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Towards an Integrated Spot LNG Market: An Interim Assessment

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Abstract

This paper examines whether, and to what extent, the spot LNG markets in different regions (East Asia, Iberia, Northwest Europe, and South America) are integrated and how market integration evolves over time. We first lay out a framework of market integration in the context of global LNG market where the main supplier (e.g. Qatar) may have market power. Estimating a time-varying coefficients model, we find that a varying degree of market integration exists between all four LNG indices particularly after the Fukushima incident in 2011. We complement the time-varying coefficient analysis with a test of price convergence among the LNG indices using the Phillips-Sul (2007) methodology. The results reveal that, there is strong evidence that the spot LNG prices are converging after the Fukushima accident and they are also converging with the price of NBP in the UK. The empirical result is consistent with the change of market power of the main supplier.

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1. Introduction

Traditionally, international trade of liquefied natural gas (LNG) has been characterized by long-term contracts that last for 20-25 years, under which a limited number of sellers supply certain regional or country markets with minimum "take-or-pay" requirements.[1] These long-term contracts leave little flexibility for market arbitrage. As the industry expands, market players have sought more flexibility, in terms of both price and quantity, in order to arbitrage across different LNG markets. Consequently, the spot and short-term LNG trade has grown. As shown in Figure 1, the volume of LNG traded on the spot and short-term markets has grown steadily in recent years and reached 69 million tons per year in 2014, accounting for 29 percent of the total LNG trade worldwide.

In this paper, we take a first look at the emerging spot and short-term LNG markets.[2] We are particularly interested in investigating whether, and to what extent, spot LNG markets in different regions are integrated, how market integration evolves over time, and how the spot LNG markets interact with the more mature natural gas market in the United Kingdom (UK).[3] If the spot markets are integrated, the law of one price (LOOP) will hold in that prices in different regions will differ only by transportation costs. We primarily examine the degree of market integration by comparing four regional spot LNG price indices, namely, the East Asia Index, the Iberian Index (Spain and Portugal), the Northwest Europe Index, and the South America index. We estimate a time-varying coefficient model to test the LOOP among the four regional indices, which is then complemented by a test of convergence over time employing the convergence test developed by Philips and Sul

[1] See Griffin (2006, Chapter 1) for a complete discussion of the LNG business model. With a take-or-pay contract, the buyer either takes the product from the supplier or pays the supplier a penalty if he/she does not take the product.
[2] Short-term contracts are those with a duration of less than four years, also see Hartley (2015). Hereinafter, we refer to both spot and short-term trade as "spot market".
[3] We omit the US market from the empirical analysis as the shale gas revolution effectively made the US disconnected from the rest of the world over the sample period.

(2007). We also test for integration between the regional LNG markets and the National Balancing Point (NBP) price in the UK.

Using weekly data for the period of 02 August 2010 to 27 February 2015, we find varying degrees of integration not only among the four regional LNG spot markets, but also between the regional spot LNG markets and the UK natural gas market. Moreover, our results from the Phillips Sul (2007) convergence test further reveal that, the spot LNG prices are converging towards the end of the sample period and they are also converging with NBP price in the UK. The convergence test results are consistent with predictions from a model where the major producer (e.g. Qatar) has market power and the market power changes following an extremely large demand shock such as the Fukushima accident.

Our study is related to the growing literature on the integration of natural gas markets. The existing work on the *regional* integration of natural gas markets (e.g. De Vany and Walls, 1993; King and Cuc, 1996; Cuddington and Wang, 2006; Neumann *et al.*, 2006) generally finds that, in North America, the gas market liberalization in the 1980s stimulated its market integration but a fully integrated gas market between the east and west regions is yet to come. In Europe, the opening of the interconnector between Belgium and UK facilitated price convergence between the UK market and the largest continental European market (the Zeebrugge), but the continental European market is still loosely integrated at best. As for the *global* integration of natural gas markets, studies have variously found no integration or rising integration across regions, depending on geographic area and sample periods used. Siliverstoves *et al.* (2005) perform cointegration analysis on the prices of imported gas in Europe, North America and Japan from early 1990s to 2004 and show that the European and Japanese gas markets are integrated but not with the North American market. Brown and Yucel's (2009) examination of weekly natural gas prices across the Atlantic from 1997 to 2008 indicates a long-run cointegrating relationship between the Henry Hub and the NBP prices. However, they argue that the cointegrating relationship is driven primarily by the comovements with crude oil prices rather than gas-on-gas competition.

The papers closest to ours are Neumann (2009) and Li *et al.* (2014). Applying the Kalman filter to three natural gas spot prices in the US (the Henry Hub), the UK (the NBP) and the continental Europe (the Zeebrugge) markets, Neumann (2009) provides evidence for a movement towards market integration between 1999 and 2008. She also confirms that, while LNG may have reinforced the linkage between markets, the observed price comovement is again largely driven by their correlations with crude oil prices. Recently, Li *et al.* (2014) apply the convergence test developed by Philips and Sul (2007) along with the Kalman filter to monthly natural gas prices in the US, UK and three East Asian markets (Japan, Korea and Taiwan) for the period of January 1997 to May 2011. They find a clear divide between the North American market and the rest of the world. Specific to the LNG market, Ritz (2014) develops a model and argues that if a producer has market power in two regional markets, prices could differ by more than the transportation cost. The model helps explain the observed price gap between Asia and Europe from 2011 to 2013.

Our work departs from existing studies by focusing on the integration of spot and short-term LNG markets. While previous studies have postulated a role for LNG in strengthening the linkage among different regional natural gas markets, the extent to which spot LNG markets across regions integrate remains unexplored.[4] In this paper we provide the first empirical assessment of integration among different spot LNG markets. There has been considerable debate, especially in

[4] In Li *et al*. (2014), an average of spot and long-term contract prices is used for Japan and only the Asia markets (Japan, Korea and Taiwan) were included. Here in this study we focus on the spot LNG markets across both the Pacific and Atlantic markets.

anticipation of LNG exports from the US, about whether internationally traded natural gas pricing will remain regional or become global as is the case with crude oil. A related question is whether the latter will lead to the decoupling of gas pricing from oil-indexation and eventually a shift to gas on gas competition (see, for example, Rogers (2012), Stern (2012) and Rogers and Stern (2014)). However, a "global" gas market will not occur if the market for LNG, which is still the only feasible means of transporting gas in large volume across oceans, remains regional. In a recent study, Hartley (2015) argues that increased liquidity in the spot and short-term markets will reduce short-term fluctuations in spot prices while an increase in the numbers of buyers and sellers of spot LNG cargoes could both increase spot market liquidity and reduce geographic price differentials. Thus, to better understand the future trajectory of the market integration for internationally traded gas, it is especially relevant and important to assess the evolution of integration among spot and short-term LNG markets as well as their interactions with the more mature natural gas markets.

The rest of the paper proceeds as follows. The next section provides a brief overview of the LNG market. Section 3 lays out a conceptual framework of market integration in the context of spot LNG market where the producer's market power is considered based on the Ritz (2014) model. The data and empirical methodology are described in Sections 4. Section 5 presents the estimation results, and concluding remarks are offered in Section 6.

2. Overview of the LNG market

The LNG market was traditionally divided into the Pacific Basin and Atlantic Basin, with minimal trade between the two. In the Pacific Basin, Japan, Korea and Taiwan are historically the main LNG importers due to their lack of indigenous supply and disconnection from gas-producing continents, although China and India have been rapidly catching up in recent years. Japan is by far still the largest importer of LNG in the world. In 2015, Japan imported 118 billion cubic meters

(BCM) of LNG, accounting for 35 percent of the total world trade volume.[5] Indonesia and Malaysia used to be the major exporters in the Pacific Basin market but have been surpassed, in terms of export volume, by Qatar and, to a lesser extent, Australia. The pricing of long-term LNG contracts in Asia has historically been tied to the price of crude oil (Li *et al*., 2014) with certain formulas. For example, the price of Japanese imported LNG is indexed with an S-curve to the price of the so-called Japanese Crude Cocktail (JCC), which is an average price of a basket of crude oils imported to Japan.[6]

Historically, the main importers in the Atlantic Basin were the US, Spain, Italy, and France, with Algeria and Libya being the principal suppliers. Since the late 1990s, the Atlantic LNG market has expanded dramatically. New liquefaction facilities have been built or added in Egypt, Nigeria, Equatorial Guinea, Angola, Norway, and Trinidad and Tobago, while new regasification capacity has been added in the UK, the Netherlands, Belgium and elsewhere in Europe, and Argentina, Brazil, and Chile in South America. In terms of pricing, due to the liquid natural gas markets in the UK and US, LNG imported to UK and the US Gulf coast (prior to early 2010) has to compete with supplies from local markets, which has led to a true gas-on-gas competition in these markets.[7] As a matter of fact, the pricing of imported LNG in the UK, even under long-term contracts, is often linked to the prices of NBP. In contrast, the pricing of gas imported to continental Europe, both through pipelines and via LNG, has been traditionally linked to oil-based products,

[5] Unless otherwise noted, the data in this section are all sourced from BP Statistical Review of World Energy, various years.

[6] JCC more correctly stands for the Japanese Customs-cleared Crude. The purpose of the *S*-curve is to mitigate the price risk so that when the price of crude oil is high the formula would adjust to the benefit of the buyer and when the price is low it would adjust to the benefit of the seller.

[7] This was true when substantial LNG was imported to US Gulf Coast prior to early 2010. However, once the “shale gas revolution” made such imports rarely profitable, US LNG imports have largely been restricted to end of pipe markets where local prices can become disconnected from the Henry Hub price.

such as diesel oil or residual fuel oil, with an adjustment of the natural gas price to reflect changing market conditions for these oil-based products.

In the past decade or so, the LNG business has undergone some profound changes in both the scope of markets and the mode of transactions. First, as more countries enter the market as either an importer or an exporter, the once-segmented markets start to connect. For example, in 2008, there were few LNG flows between the Pacific Basin and Atlantic Basin. In 2015, Nigeria alone sent 12.3 BCM of LNG to the Asia Pacific, representing 45 percent of its total LNG export. Of particular importance is the surge of Qatar as the largest LNG exporter. Qatar has drastically boosted its production capacity. Between 2007 and 2011, Qatar increased its LNG export capacity by nearly three times, making it the highest in the world at 77 million tons per year. It has become the largest LNG exporter since 2007 and has been exporting to both Asia Pacific and the Atlantic. Thanks to the location, Qatar and other LNG exporters in the Middle East play an important role in connecting the two regional markets.

Second, the US "shale gas revolution" has significantly reduced the quantity demanded from the Atlantic basin. As noted by Li *et al.* (2014), as recently as in 2008 the US was widely deemed as one of the major LNG markets and much of the global investment in new LNG liquefaction plants and shipment was targeted to the US market. However, thanks to the "shale gas revolution", US domestic production has boomed and consequently the demand for LNG import has dramatically reduced. In 2015, the US imported only 2.6 BCM of LNG, 12 percent of its level in 2007. Instead of becoming a major importer, the US is now on its way to becoming an exporter.

Third and most importantly, an increasing share of LNG is now traded in spot markets or via short-term (less than 4 years) contracts rather than fixed long-term contracts. Because of market fragmentation, high capital intensity and asset specificity, traditionally the majority of LNG projects were committed to a specific market under long-term contracts.[8] While the long-term contracts can help sellers mitigate the risk of being displaced when cheaper or closer gas sources become available and buyers from being forced to pay a high price when markets tighten, they are fairly inflexible, especially in the face of demand uncertainty. Originally, the spot and short-term trade were typically limited to either cargo diversion, which is often due to unforeseen changes in demand, or volumes in excess of long-term contractual commitment due to debottlenecking of production capacities (see Griffin, 2012, pp. 53-56). However, as the market expanded, both buyers and sellers have started to seek contractual flexibility in order to explore arbitrage opportunities in the natural gas markets, which gives rise to increasing trade in spot and short-term LNG markets. As shown in Figure 1, the share of spot and short-term trade in total LNG trade has grown from a little over 10 percent in 2000 to nearly 30 percent in 2014.

3. Market Integration in LNG Markets

3.1 The Concept of Market Integration

The idea of market integration and the law of one price (LOOP) centres on the concept of an economic market. The classic definition of market due to Cournot is "A market for a good is the area within which the price of a good tends to uniformity, allowance being made for transportation costs."[9] This definition of an economic market has been used to motivate a voluminous literature on testing variations of the LOOP such as market integration and purchasing power parity in international finance. For example, Stigler and Sherwin (1985) employ "the similarity of price

[8] An LNG project includes the development of often multiple gas fields which are in many cases located in isolated places, a liquefaction plant and a fleet of specially manufactured LNG tankers.
[9] This definition was expounded by Marshall "The more nearly perfect a market is, the stronger is the tendency for the same price to be paid for the same thing at the same time in all parts of the market; but of course if the market is large, allowance must be made for the expense of delivering the goods to different purchasers; each of whom must be supposed to pay in addition to the market price a special charge on account of delivery" (Marshall, 1920, p. 270).

movements within the market" as the criterion of testing a market. Spiller and Huang (1986) emphasize the role of arbitrage in linking two markets and relate to the concept of antitrust market. Cuddington and Wang (2006) further defines market integration as "Assuming transactions (including transport costs) are stationary for the time period under consideration, *k* locations are said to lie within a single (unified or integrated) market, if (small) shocks to supply or demand from any location in the market cause equal price changes at all *k* locations." In this paper, we follow this more or less standard definition of market integration.

Let P_{it} and P_{jt} be the LNG prices at market *i* and *j* respectively, and T_{ji} the transportation cost (arbitrage cost) from *j* to *i*.[10] For convenience, let's assume $P_i > P_j$. When $P_i - P_j < T_{ji}$, then no arbitrage opportunity arises between market *i* and *j*. The prices are independent in that a *small* shock in *i* would have no impact on P_j.[11]. The markets are segmented due to high transportation cost. If $P_i - P_j > T_{ji}$,, in the absence of trade frictions, arbitrage would push down P_i and push up P_j. In equilibrium, the LOOP holds in that prices between the two markets differ by only transportation cost $P_i - P_j = T_{ji}$ and the two markets are said to be fully integrated.

3.2 An LNG Market Model[12]

Specific to the LNG market, Ritz (2014) develops a static model and shows that the regional price differential can be different from transportation cost if the main supplier, such as Qatar, has market power in the two markets. Let P_i and P_j denote the spot prices of LNG in market *i* and *j* respectively, and T_i, T_j the unit transportation cost for the supplier to ship LNG to the markets. Ritz (2014) shows that

[10] T_{ji} could include other transaction costs. In what follows, we will also refer to T_{ji} as arbitrage costs to distinguish the transport cost from producing country to markets.
[11] That is the autarky price in Spiller and Huang (1986) and Kleit (1998).
[12] The model is directly from Ritz (2014). We recap the model predictions here. The setup and derivation of the model is presented in the appendix.

$$\frac{P_i - P_j}{P_i} = \frac{\eta_i}{\eta_i - 1}\left[\left(\frac{1}{\eta_i} - \frac{1}{\eta_j}\right) + \left(\frac{T_i - T_j}{P_i}\right)\right], \tag{1}$$

where η_i denote the price elasticity of demand faced by the supplier in market i.[13] The price gap between the two markets is determined by not only the transportation cost but also the supplier's market power. The result follows from the first order-condition of the main supplier's profit maximization problem where the supplier equalizes the marginal revenue from additional spot trades, not necessarily the prices, across the two markets.

Two important implications follows from Equation (1). First, if the supplier has no market power in both *i* and *j*, $\eta_i \to \infty$, then $P_i - P_j = T_i - T_j$. Thus, in equilibrium, the price gap between the markets *i* and *j* is equal to the transport cost differential. Note, in this case there is no arbitrage opportunity between the two markets as $T_i - T_j \leq T_{ji}$[14]. However, the two markets should still be regarded integrated as the supplier is able to arbitrage between the two markets such that a shock in one market would have an impact on the price of the other.

Second, if the supplier has market power in the two markets, then the prices could differ by more than the transportation cost. For example, if the producer has equal market power in the two markets such that $\eta_i = \eta_j = \eta < \infty$, then the price gap becomes $P_i - P_j = \frac{(T_i - T_j)\eta}{(\eta - 1)}$. The supplier's market power in the two markets amplifies the price gap that is caused by transportation costs. On the other hand, if the transportation costs from the supplier to the two markets are identical, then the result reduces to $\frac{P_i - P_j}{P_i} = \frac{\eta_i - \eta_j}{(\eta_i - 1)\eta_j}$. In this case, $P_i > P_j$ if and only if $\eta_i < \eta_j$. That is, the supplier could charge a higher price in a market where the demand is less elastic. Note, in both

[13] This is the elasticity of demand faced by the supplier (i.e. the residual demand) and should be higher than 1. The market level demand elasticity could be significantly lower.
[14] If $T_i - T_j > T_{ji}$,then the supplier is better off to ship via market *j* to *i*.

cases the no arbitrage condition implies that $P_i - P_j \leq T_{ji}$ must hold in equilibrium and the preceding discussion on market integration still applies.[15]

Although the main purpose of this paper is not to test the Ritz (2014) model, the above discussion provides some useful insights for our empirical analysis. First, if the market is perfectly competitive, we expect the prices of LNG across spot markets to differ by the costs of shipping LNG from producing countries to the relevant markets and the markets are fully integrated. Second, when the market is less competitive, as likely the case during the period immediately following the Fukushima accident in 2011, the prices across markets could differ by more than the transport costs, but should be bound by the no arbitrage condition. In next section, we will first test whether, and to what extent, the spot LNG markets are spatially integrated as implied by perfect competition. This is followed by a test of whether the markets converge to a competitive equilibrium after the Fukushima accident.

4. Data and Empirical Methodology

4.1 Data Description

The data used in this study was generously provided to us by ICIS. ICIS publishes daily market prices in over two dozen locations based on information collected by their reporters and analysts from market participants about spot transactions and spot bid and ask levels in the absence of actual transactions. According to ICIS (2014), their price assessment methodology "*is designed to discover the tradable value of a commodity at a particular point in time. The single value represents the price at which the commodity is most likely to transact. As transactions are not*

[15] When $P_i - P_j < T_{ji}$, even if the two markets are served by the same supplier, a small shock in one market would have no impact on the other unless the residual demand elasticity is so low that a small shock would cause the $P_j > P_i$. The markets are integrated when $P_i - P_j = T_{ji}$. This is possible when the arbitrage cost is relatively low so that a shock in one market can affect the price on the other.

regular for many LNG destinations, the value frequently represents a point in between the highest firm bid and the lowest firm offer. The published price does not always represent the midpoint of this bid/offer spread and ICIS uses its knowledge of market direction and market length/tightness to determine value in all instances where the firm bid/offer spread is more than 10 US cents wide and there is no confirmed transaction." [16] The prices from ICIS are quoted as either DES (Delivered ex-ship, meaning the seller or supplier arranges shipping), or FOB (Free on board, meaning the buyer pays the costs of transportation and arranges shipping). The former represents the price most likely to transact at a specific delivery point, which is typically the most active spot cargo receiving terminal, within the named region. Given the fact that spot LNG markets are still relatively thin compared to the spot natural gas markets in the US or UK,[17] in this analysis we use the weekly averages of the following four regional spot LNG indices.[18]

- The East Asia Index (EAX) is the arithmetic average of the day's DES front month and second month ahead assessed prices for Japan, South Korea, Taiwan and China;
- The South America Index (SAX) is the arithmetic average of the day's DES front-month and second month ahead assessed prices for Argentina, Brazil and Chile;

[16] One concern with these price assessments is their reliability, i.e. whether they truly reflect the value of spot market trades. In relation to oil market, the International Organisation of Securities Commissions (IOSCO) in collaboration with the International Energy Agency (IEA), International Energy Forum (IEF), and the Organisation of the Petroleum Exporting Countries (OPEC), published a report in October 2012 which set out principles "intended to enhance the reliability of oil price assessments." These principles were "developed with due regard for the specific nature and dynamics of price assessments in the physical oil market." Subsequently, in 2014 and 2015, IOSCO published reports on the *Implementation of the Principles for Oil Price Reporting Agencies (PRAs).* The reviews focused on the four main PRAs which includes ICIS and concluded that the "PRAs have instituted processes and procedures to implement the principles and good progress has been made. The external assurance reviews that were conducted corroborated IOSCO's view at the time that PRAs had policies and procedures in place that are consistent with the PRA Principles." (IOSCO, 2015).
[17] For example, it is estimated that approximately 1000 cargos were traded on spot market in 2011. That is, on average, less than 3 cargos per day were traded.
[18] The indices are defined by ICIS and quoted by industry publications.

- The Iberian Index (IBX) is the arithmetic average of the day's DES front-month and second month ahead assessed prices for Spain and Portugal; and
- The Northwest Europe Index (NWE) is the arithmetic average of the day's DES front-month and second month assessed prices for Britain, Netherlands, Belgium and France.

Our sample starts from August 2, 2010, the earliest date that we can obtain a continuous time series, and ends at the week of February 23, 2015, with a total of 239 weekly observations. To get a sense of the structure of spot LNG markets worldwide, we calculate the market share of each regional spot index as the average share of import volume by the relevant region in total spot LNG trade over the period of 2011-2014. As shown in Figure 2, East Asia dominated the world market with a share of nearly 60 percent followed by South America with a share of 11 percent. The two European markets collectively account for 13 percent of the world spot LNG market.

4.2 Preliminary Analysis

Figure 3 plots the time paths of the four regional spot LNG indices along with the NBP and Henry Hub (HH) prices, all of which are expressed in \$/MMBtu terms.[19] The regional spot LNG indices appeared to move closely with each other and also with the NBP before March 2011, after which the EAX jumped to a higher level, and the SAX followed suit with a lag of about three months. The jump of the EAX was obviously triggered by the loss of nuclear power in Japan following the March 11, 2011 earthquake and the Fukushima accident, which was replaced largely by natural gas along with coal and oil-fired capacity.[20] The increase of the SAX in June 2011 also

[19] Nominal prices are used in this study. We also tried using real prices where we deflate the nominal prices with US CPI. The results are not materially different. Because the highest frequency for CPI (or other deflators) is monthly, we linearly interpolated the CPI data to weekly. The results are available from the authors upon request.

[20] In the immediate aftermath of the earthquake and tsunami, Japan lost 12 gigawatts of nuclear power. By the end of 2011, Japan was left with only 7.98 GW, or 16.3% of the pre-crisis nuclear capacity of 48.96 GW at 54 reactors and that capacity was shut down too by May 2012 (Platts, 2012). According to EIA data, Japanese electricity generation from nuclear power reduced from 280 GWh in 2010 to 156 GWh in 2011, and a mere of 17 GWh and 14

coincides with the subsequent shut-down of other nuclear power plants in Japan since June 2011. The IBX and NWE also increased in the second half of 2011, but the increase was not as pronounced as the EAX and SAX. Although the price gap between the EAX and the European indices can be as large as $10/MMBtu, the Asian and European spot LNG markets still show clear signs of comovements with each other. Despite large price differentials between mid-2011 and late 2014, the four regional spot LNG indices appear to be converging again towards the end of our sample period. Note that the NWE index closely mirrors the NBP price, which probably reflects the fact that much of the long-term LNG import is indexed to the price of NBP in this area and the spot LNG price simply adjusts to changing conditions in natural gas markets. It is also worth noting that the Henry Hub price seems to evolve on its own, fluctuating independently of other indices around a much lower price level. During the study period, there were no operational LNG exporting facilities in the lower 48 states of the US or Canada.[21] The significant increase in natural gas production thanks to the "shale gas revolution" has displaced imports and depressed the price of natural gas in North America, and consequently, the Henry Hub market is essentially disconnected from the rest of the world. In what follows, we will omit the Henry Hub price from the analysis to save space. However, the result is available from the authors upon request.

In Panel A of Table 1 we apply three unit root tests to the logarithm of the four LNG indices as well as the NBP index. Hereafter we designate the logarithms of the price indices by labels that begin with the letter "L" (e.g. LEAX for the logarithm of EAX). The unit root rests we use include the augmented Dickey-Fuller (ADF) test, the Philips Perron (PP) test, and the Kwiatkowski-

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GWh in 2012 and 2013 respectively. Further, according to BP Statistical Review, natural gas consumption in Japan jumped 12% from 2010 to 2011 and another 7% from 2011 to 2012.

[21] During the study period, the only LNG exporting facility in North America is the Kenai LNG plant in Alaska which is disconnected from the mainland US or Canada. In any case, it was mothballed from mid-2011 to the end of the study period. See http://alaska.conocophillips.com/newsroom/news-releases/Pages/kenai-lng-plant.aspx and http://www.platts.com/latest-news/shipping/anchorage/conocophillips-to-resume-lng-exports-from-kenai-21478299.

Phillips-Schmidt-Shin (KPSS) tests.[22] While the ADF test and the PP test cannot reject the null hypothesis that LEAX, LIBX and LSAX are nonstationary at levels, the KPSS test rejects that they are stationary at least at the 10 percent level. We interpret that LEAX, LIBX and LSAX are nonstationary. Both the ADF and PP tests reject the null of unit root at the 10 percent level for LNBP and the KPSS test fails to reject the null of stationarity, suggesting LNBP is stationary. For LNWE, the results are more indecisive, but there is some evidence to suggest that it is stationary. Although the PP test cannot reject the null of nonstationarity even at the 10 percent significance level, the ADF test is able to reject at the 5 percent level. The KPSS test rejects the null of stationarity at the 10, although not the 5 percent level.

Following previous studies, we also test for cointegrating relationships for each pair of the four logged LNG indices. As shown in Panel B of Table 1, there is some evidence of cointegration between the pairs of LIBX-LSAX and LSAX-LNWE, but not for others. However, given the somewhat conflicting result in the unit root test for LNWE and the relatively short time spans of our data, the cointegrating relation found in LSAX-LNWE should be read with caution as they may not necessarily reflect the true long-run equilibrium relations. Nonetheless, the lack of cointegration between LEAX and the other three indices suggest the spot LNG market is not well-integrated during the sample period. In what follows, we re-examine the relationships using an empirical methodology that does not require the data to be cointegrated.

4.3 Empirical Methodology

To evaluate the degree of market integration among regional spot LNG markets, we take a two-step approach to examine the relations among different regional spot LNG price indices. We

[22] Before the unit root analysis, we applied tested Bai and Perron's method (1998, 2003) for testing structural breaks, and found no statistically significant evidence of structural breaks in any of the regional spot LNG indices when heteroscedasticity and autocorrelation consistent standard errors were used.

start with a test for the LOOP, as implied by the arbitrage conditions in Section 3.1, by estimating time-varying regression coefficients for each pair of regional spot LNG indices and also between each spot LNG index and the NBP index. We then proceed to test for price convergence among these indices with a method recently developed by Phillips and Sul (2007).[23] While the time-varying coefficients can shed light on how well the market is integrated at each point of time, the Phillips-Sul convergence test provides insight to whether these regional spot LNG indices are transitioning towards a common long-run equilibrium. An appealing feature of both methods is that neither relies on assumptions about the stationarity of the time series.

4.3.1 Test for the LOOP

While we don't have time series data on transportation cost by routes, it is reasonable to assume the transportation cost differential between markets are proportional to the level of price.[24] The LOOP can be empirically tested with the following specification:

$$p_{i,t} = \alpha_{i,j} + \beta_{i,j} p_{j,t} + \varepsilon_{i,t} \tag{2}$$

where $p_{i,t}$ and $p_{j,t}$ are respectively the price indices (in natural logarithm) in region *i* and j, $\alpha_{i,j}$ captures the price differential between the two regions due to transportation costs, and $\beta_{i,j}$ is the regression coefficient.[25] When $\beta_{i,j}$= 0, the price change in market *j* has no effect on price in market *i* and hence the two regional markets are segmented. When $\beta_{i,j}$=1, there is unit elasticity between the two prices and the two regional markets are said to be fully integrated. The closer $\beta_{i,j}$ is to one,

[23] This convergence test has recently been applied by Li *et al*. (2010, 2014) to examine price convergence in international coal and gas markets.

[24] Tanker charter and fuel costs are the two main components of the transportation cost. Since LNG tankers use LNG and fuel oil as fuel, it is reasonable to assume the fuel costs to be proportional to the price of LNG. As for the tanker charter costs, our monthly data on spot LNG tanker charter rate indicates it also fluctuates with the price of LNG. For example, the correlation coefficient between the logged tanker charter rate and the EAX index is 0.66 over the sample period.

[25] Hereafter we use *P* to denote price levels and *p* to denote the logged prices.

the more integrated are the two regional markets. Note Equation (2) assumes immediate price adjustments and constant relation between two prices. To capture the dynamics in price adjustment process and better understand the evolution paths of price relationships, one can also estimate a time-varying coefficient regression model for two regional prices:[26]

$$p_{i,t} = \alpha_{i,j} + \beta_{i,j,t} p_{j,t} + \varepsilon_{i,t} \tag{2.1}$$

$$\beta_{i,j,t} = \beta_{i,j,t-1} + \nu_{i,j,t} \tag{2.2}$$

where $\varepsilon_{i,t} \sim N(0, \sigma^2_{i,t})$ and $\upsilon_{i,j,t} \sim N(0, \sigma^2_{i,j,\upsilon})$.

In this system, the regression coefficient β is allowed to vary with time. When the variance $\sigma^2_{i,j,\upsilon}$ is zero, however, the $\beta_{i,j}$ coefficient is simply reduced to a constant. This model can be estimated using the Kalman filter. Specifically, the $\alpha_{i,j}$ and $\beta_{i,j}$ coefficients are first estimated using information up to *t-1* and then their estimated values are updated by incorporating prediction errors from the previous step when information at time *t* becomes available. In what follows, we report results based on equation (2.1) and (2.2). The estimation is conducted using the Oxmetrics software. The initial values of parameters are based on OLS regression.

4.3.2 Phillips-Sul Convergence Test

In their seminal work, Phillips and Sul (2007) argue that if a group of time series is converging towards a long-run equilibrium but the speed of convergence is not fast enough to reach the full convergence before the end of the sample period, the cointegration test may not be able to detect the comovement in the data. They designed a framework where each time series within the group is decomposed into a permanent common factor representing the aggregated common trend of the group and a transitory idiosyncratic component capturing individual

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[26] Some authors (e.g. Slade, 1986; Asch *et al*., 2006) also introduced lagged prices to Equation (2) to model the dynamics in price adjustments.

deviations from the common trend. They further developed a regression-based convergence test methodology which allows one to test whether a group of time series converge to a long-run equilibrium path or a common trend while allowing for temporary individual divergences from the long-run equilibrium.[27]

The method can be readily applied to testing whether prices in different regional markets are converging over time. The idea is that if the markets in question are undergoing the process of integration during the study period, it is more likely to be accomplished towards the end of the sample period because in the earlier period, trade volume is low and market barriers such as incomplete information, constraints in transportation and legal barriers may segment the market (Li *et al*, 2014). As the trade volume grows over time and market barriers diminish, no arbitrage opportunities imply that the prices in different regions would converge to the LOOP in equilibrium (Spiller & Huang, 1986; Padilla-Berna *et al*., 2003). Furthermore, in our context the change of the producer's market power should also be considered as two large demand shocks occurred in the early part of the study period. First, as aforementioned the Fukushima accident in 2011 drastically increased the demand for LNG in Japan. Second, there was a negative demand shock in Europe in 2012-2013 both as a result of post global financial crisis recession and the switch to coal for electricity generation as coal prices fell.[28] Together these imply the demand elasticity for the leading supplier, Qatar, is much lower in Japan than in Europe in the period immediately following the Fukushima accident. As the effect of the shocks lessened over time, we conjecture the LNG market converges to perfect competition.

[27] A more detailed description of the procedure can also be found at Li *et al.* (2010, 2014).

[28] We thank an anonymous referee for this point. The LNG import in Europe fell by 25% from 90.7 billion cubic meters (BCM) in 2011 to 69.3 BCM in 2012 and another 25% to 51.5 BCM in 2013. It gradually recovered in 2014 and 2015 (BP, various years; also see Koyama, 2013).

Recall that under perfect competition the price gap between two markets is equal to the difference in transportation costs: $P_i - P_j = T_i - T_j$. If the prices converge over time to a competitive equilibrium, we expect the following to hold

$$\lim_{s\to\infty} \frac{P_{jt+s}}{P_{it+s}} = 1 - \delta_{i,j}, \text{ for all } i \text{ and } j, \quad (3)$$

where $\delta_{i,j} = \frac{Ti - Tj}{P_i}$.[29] Phillips and Sul (2006) shows that the convergence in N series can be tested by constructing a cross-sectional variance ratio, H_1/H_t. Specifically,

$$H_t = \frac{1}{N}\sum_{i=1}^{N}(h_{it} - 1)^2 , \qquad \text{where } h_{it} = \frac{P_{it}}{\frac{1}{N}\sum_{i=1}^{N} P_{it}} . \quad (4)$$

Here h_{it} traces the transition path of price P_{it} in relation to the cross-sectional average at time t and H_t is the cross-sectional variance at t. The convergence among prices implies that H_t should converge to zero and, as a result, the variance ratio, H_1/H_t, would approach infinity.

Therefore, the null hypothesis of convergence can be tested by estimating the following equation:

$$\log(\frac{H_1}{H_t}) - 2\log L(t) = a + b\log t + u_t \quad (5)$$

where $L(t) = \log(t+1)$, $t = [rT], [rT]+1, \ldots, T$, and r is the fraction of data to be excluded from the regression.[30] Under convergence, $\log(H_1/H_t)$ approaches infinity as t goes to infinity. Convergence among the prices series p_{it} can be conveniently tested on the coefficient b with a null hypothesis of $b \geq 0$. The term $2\log L(t)$ in Equation (5) serves as a penalty factor as $\log t$ and $-2\log L(t)$ are negatively correlated. Further, the term $2\log L(t)$ ensures $\log(H_1/H_t)$ diverges to infinity even if

[29] Because Qatar, the largest supplier, which provided one third of the LNG volume in the spot market over the sample period, is located in essentially equal distance to East Asia, Europe and South America, the cost differential due to transportation from Qatar to the three markets is negligible.

[30] According to Phillips and Sul (2007), the reason for excluding a fraction of data from the convergence test regression is to better focus on what might happen as the sample size gets larger. Based on simulation experiments, Phillips and Sul (2007) suggest setting $r = 0.3$.

$b = 0$. Phillips and Sul (2007) suggest using a left-tailed *t*-statistic with a Heteroscedasticity and Autocorrelation-Consistent (HAC) standard error for the estimated coefficient *b*.

In case the null of convergence for the full group is rejected, it is possible that a subgroup of individual series converge (club convergence). Phillips and Sul (2007) also suggest an algorithm using repeated regression to identify converging clubs. They argue that evidence of club convergence is usually most apparent in the last portion of the time series and suggest a two-step procedure. The first step is to order the individual series according to some time series average of the last fraction of observations and the second step is to repeatedly run the convergence log *t* test on the first *k* ($k \geq 2$) highest series to select a core convergence group. A core convergence group is formed by maximizing the *t*-statistic over *k* provided the null of convergence is not rejected for each *k*. If the null of convergence for $k = 2$ is rejected, then the highest series can be dropped. The procedure is repeated with successive series until a core subgroup is formed after which the remaining individual series are added to this subgroup one at a time and a convergence *t*-test is performed to determine whether that series should be included in the subgroup. In what follows, we perform this subgroup convergence test as well.

5. Empirical Results

5.1 Results from Time-Varying Coefficient Regressions

Figure 4 exhibits the pairwise time-varying regression coefficients (β_t) along with the two standard deviation confidence band for the four regional spot LNG price indices (in log form).[31] Because of the dominant role of East Asia in LNG markets, LEAX was chosen as an anchor and

[31] We also estimated the time-varying coefficient regressions (not in logs) for each pair of the regional spot LNG price indices. The results are qualitatively similar and available from authors upon request.

the other three LNG indices are regressed on LEAX. The results are reported in panel (a)-(c). In the Atlantic basin, because the average volume and price are both higher in South America than in Iberia and Northwest Europe, we choose to regress LIBX and LNWE, respectively, on LSAX and the results are displayed in panels (d) and (e). Finally, panel (f) shows the estimated coefficient of regressing LNWE on LIBX.

Several patterns are worth noting. First, there is a varying degree of market integration between all six pairs of the four indices, for a majority of the sample period the estimated time-varying coefficients are statistically different from zero. Second, currently spot LNG markets are still far from being fully integrated. Except for the pair of LIBX-LNWE which exhibits a higher elasticity of 0.65-0.75, the estimated coefficients for other pairs are far from unity. For example, the estimated coefficients range between 0.2-0.3 for the pair of LNWE-LEAX, 0.4-0.45 for LIBX-LEAX, 0.4-0.5 for LNWE-LSAX, and 0.55-0.65 for LIBX-LSAX. Overall, it appears that the South America index (LSAX) has a higher relationship with the East Asia index (LEAX) than do the European indices and that, in the Atlantic basin, the Iberian index has a higher relation with the South America Index than does the Northwest Europe index. This can be largely understood from the liquidity perspective as the South American buyers, particularly Argentina and Brazil, rely on the spot market for their LNG supply and therefore compete directly with Asian buyers whereas, in southwest Europe (Iberia), the LNG market is still dominated by long-term contracts with spot and short-term contracts playing a supplemental role only.[32] In fact, as we shall show, the Northwest Europe index mainly interacts with the price of NBP. It is less influenced by other

[32] According to the industry magazine, *Petroleum Economist (2013)*, Brazil has tried to avoid committing to long-term contracts as the country's energy mix is heavily influenced by the availability of hydropower and consequently its demand for LNG is likely to fluctuate significantly from year to year. Similarly, Argentina did not commit to long-term contracts as it had hoped it would be able to return to gas self-sufficiency with a resurgence of supply from shales and with the deregulation of the energy sector which should stimulate domestic supply and reduce demand.

LNG markets than the Iberian market because of some existing market barriers. Third, the degree of integration in spot LNG markets shows some seasonal movements. The estimated β coefficients tend to spike in winter months, presumably because fluctuation of demand is likely to be higher in winter because of unexpected weather conditions,[33] which leads to more active spot trading and consequently, drives prices to a higher degree of integration. Fourth, in terms of trend, while the estimated regression coefficients are largely stable for the pairs in the Atlantic basin, a slightly upward trend is found in the LSAX-LEAX, and to a lesser extent, the LIBX-LEAX pair. This suggests an overall modestly increasing degree of market integration between the Pacific basin represented by EAX and the Atlantic basin represented by SAX and IBX as the spot market expands. The estimated β coefficients for the three pairs involving LNWE all experienced a sharp drop during the first half of 2014 before returning to their respective normal levels towards the end of the sample period. The drop is almost certainly related to the weak demand for spot LNG in Northwest Europe during this period and logistic constraints which separated the Northwest European market from Iberia, a point which we will turn to in the next section.

Next, we estimate the time-varying coefficients by regressing each of the four regional spot LNG indices on the logged NBP price. As shown in Figure 5, while the NBP index displays a strong relationship with all four regional LNG indices, the two European indices (i.e. the NWE and IBX) tend to be more integrated with the NBP than EAX and SAX. Particularly, the elasticity of the NWE index with respect to NBP is fairly stable, fluctuating around 0.8-0.85 for most of the time during the sample period, indicating a higher degree of integration between the two markets. In contrast, the estimated coefficient for the pair of LEAX-LNBP ranges from 0.1 to 0.3 even after

[33] For example, on February 14, 2014 the Wall Street Journal reported that “Energy prices aren't just soaring in the U.S. as a cold winter sets in. In Asia, liquefied natural gas has surged to a record”.

the Fukushima incident, suggesting little influence of the UK gas prices on the pricing of spot LNG in Asia.

Given that the pricing of a significant share of long-term LNG contracts are still linked to the price of crude oil or that of refined oil products, one may argue that it is the price of crude oil rather than gas-on-gas competition that underlies market integration in LNG markets. To address this issue, we follow Neumann's approach (2009) by examining the time-varying coefficients on natural gas price data adjusted for the price of crude oil. Specifically, as a first step, we regress each of the LNG indices on crude oil prices represented by the price of Brent oil using ordinary least squares and generate a set of residual time series ($e_{i,t}$) as in equation (6):

$$p_{i,t}^{LNG} = c + k_i p_{i,t}^{Oil} + e_{i,t} \tag{6}$$

In the second step, we use equation (7) to generate the adjusted LNG price series ($\tilde{p}_{i,t}^{NG}$) by first normalizing the standard deviation of the residual series ($\sigma_{e_{i,t}}$) to the standard deviation of the original LNG price ($\sigma_{P_{i,t}^{LNG}}$) and then adding back the mean of the original price ($\overline{p}_i^{LNG}$):

$$\tilde{p}_{i,t}^{LNG} = \frac{e_{i,t} \cdot \sigma_{P_{i,t}^{LNG}}}{\sigma_{e_{i,t}}} + \overline{p}_i^{LNG} \ . \tag{7}$$

In doing so, the generated price series should be uncorrelated with the price of oil, but highly correlated with the price of LNG. Finally, we re-estimate the time-varying coefficients for each pair of the generated price series and plot the results in Figure 6.

Notably, the patterns of the estimated coefficients in Figure 6 are strikingly similar to those depicted in Figure 4. In terms of the magnitude, the estimated coefficients for LSAX-LEAX and LIBX-LEAX are noticeably lower than their counterparts in Figure 4 but still statistically significant, suggesting the oil price might still play a role in linking the spot LNG prices between the Pacific and Atlantic basins.[34] Interestingly, the estimated coefficients of LNWE-LIBX are slightly higher in the generated series than in the original series, indicating a slightly higher degree of market integration between the two markets when the effect of the oil price is purged off. The estimated coefficients for other pairs are almost identical to those reported in Figure 4. Thus, we conclude from this exercise that the varying degree of market integration in the spot LNG markets appears to be mainly driven by gas-on-gas competition rather than by links to the oil price as found in previous studies.

5.2 Results from Phillips-Sul Convergence Test

Since the Phillips-Sul (2007) methodology focuses on the long-term trend, following *Li et al.* (2014), we apply the Hodrick-Prescott (HP) filter with a smoothing parameter (λ) of 270400 to the logged price series to remove the transitional components and test the convergence among the HP trend components of the logged price indices. To visualize the relative transition paths to the cross-section average, we calculate the transition parameters h_t according to Equation (4) for the four HP trend of LNG indices. Figure 7a displays the transition paths.[35] The tendency of a path moving towards unity is considered as evidence for convergence. As shown in Figure 7a, the LEAX and LSAX, and to a lesser extent LIBX, have a clear tendency to move towards unity. In contrast, the LNWE initially moves in the same direction as the LIBX, but diverges from the rest until the second half of 2014 after which it also moves towards unity. LNWE appears to be somehow driven by a different force than that of other indices until the end of the sample period. Given the close similarity between NBP and NWE as shown in Figure 2, we perform a separate

[34] Assuming the estimated coefficients are independent from their counterparts in Figure 4, a test of the mean coefficients strongly rejects the null hypothesis that they are equal at 1% level for LSAX-LEAX, LIBX-LEAX, and LNWE-LIBX.

[35] As suggested by Phillips and Sul (2007), the first 30 percent of observations, the period from the week of August 2, 2010 to December 05, 2011, are excluded to avoid the initial effect. This applies to the Log *t* test below.

transition analysis for the LNWE and LNBP pair only in Figure 7b. Indeed, the figure displays a tight relationship between their trend components. In what follows we formally test the hypothesis of convergence among the indices using the Phillips and Sul (2007) methodology.

We start with a test for overall convergence among the four LNG indices as a group. The estimated equation with heteroscedasticity and autocorrelation consistent standard error is:

$$\log(\frac{H_1}{H_t}) - 2\log L(t) = -6.321 + \underset{(1.879)}{0.232}\log t.$$

The *t*-statistic is reported in parenthesis. The null hypothesis of convergence among the four LNG indices cannot be rejected. This implies that despite the initial divergence after the Fukushima accident in 2011, the spot LNG prices are converging towards the end of the sample period.

Even within the group convergence, it is interesting to identify the core convergence group among the spot LNG indices. Phillips and Sul (2007) suggest that if there is significant time series volatility, the individual time series may be ordered according to the averages of the last fraction (⅓ or ½) of each time series. The ordering of the four LNG indices according to the average of the last 60 observations is listed in the first column of Table 2. Using LEAX as the base, we perform the log*t* test by adding further indices one at a time. As reported in Table 2, the *t*-statistics are 7.236, 7.151 and 1.879 for k = [1, 2], [1, 2, 3] and [1, 2, 3, 4], respectively. Thus, it can be concluded that LEAX and LSAX constitute the core group, which is not surprising given the transition paths depicted in Figure 7a.

We are also interested in the interaction between NBP and the spot LNG indices. When LNBP is added, the Log *t* statistics for the group of five indices becomes -0.455 (also shown in Table 2) while the five percent critical value for the left-tailed *t* test is -1.645. Thus, we cannot reject the null hypothesis of overall convergence between spot LNG prices and the price of NBP. In addition, we also perform a convergence test for the pair of LNWE and LNBP. As reported in the bottom row of Table 2, the resultant *t*-statistic is -1.038 and hence we cannot reject the null hypothesis of convergence between LNWE and LNBP.

In sum, there is strong evidence that the spot LNG price indices are converging in the period after the Fukushima accident, with EAX and SAX being the core group. We can also conclude that the spot LNG prices are converging with the price of NBP because we cannot reject the null hypothesis of convergence. The results appear to be consistent with our conjecture about the change of market power of the leading supplier, Qatar, in the wake of the Fukushima accident and the negative demand shock in Europe over the 2012-2013 period. As the effects of the shocks dissipate over time, the LNG market converges to a more competitive equilibrium towards the end of the sample period.

Finally, it is somewhat surprising that the price of spot LNG in Northwest Europe did not converge with other regional indices until late 2014. There are two plausible explanations. The first is logistic constraints between the Spanish and French gas pipeline networks. If there were no logistic barriers between the Iberian market and Northwest Europe, competition in the pipeline gas market would push gas prices in the two markets to converge. However, at least prior to the end of 2013, there is limited interconnection capacity from Southern France into Spain and also between South and North France (Timera Energy, 2013). As such, the Iberian market was largely separated from the Northwest Europe market (see the joint report by Naturgas energia *et al.*, 2009).[36] With the upgrade and development of new interconnection capacity between Spain and South France, the relative separation should decline.[37] Second, since in the East Asia and Iberian

[36] There is also anecdotal evidence. For example, speaking at meeting attended by leaders of France, Spain and Portugal along with European Commission President in March 2015, the Spanish Industry and Energy Minister said "If there was an interconnection between Spain and the rest of Europe, Europe's vulnerability … would decrease." http://www.naturalgaseurope.com/south-west-europe-the-new-energy-frontier-22517.

[37] The upgrade of the west corridor of the interconnection was completed by end of 2013. The east corridor is expected to enter into operation by 2016 (European Commission, 2013).

markets the spot LNG competes with supplies of LNG or pipeline gas with long-term contracts whose prices are usually oil-indexed, yet the LNG import in Northwest Europe mainly compete in liquid gas markets, it is possible that the decoupling of oil and gas prices during the sample period also plays a role in the price non-convergence. Notably, as shown in Figure 6, when the effect of the oil price was removed the estimated coefficients turned slightly lower between IBX, SAX and EAX and slightly higher for IBX and NWE. The pattern could be consistent with this conjecture in that indexation to oil prices could reinforce the relationship between IBX, SAX and EAX, but weaken the link between IBX and NWE.

6. Conclusions

This paper provides the first empirical evaluation on the degree of integration and price convergence in four regional spot LNG markets using weekly data from August 2010 to February 2015. A conceptual framework of market integration in the context of LNG market is laid out. Estimating a time-varying parameters model, we find that there exists a varying degree of integration among the spot LNG indices and this integration appears to be driven more by competition in LNG markets than their links to oil prices. However, we also notice that the integration in spot LNG market is far from complete, with the elasticity between two price indices barely different from zero in some cases. We then employed Phillips and Sul's (2007) methodology to test whether the market indices after the Fukushima accident are converging towards an equilibrium implied by perfect competition. The test finds clear evidence of price convergence between the spot LNG prices and also between spot LNG and NBP prices, particularly towards the end of the sample period. The results are consistent with predictions from a model of LNG market where the major supplier have market power across different markets and the level of market power could change following a large demand shock such as the Fukushima accident.

A global gas market will occur only if the markets for LNG are reasonably integrated. Our convergence test results lends additional confidence that such a market might emerge as the volume of LNG available for spot and short-term markets further increases and infrastructure for interconnection improves in the future.

A limitation of our study is the relative short time span of the sample period which may prevent us from finding a stable long-run equilibrium between the price indices, which warrants further research as the market grows. We are also silent on the interaction between spot market prices and the prices of long-term contracts, which may be another area for further research, both theoretically and empirically.

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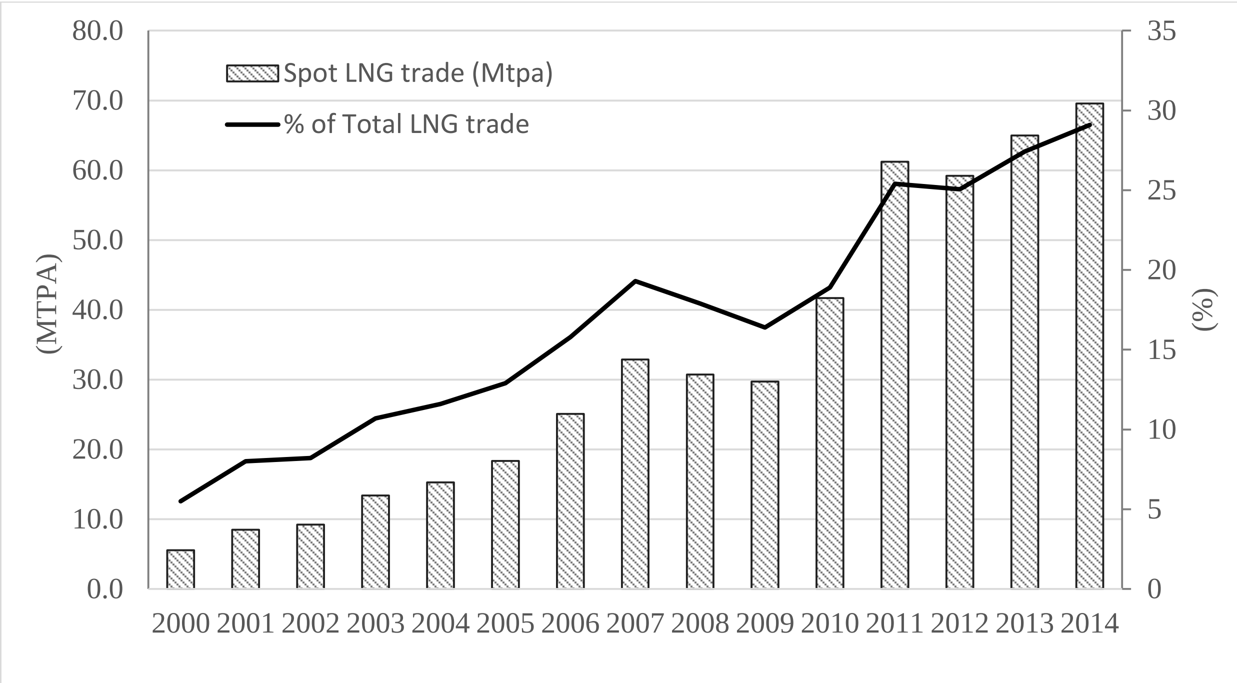
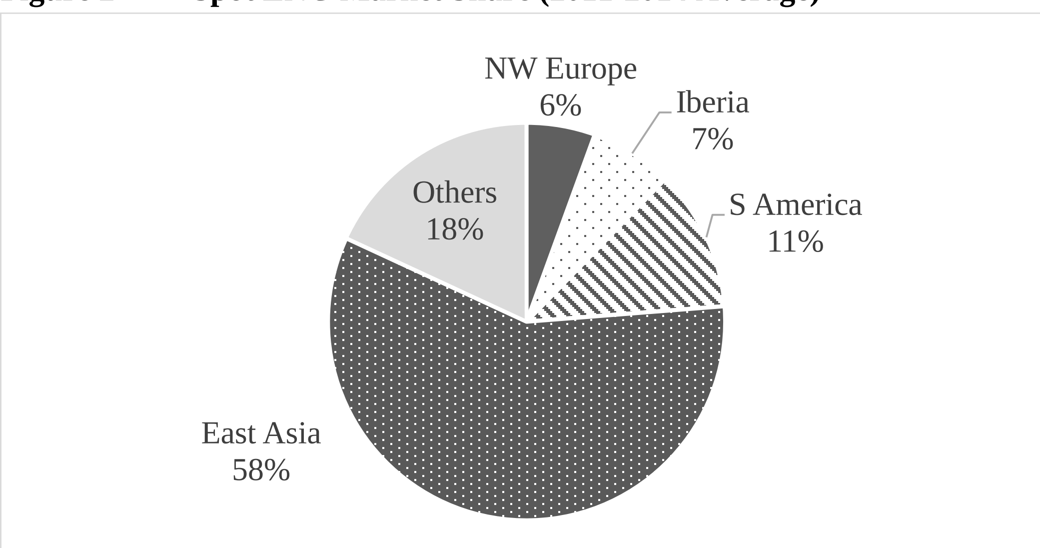
Figure 1 Spot and short-term LNG trade



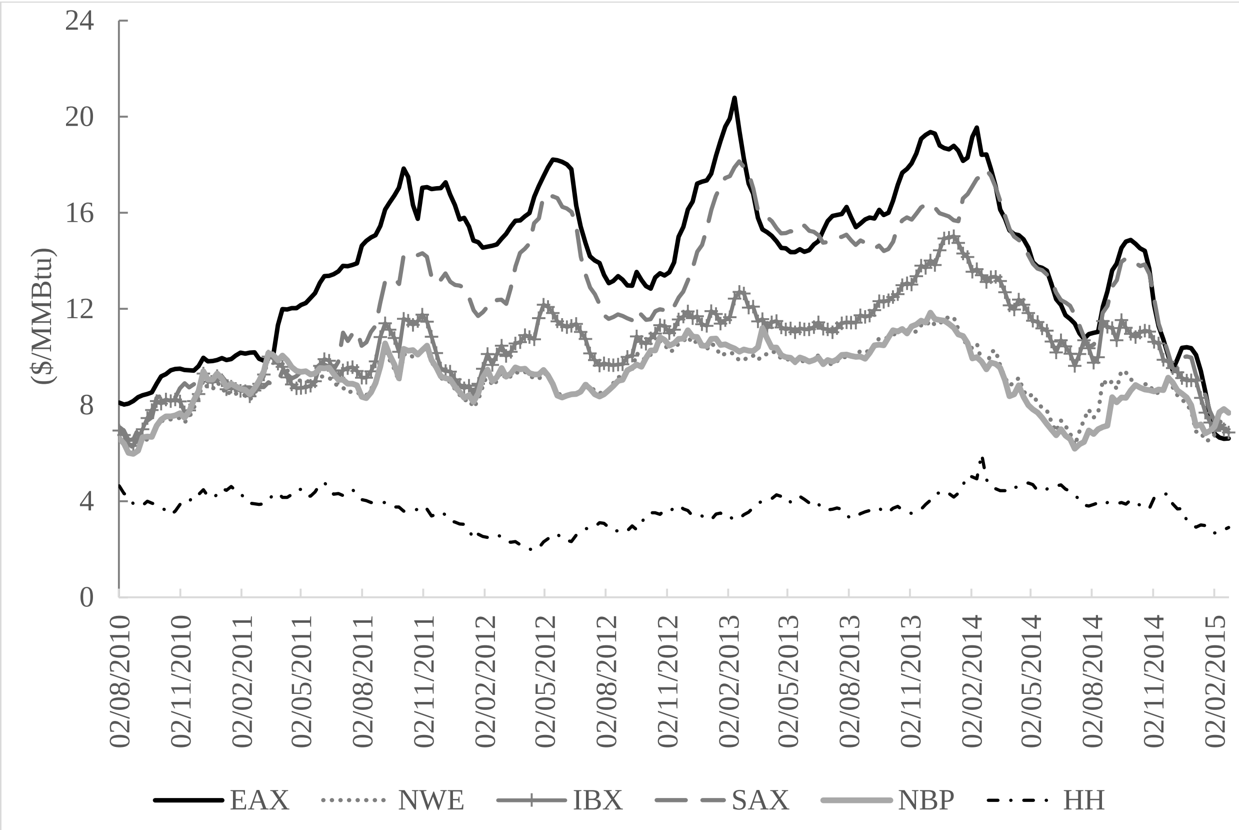
Notes: Short-term trade refers to trades under contracts of less than 4 years duration. The columns (the left axis) depicts the volume of spot and short-term LNG trade and the line (the right axis) depicts the share of spot and short term trade in total LNG trade for a given year. Data source: GIIGNL (2014) "The LNG Industry 2014".

Figure 2 Spot LNG Market Share (2011-2014 Average)



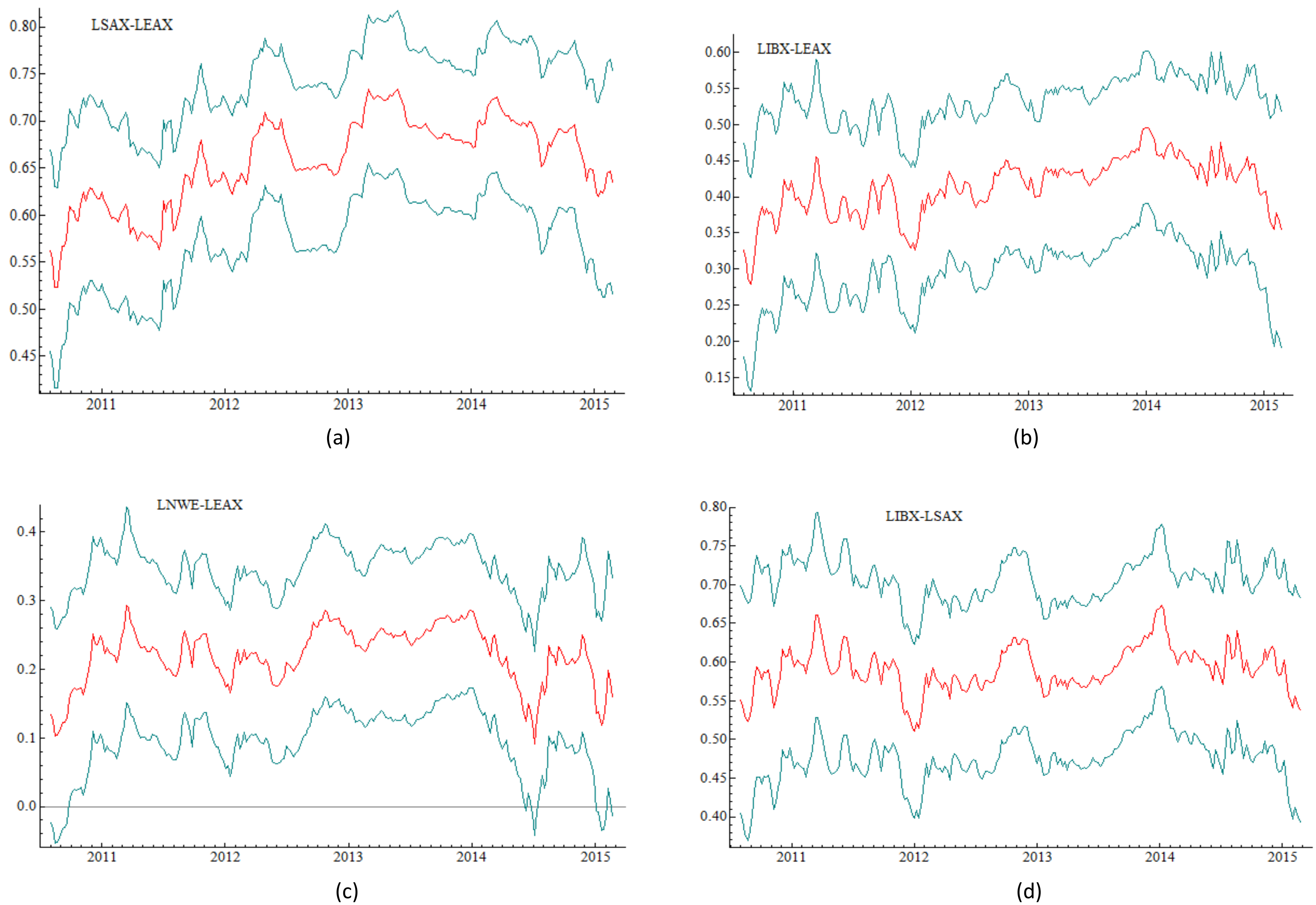
Note: The market share is calculated as the share of import volume, by region, in the total spot LNG trade over the period of 2011-2014. Data source: GIIGNL, "The LNG Industry", various years.

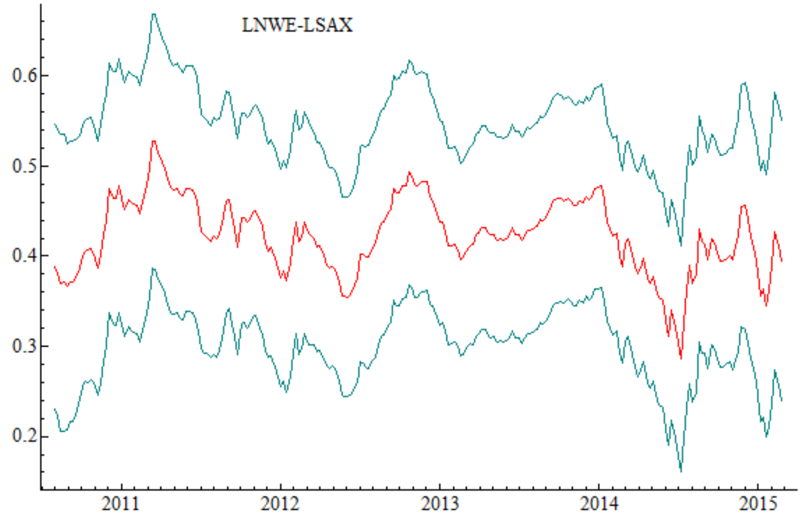
Figure 3 Spot LNG Prices



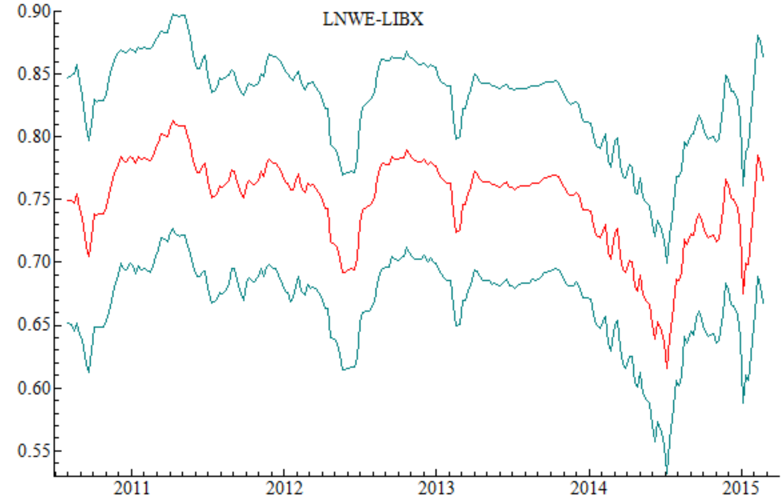
(Data source: ICIS)

Figure 4 Time varying coefficients between spot LNG indices





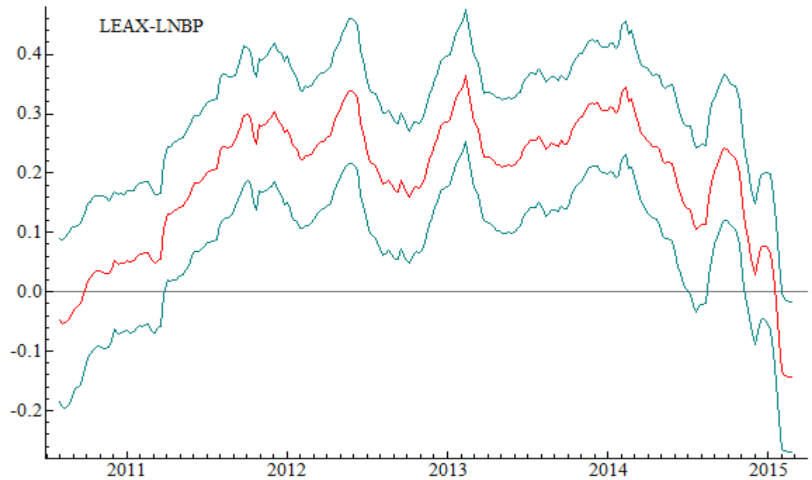
(e)



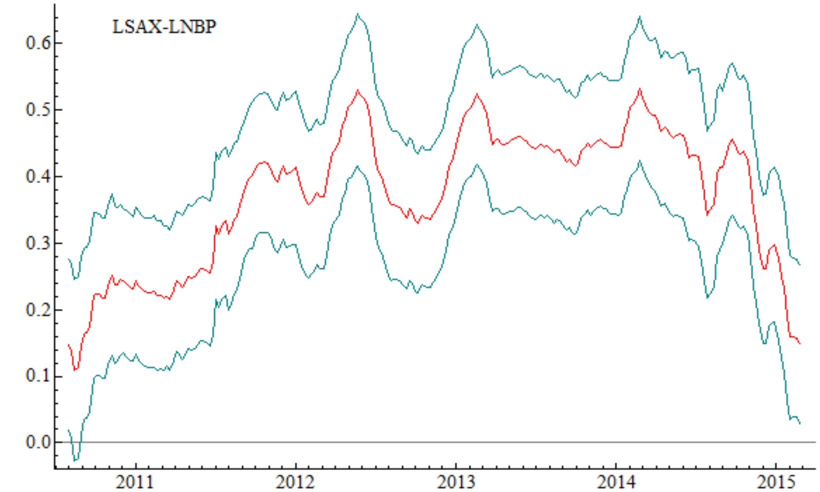
(f)

Notes: This figure depicts the time-varying coefficient estimates of regressing Y on X as in equation 2.1 and 2.2. In each panel, the first index indicates Y and the second indicates X. For example, the first panel depicts the random walk coefficient (red line) along with the two standard deviation confidence band (green lines) of regressing LSAX on LEAX.

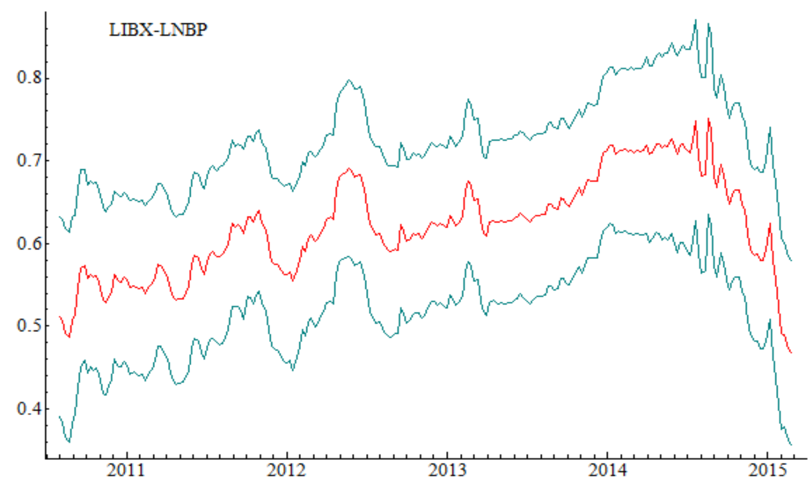
Figure 5 Time varying coefficients with NBP



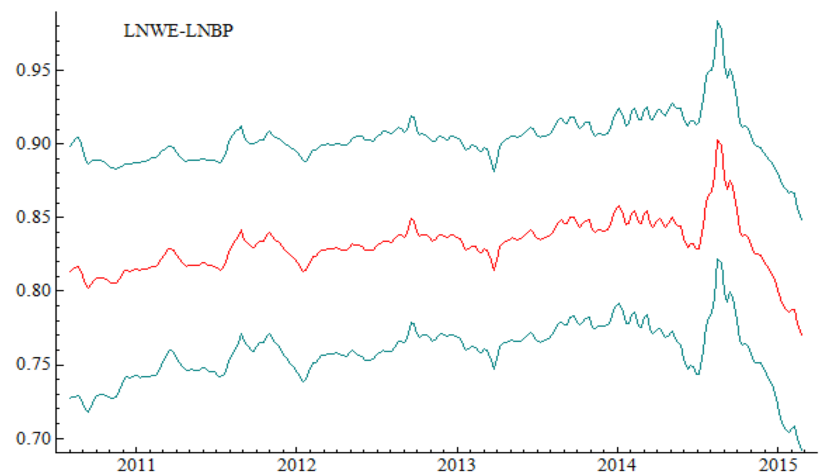
(a)



(b)

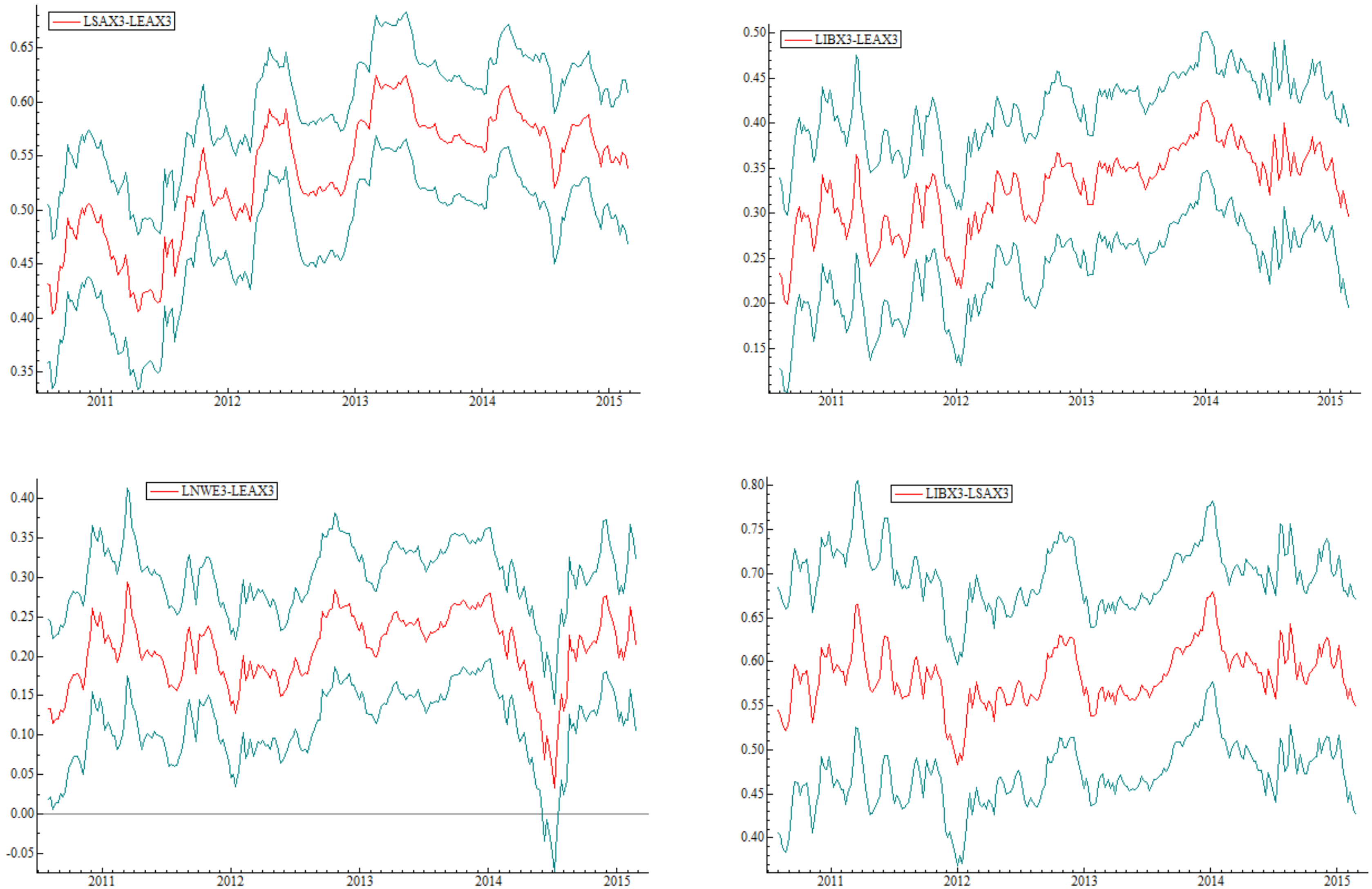


(c)



(d)

Figure 6 Time-varying coefficients when oil price was purged off



Notes: This figure depicts the time-varying coefficient estimates of regressing Y on X with the generated LNG price index data (equation 6-7). In each panel, the first index indicates Y and the second indicates X. For example, the first panel depicts the random walk coefficient (red line) along with the two standard deviation confidence band (green lines) of regressing LSAX on LEAX, both of which are uncorrelated with the price of oil.

Figure 7a **Relative Transition Paths of the LNG Indices**

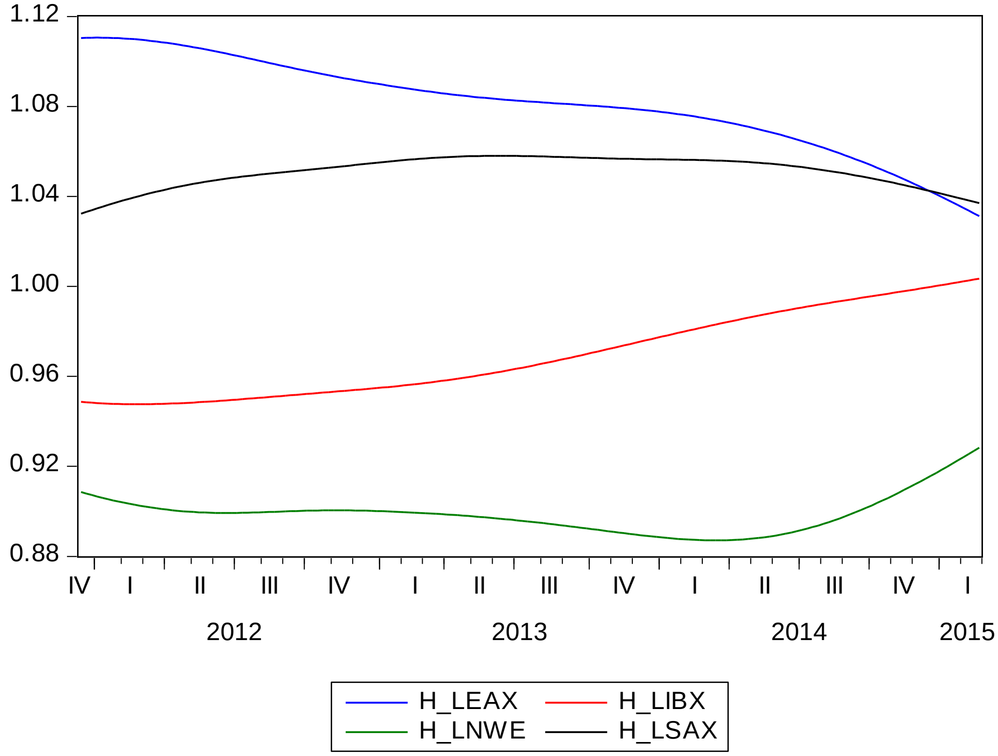


Figure 7b **Relative Transition Paths for LNWE and LNBP**

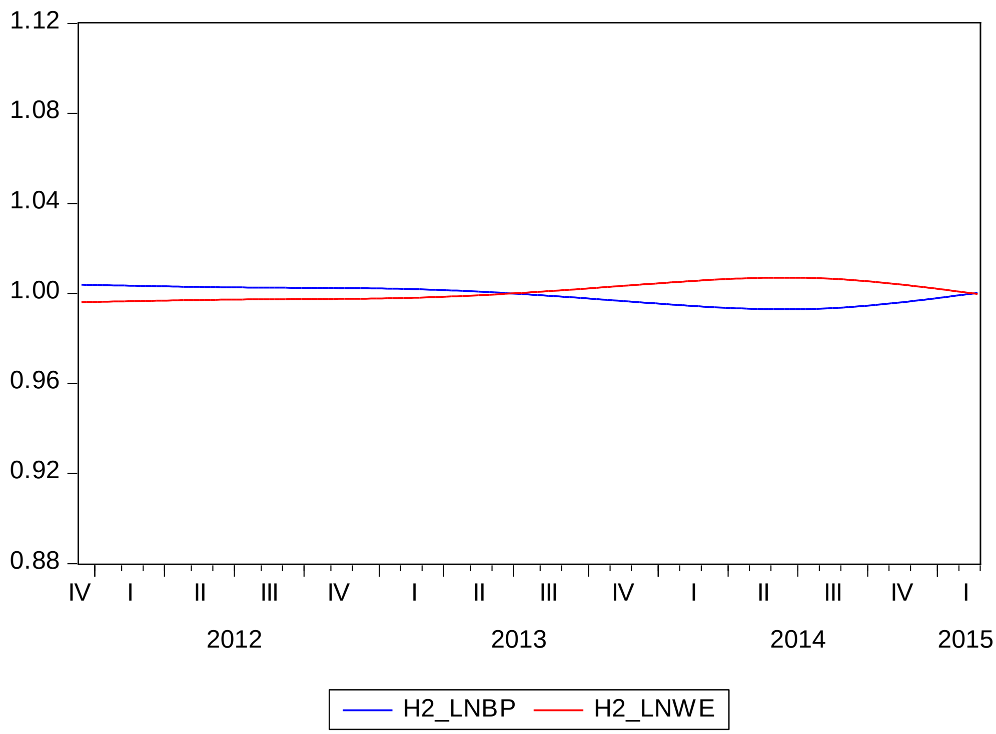


Table 1 Tests for Unit Root and Cointegration

Panel A. Unit Root Tests

	ADF	PP	KPSS
LEAX	-1.762 (0.399)	-1.268 (0.645)	0.441*
LIBX	-2.100 (0.245)	-1.866 (0.348)	0.841***
LSAX	-2.319 (0.167)	-1.817 (0.372)	0.782***
LNBP	-2.589* (0.097)	-2.604* (0.094)	0.287
LNWE	-3.071** (0.030)	-2.546 (0.106)	0.350*

Notes: The sample period is 08/02/2010 – 2/23/2015. All price indices are in natural logarithms. Lag lengths in the ADF test are selected by the Akaike information criterion (SIC). The PP test and the KPSS test use the Bartlett kernel with the Newey-West bandwidth. P-values are included in parentheses. The superscripts, ***, **, and *, denote the rejection of the null at the significance levels of 1%, 5% and 10%, respectively.

Panel B. Johansen Cointegration Tests

Variables	H_0: rank = r	Trace Statistic	Max. Eigenvalue Statistic	Lag Length
LEAX & LIBX	r = 0	13.216 (0.347)	10.634 (0.280)	5
	r ≤ 1	2.582 (0.661)	2.582 (0.661)	
LEAX & LSAX	r = 0	10.392 (0.601)	7.584 (0.598)	5
	r ≤ 1	2.808 (0.617)	2.808 (0.617)	
LIBX & LSAX	r = 0	20.745** (0.043)	17.192** (0.031)	1
	r ≤ 1	3.556 (0.482)	3.556 (0.482)	
LEAX & LNWE	r = 0	15.674 (0.190)	12.547 (0.156)	5
	r ≤ 1	3.127 (0.557)	3.127 (0.557)	
LIBX & LNWE	r = 0	16.535 (0.151)	10.023 (0.3323)	1
	r ≤ 1	6.512 (0.155)	6.512 (0.155)	
LSAX & LNWE	r = 0	21.882** (0.030)	16.995** (0.034)	1
	r ≤ 1	4.886 (0.296)	4.886 (0.296)	

Notes: Lag length (in first differences of logged price indices) is selected by the AIC. No deterministic trend is allowed in the tests. P-values are included in parentheses. The superscripts, ***, **, and *, denote the rejection of the null at the significance levels of 1%, 5% and 10%, respectively.

Table 2 Convergence Test Results

Order	Name	*t*-stat	
1	LEAX	base	Core
2	LSAX	7.236	Core
3	LIBX	7.151	
4	LNWE	1.879	
5	LNBP	-0.455	
	LNWE, LNBP	-1.038	

Note: The table reports the *t*-statistics with HAC standard errors of the log*t* coefficient in equation (5). The first column shows the ordering of the series according to the average of the last 1/3 observations. The *t*-statistics are respectively for k = [1, 2], [1, 2, 3], [1, 2, 3, 4] and [1, 2, 3, 4, 5] with 166 degree of freedom.

Appendix: **The Ritz (2014) LNG Market Model**

Consider an LNG supplier M which sells LNG to other markets. Let $P_i(x_i, y_i, X_{-i}, Y_{-i})$ denote the inverse demand function faced by the supplier in market *i (i=1, 2, …N)*, where P_i is the spot price of LNG, x_i is the quantity sold by the supplier to market *i* on the spot market, y_i is the quantity of LNG sold on long-term contract basis to market i, X_{-i} and Y_{-i} are respectively the quantity supplied by all other suppliers in the spot and long-term contract markets. Let T_i denote the unit transportation cost for shipping LNG from supplier *M* to market *i*. If arbitrage occurs between markets *i* and *j*, then the transport cost is T_{ji} consistent with the preceding notation.

Let C(.) denote the supplier's cost function which depends on the sum of total quantities of sold in all *N* markets, including both spot and contract sales. Assuming the volume sold on the long-term contract is given, the supplier's profit-maximizing problem is:

$$\text{Max } \pi = \sum_{i=1}^{N} P_i x_i - C(\sum_{i=1}^{N}(x_i + y_i) - \sum_{i=1}^{N} T_i\, x_i \qquad \text{(A.1)}$$

$$\text{subject to } \left(\sum_{i=1}^{N}(x_i + y_i\right) \leq \bar{Q}$$

where $\bar{Q}$ is the production capacity constraint. The first order conditions of (1) require that

$$MR_i - T_i = MR_j - T_j \text{ for all } i \neq j. \qquad \text{(A.2)}$$

where MR_i is the marginal revenue from selling into spot market *i*. The first order condition suggests that the profit-maximizing supplier would equate the marginal revenue net of transportation cost from selling into market *i* to that of selling into market *j*. Let η_i denote the price elasticity of demand faced by the supplier in market *i*. The supplier's marginal revenue from market *i* can be rewritten as: $MR_i = P_i(1 - 1/\eta_i)$ and we have

$$\frac{P_i - P_j}{P_i} = \frac{\eta_i}{\eta_i - 1}[\left(\frac{1}{\eta_i} - \frac{1}{\eta_j}\right) + (\frac{T_i - T_j}{P_i})]. \qquad \text{(A.3)}$$