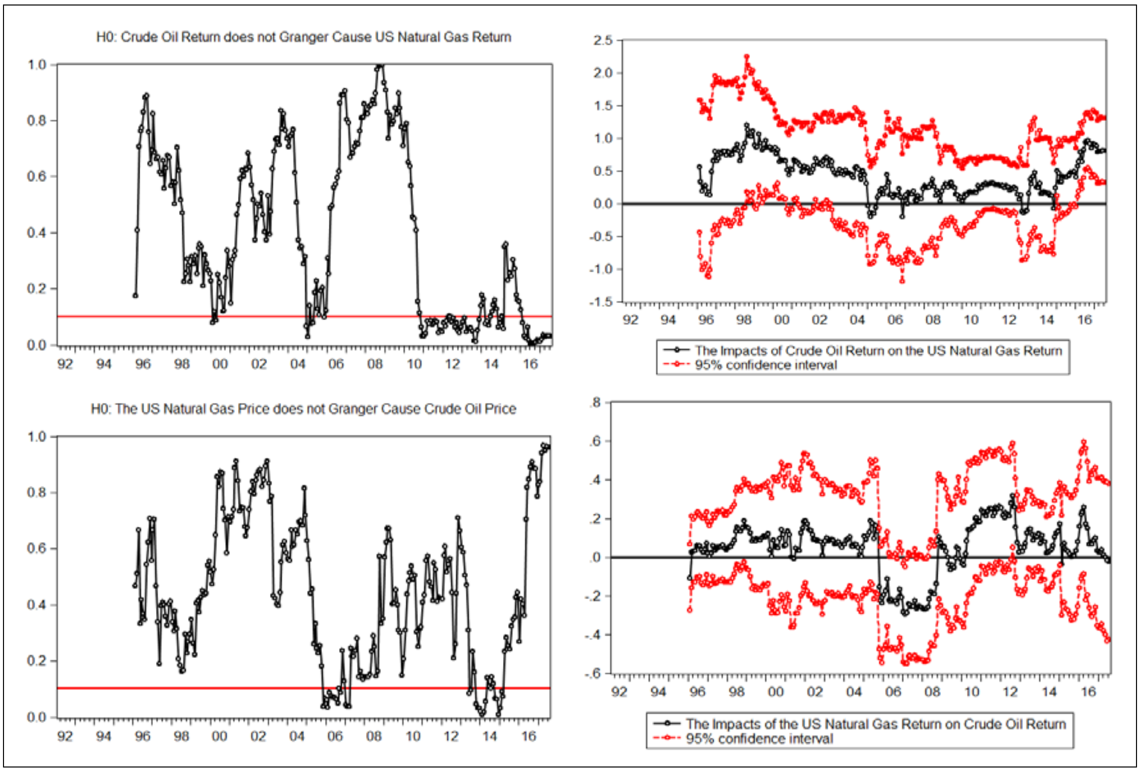
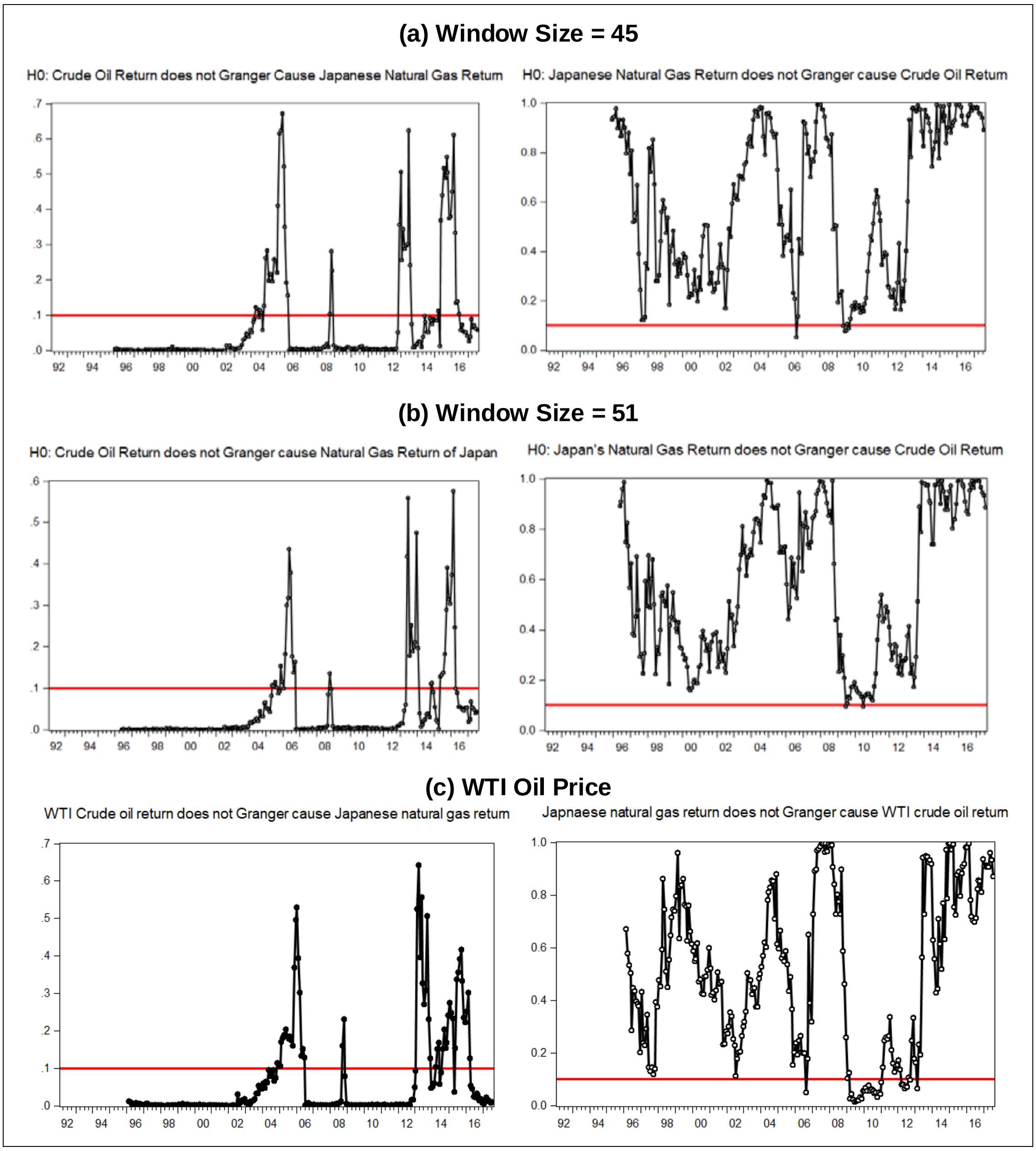


Figure 6: Robustness Checks (Japanese Market)



5.3 Robustness Checks

As robustness checks, we consider several options. Our first option is to use a smaller window, *l* = 45. The other parameters remain the same. Panel (a) of Figure 6 presents the estimation results (for the Japanese case only for the sake of saving space).[4] The results of the time-varying causal nexus analysis with a smaller window are consistent with those using the window size of 48. Our second option is to consider a larger window, *l* = 51, in panel (b) of Figure 6. Once again, the estimation results are almost the same as those from the models using a smaller window (45 and 48). Finally, we replace the Brent oil prices with WTI prices and repeat the exercises. Panel (c) of Figure 6 reports

[4] The results for the European and US cases are available on request from the authors.

one set of results using the window size of 48. There are minor changes, which, however, do not alter our conclusion from the other models. Our analytical results are in general robust in terms of the window size and the selection of oil price indices.

6. POLICY IMPLICATIONS AND CONCLUDING REMARKS

The natural gas pricing mechanisms vary across Europe, Japan, and the US with market-specific features. Traditionally, the US gas market relies on competitive pricing through the Henry Hub. It is possible to view the gas price in Europe as a combination of the national balancing point of the UK and oil price indexation. In contrast, the Japanese market indexes the gas price to the crude oil price (Zhang, Shi, and Shi 2018). In fact, the main gas consumer is East Asia. Since the Fukushima nuclear accident in 2011, the natural gas consumption in Japan has risen. In the People's Republic of China, the rising consumption of natural gas is attributable to strong economic growth and restrictions on the use of dirty fuels. Moreover, the shale gas revolution triggered a structural break in the US energy market.

This paper utilizes the bootstrap sub-sample rolling-window Granger test to explore the crude oil and gas price nexus. Unlike full-sample estimations, the rolling-window technique that the paper adopts can investigate time-varying causal dynamics and avoid constant parameter assumption in the VAR system. As the empirical results show, a change in the crude oil price cannot have caused price changes in the Japanese natural gas market over a few months in 2005, 2008, 2013, and 2015. They show that, in most sample periods, a change in the crude oil price causes a price change in natural gas in Japan. This is consistent with the fact that Japan essentially indexes the gas price to the oil price. In Europe, the periods without rejection include the years of 1995, 1999, 2001, 2008, 2013, 2014, and 2015. The results imply a mixed relationship between crude oil and gas prices in Europe. In Japan and Europe, OPEC decisions, the financial crisis, and the terrorist attack interrupted the role of crude oil in gas pricing. In the US market, the study does not reject the causality running from crude oil price changes to gas price changes only in a few months of 2000 and 2005. However, it rejects the non-Granger causality hypothesis in more periods after 2010. This reflects the shale gas boom significantly affecting the decisive role of crude oil prices in natural gas pricing in the US.

According to the empirical results, the dynamic causal nexus between crude oil and gas prices is likely to vary over time. Important oil price changes in the world are likely to affect the natural gas price changes in Japan and Europe. Specifically, the status of low spare capacity in 2005, the financial crisis in 2008, and the OPEC production quota change in 2015 are key factors affecting the oil indexation in Japan. Similarly, the decisions of OPEC and the terrorist attack affected the relationship between crude oil and gas markets. In Japan and Europe, the rejection of non-causality is apparent in most periods. Thus, the natural gas price is still linked with the crude oil price. In contrast, changes in the crude oil price cause natural gas price changes only in some periods in the US. The natural gas performance in the US has changed due to the expansion of shale gas production.

We can draw important policy implications from the results in this study. First, the relationship between crude oil and gas price changes is time varying. Governments in Asia and Europe should care about the impacts of fluctuations in the crude oil price on the domestic natural gas price because the pricing mechanism of gas still uses oil indexation. In the US, the Fed should monitor the impacts of oil prices on the Henry Hub gas price because causal evidence exists after the shale gas disruption in 2010. Second, geopolitics and economic events influence the time-varying causal nexus, especially in Asia and Europe. In addition, the crude oil market price changes when OPEC changes its supply target affect the natural gas price movement. To avoid the spillover risks from the crude oil market, Asia and Europe should establish an independent pricing mechanism. For the US, though the shale gas production growth reduces the role of natural gas in the domestic energy consumption structure, the crude oil price changes, in contrast, cause Henry Hub price changes, which are present first. Third, we propose to build a uniform natural gas trading system worldwide and develop a common price index to reflect the actual demand and supply of natural gas. When extreme natural disasters occur, the natural gas price will be more elastic to reflect the supply and demand to prevent the spillover risks from the crude oil market.

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