Determinants of Liquefied Natural Gas Prices:
Academic Literature on Hubs Development and Market Integration

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Abstract

This study provides a literature review of academic research related to LNG hubs development and market integration. Studies show that Asian markets lack a transparent pricing benchmark and multiple initiatives are underway to facilitate price discovery in Asian LNG markets. As a result, the formation of functional NG market hubs in the Asia Pacific region will take time. Research publications show strong evidence of an initial cointegrating relationship between LNG and crude oil. However, we show that LNG's statistical relationship to both WTI and Brent ceases after the break dates of August 2008 and October 2015, respectively. Conclusions found within prior literature are highly dependent upon the sophistication of the estimation model and sample ranges employed

1. INTRODUCTION

The growth of U.S. LNG exports is transforming natural gas NG markets from a collection of segmented regional markets into an integrated global market. The first-ever export of domestically produced LNG from the lower-48 states occurred in February 2016 with a shipment from Cheniere Energy's Sabine Pass Terminal in Louisiana to Brazil. As of the end of 2021, the U.S. ranks first in the world for LNG export capacity of 92.5 million metric tons per year, ahead of Australia (87.6) and Qatar (77.4). The development of U.S. LNG becoming a major global player has implications for global NG prices and the behavior of those prices. By the end of 2022, the EIA forecasts U.S. nominal capacity to increase to 11.4 Bcf/d, and peak capacity to increase to 13.9 Bcf/d, exceeding capacities of the two largest LNG exporters, Australia (which has an estimated peak LNG production capacity of 11.4 Bcf/d) and Qatar (peak capacity of 10.4 Bcf/d).[1]

On March 25, 2022, President Biden announced the U.S. will supply an incremental 15 billion cubic meters (bcm) in addition to the volumes that have been flowing to Europe this winter (7 Bcf/d in peak months). Europe imports 16 Bcf/d of LNG in peak months, so this will account for additional 10% of LNG supplies. European LNG infrastructure has been tested to its maximum this winter and Europe is not likely to be able to absorb more than the volumes imported this past winter because of pipeline constraints between south and north. Europe imported 36 Bcf/d of natural gas in 2020, 16 Bcf/d of which came from Russia. 1.5 Bcf/d of this is only 4% of the total NG imports or 9% of total imports from Russia. This is a significant step in helping Europe reduce its dependence on Russian gas. This step alone makes LNG one of the most important energy resources in the world today. Understanding what drives LNG prices will be paramount in the next months and years.

This paper provides a comprehensive review of the academic and industry publications related to LNG hubs development and market integration. Section 2 describes the long term LNG contract specifications, Section 3 investigates LNG hubs development, Section 4 reviews articles related to market integration and Section 5 concludes.

[1] See https://www.eia.gov/todayinenergy/detail.php?id=50598 and https://www.eia.gov/naturalgas/U.S.liquefactioncapacity.xlsx.

2. LNG CONTRACT DESCRIPTION

Most LNG contracts are long-term with maturities greater than four years. Sale and purchase agreements (LNG SPAs) contain several provisions that set the obligations of the parties. Usually, the basic obligations are to sell and purchase certain quantities of gas, with specified volumes and prices. There are other commitments such as take-or-pay provisions, extraction, marketing obligations, restrictions on the destination, allocation of liability in the event of accidents, most favored nation provisions, and force majeure provisions.

There are two types of loading and delivery terms: Free On Board (FOB) and Delivered Ex-Ship (DES). They determine the point of transfer of the title, where the risk and ownership of LNG will be passed on from seller to the buyer. FOB contract transfers occur at the loading point. The buyer provides its vessel in a ready to load condition. The buyer has the freedom to divert cargoes, for example, if there is a better price at a different receiving terminal. DES contract transfers are at the destination port. The seller is responsible for delivering the LNG. The buyer may not have destination freedom unless there is a diversion provision. In general, buyers prefer FOB over DES contract structures.

The take-or-pay provisions require the buyer to purchase a minimum annual quantity, which is defined as annual contract quantity (ACQ). A take-or-pay provision ensures that the buyer bears the full quantity risk, while providing comfort to investors that they would be able to recover the amount of capital invested for the construction and operation of gas production facilities.

The destination restrictions exist since the seller usually aims to prevent a buyer from being able to deliver cargoes to other destinations, as the seller does not want the buyer to compete with its other buyers.

In general, most U.S. purchase agreements are free of take-or-pay and destination restrictions. Their pricing is on the Henry Hub basis. The EU also does not allow destination restrictions. However, the Asian market does not have such flexibility. Recently, the Japanese Fair-Trade Commission announced that they may restrict the use of destination clauses. South Korea is following Japan on this issue as well. The diversion provisions provide buyers with the flexibility to divert gas to more profitable destinations. These provisions are more prevalent since they allow for profit sharing agreements.

Price review provisions: In 2020, most of the global LNG traded was still under long-term contracts, see (GIIGNL, 2020). Creti and Villeneuve (2004) review the literature on long-term natural gas contracts. In particular, they analyze the take-or-pay clauses, price indexation rules, and question whether regulation is in the way of having optimal contract duration. Christie et al., (2020) describe LNG contract terms and emphasize the issues surrounding the force majeure clauses following the Covid-19 crisis. They conclude that price review clauses will become more detailed and include more flexible terms. It is also likely that Asian markets will evolve and require shorter price review periods. Additionally, the Covid-19 crisis may be a trigger for new efforts for the development of a local hub.

3. LNG HUBS DEVELOPMENT

Table 2 summarizes the published literature described in this section.

Table 1: Key Characteristics of Section 3 Literature

This table summarizes research related to the Section 3 question. The quality of the journal is indicated using the Australian Business Deans Council (ABDC) list. ABDC's highest rank is A*, followed by A, B, and C. The ABDC list only ranks academic business journals so a dash (-) indicates the rank is not available. A dash in the Data Frequency indicates it is not relevant. Google Scholar Citations are provided as of March 24, 2022. Refer to the Bibliography section for full article citations.

Paper	Name	Author(s)	Year	Journal	ABDC	Google Scholar Citation
1	The development of gas hubs in Europe	Miriello and Polo	2015	Energy Policy	A	46
2	Development of Europe's gas hubs: Implications for East Asia	Shi	2016	Natural Gas Industry B	-	22
3	Balancing systems and flexibility tools in European gas markets	Dickx et al.	2014	IEFE - Cent. Res. Energy Environ. Econ. Policy Bocconi Univ	-	8
4	European traded gas hubs: German hubs about to merge	Heather	2021	Oxford Inst. Energy Stud.	-	0
5	Gas and LNG trading hubs, hub indexation and destination flexibility in East Asia	Shi and Variam	2016	Energy Policy	A	71

6	The future of Asia's natural gas market: the need for a regional LNG hub	Guzman	2018	Asia policy	C	1
7	Asian LNG market changes under low oil prices: prospects for trading hubs and a new price index	Kim	2017	Geosystem Engineering	-	16
8	Key elements for functioning gas hubs: A case study of East Asia	Shi and Variam	2018	Natural Gas Industry B	-	14
9	Oil indexation, market fundamentals, and natural gas prices: an investigation of the Asian premium in natural gas trade	Zhang, Shi and Shi	2018	Energy Economics	A*	91
10	International gas pricing in Europe and Asia: A crisis of fundamentals	Stern	2014	Energy Policy	A	98
11	Strategic analysis on establishing a natural gas trading hub in China	Tong, Zheng, and Fang	2014	Natural Gas Industry B	-	38
12	A fundamental analysis on the implementation and development of virtual natural gas hubs	Valle, Duenas, Wogrin, and Reneses	2017	Energy Economics	A*	8
13	LNG import diversification in Asia	Vivoda	2014	Energy Strategy Reviews	-	69
14	Natural gas in Asia: trade, markets, and regional institutions	Vivoda	2014	Energy Policy	A	56
15	Obstacles to the creation of gas trading hubs and a price index in Northeast Asia	Kim	2019	Geosystem Engineering	-	5

3.1 HUBS DEVELOMENT IN EUROPE

Europe is often seen as a benchmark on hub development. Researchers investigate the main factors that led to efficient pricing hubs. Miriello and Polo (2015) and Dickx et al. (2014) investigate the creation of wholesale markets for NG, viewed as a consequence of balancing needs following market liberalization. The authors identify four stages in gas hub development: market liberalization, balancing platforms, wholesale trading, and financial operations. They analyze the stage development for eight European countries: Austria, Belgium, France, Germany, Italy, Netherlands, Spain, and U.K. In their research, they specify two important questions: What determines the emergence of gas hubs? Is there a predictable pattern of development? Additionally, for every country, they document several parameters that are key to market liquidity: bid-ask spread, churn ratio, volume, existence of futures markets, and internal production demand. Based on the four stages of market development they conclude that the U.K. National Balancing Point (NBP) is at the highest level of development. The Dutch Title Transfer Facility (TTF) follows closely. NetConnect Germany (NCG) and Belgian Zeebrugge follow in terms of volumes traded. These two papers are a useful starting point to analyze the hub development in Asia.

Recently, Heather (2021) argues that the vision set 20 years ago of a fully liberalized traded gas market on the wider European level is almost fulfilled. Heather points to a merger of hubs in Germany scheduled to be completed in October 2021.[2] The expectations are that this hub will become one of the most attractive and liquid gas trading hubs in Europe. However, Heather does not see a real potential for such transformation. The TTF and NBP are important benchmarks, and it is very likely that TTF will continue to be the European gas price benchmark.

Shi (2016a) identified several key factors for successful hub development such as market liberalization and competition. They concluded that market liberalization is necessary to create a competitive environment. Additionally, market liberalization is a necessary measure to create demand for wholesale trade, which is the key incentive and fundamental role of a hub. They identified key factors needed for successful hub development. Factors include: pricing transition for long-term contracts; political will; natural factors, domestic production and culture. Authors used those factors to compare hubs development in Europe and East Asia. They conclude that lack of indigenous production and inter-connectivity, vertically integrated industrial structure, the traditional preference of supply security and unclear political signals, will make LNG hub development in East Asia more difficult than in Europe. Their forecast is that even if some East Asian countries are determined to develop their hubs, there is a very small chance to have one by 2030.

[2] Two hubs, Gaspool and NetConnect Germany (NCG) merged to create a new gas trading platform, Trading Hub Europe (THE). For more information, see (Afanasley, 2021).

3.2 HUBS DEVELOPMENT IN ASIA

Recent hub development research focuses on hubs in Asia. Tong et al. (2014) argue that China has more advantages in establishing an Asian NG trading hub than other countries like Singapore, Japan, and Malaysia. Their analysis was based on internal strength/weakness and external competitiveness. The authors argue that there are many factors that favor China such as supporting policies on the NG sector, initiation of spot and futures markets, rapid growth of NG production, improved infrastructure, and Shanghai's strategic location.

Shi and Variam (2018) identify the key elements for having a fully functional NG hub applicable to East Asia. Their framework establishes nine key elements. Since these factors are relevant to this research, we replicate their Table 1 as shown below. Table 3 shows the key elements from Shi and Variam (2018).

Table 2: Key Elements for Gas Hubs

This table lists the key elements for having a fully functional NG hub and is replicated from Table 1 of Shi and Variam (2018).

EFET[3] hub element	Basic elements for all hubs	Additional elements for benchmark hubs
Entry-exit system established	A trading point; could be a virtual trading point or a physical network interconnection. The trading point is operated by the TSO.	In the case of a benchmark pricing hub, one trading point needs to be designated as the benchmark hub.
Defined role of hub operator	Provides some services in addition to the infrastructure under the trading point. Could be undertaken by TSOs or exchanges.	
Establishment of exchange	Trading platform, often an exchange.	
Standardized contract	Specification of contract and products including but not limited to standardization.	Derivatives products and market to be developed.
Price reporting agencies (PRAs)		PRA published assessment of traded prices and price indexes for various kinds of contracts.
Market makers, brokers, and access to non-physical traders	Right mix of market players including participation of financial players.	The number of players and the market liquidity have to be sufficient to allow for competition. Financial market participants.

[3] European Federation of Energy Traders.

Shi and Padinjare Variam (2016) use the Nexant World Gas Model[4] to study hub competition. They find that both price benchmark change and contract flexibility improvements will create an overall benefit for the world and East Asia importers.

Vivoda (2014) evaluates the impact of Japan's LNG strategy on regional pricing. Japan implemented several measures to challenge oil indexation with the objective to reduce transaction costs. The author argues that despite all the initiatives started by Japan, the LNG pricing will only partially shift away from oil-indexation by year 2020.

Shi (2016b) summarizes four papers on LNG and trading hubs in East Asia. He finds that a liquid futures market is the key to formulate benchmark prices while a well-developed spot market is the foundation. Additionally, political will and strong leadership are required to restructure the NG market and to overcome the power of incumbents that impede the development of completive markets. The hub development requires governments to go through tough domestic market reforms, including liberalization and cooperation with each other and with gas exporters.

Kim (2017) studies the LNG market changes under low oil prices observed in 2014. His overall conclusion is that the evolution of an Asian gas hub will be highly influenced by decisions made by both China and Russia.

Kim (2018) argues that the Asian gas hub pricing dynamics in 2014-2017 look similar to that of Europe in 2009-2012; however, the path to an Asian hub will be very different from Europe. Citing challenges and complexities, he concludes that it makes more sense to expect a virtual LNG hub and not a NG trading hub.

Stern (2014) describes the time series of events leading to transition to hub pricing in Europe. He calls the situation in Asia a "crisis of fundamentals" and concludes that a hub is still a distant prospect.

Shi et al. (2019) use a structure vector auto-regression model and monthly LNG prices of four East Asian importers to study if markets are integrated. They find that the LNG markets are fragmented

[4] Nexant World Gas Model is a simulation engine that allows exploring different scenarios. https://www.nexanteca.com/program/world-gas-model.

and recommend multiple LNG benchmark trading hubs so that each can reflect different fundamentals.

Palti-Guzman (2018) examines how the LNG market functions in Asia and argues that an opportunity exists for Asia to develop a regional trading hub. The author points to several policy implications, such as access to LNG will have an environmental benefit, a trusted Asian hub will make regional gas markets more efficient, and a regional LNG hub will foster intraregional trade and synergies.

del Valle et al. (2017) develop a model to analyze the different stages of the implementation and development of a virtual hub. The virtual hub is set up as an entry-exit framework. Assumptions regarding shippers, businesses and industries participating in the electricity market, and other players, are made to set up the virtual hub. They make a few conclusions. First, with the introduction of the virtual hub, the marginal cost of all shippers reaches a unique value, i.e., the transparent gas hub price. Second, the aggregated profit of the shippers is increasing even when anticompetitive behavior is not explicitly represented, due to the flexibility gained by shippers with the hub. Accordingly, and third, the hub is a necessary, but not sufficient condition to increase competition. The entry of new players is critical and discouraging market regulations or the anticompetitive behavior of a highly concentrated market may not facilitate it.

The research report, “Perspectives on the Development of LNG Market Hubs in the Asia Pacific Region”, by EIA (2017) analyzes the state of LNG hubs in the Asia Pacific Region. It makes the following conclusions. Global liquefaction capacity is projected to increase by one-third by 2020. U.S. LNG exports will increase liquidity in global LNG trade and enhance supply security. Asian markets lack a transparent pricing benchmark and multiple initiatives are underway to facilitate price discovery in Asian LNG markets. As a result, the formation of functional NG market hubs in the Asia Pacific region will take time.

3.3 SPOT TRADING AND REGASIFICATION CAPACITY

Annual reports by GIIGNL provide key data on LNG markets. Using data from their annual reports for the years 2004-2020, the following tables and charts are constructed to gain insights on developments in the LNG markets over time. See, for example, (GIIGNL, 2020), (GIIGNL, 2019), (GIIGNL, 2018), (GIIGNL, 2017), (GIIGNL, 2016), (GIIGNL, 2015), (GIIGNL, 2013).

Figure 2 shows the time series of regasification capacity and spot trading, including short-term contracts. Table 4 shows the correlations between regasification capacity, number of terminals and spot trading. Note that as the total number of terminals and regasification capacity increases, so does spot trading. The correlations are high, with 99.57% between regasification capacity and number of terminals, and 78.08% between number of terminals and spot trading.

Figure 1 : Time Series of Regasification Capacity and Spot Trading

This figure plots the time series of regasification capacity measured as total number of LNG terminals (left-hand axis) versus spot trading. Spot trading is measured as Short-term trading, defined as any contract that is less than four years. We obtain our data from GIIGNL annual reports over the period 2004-2021.

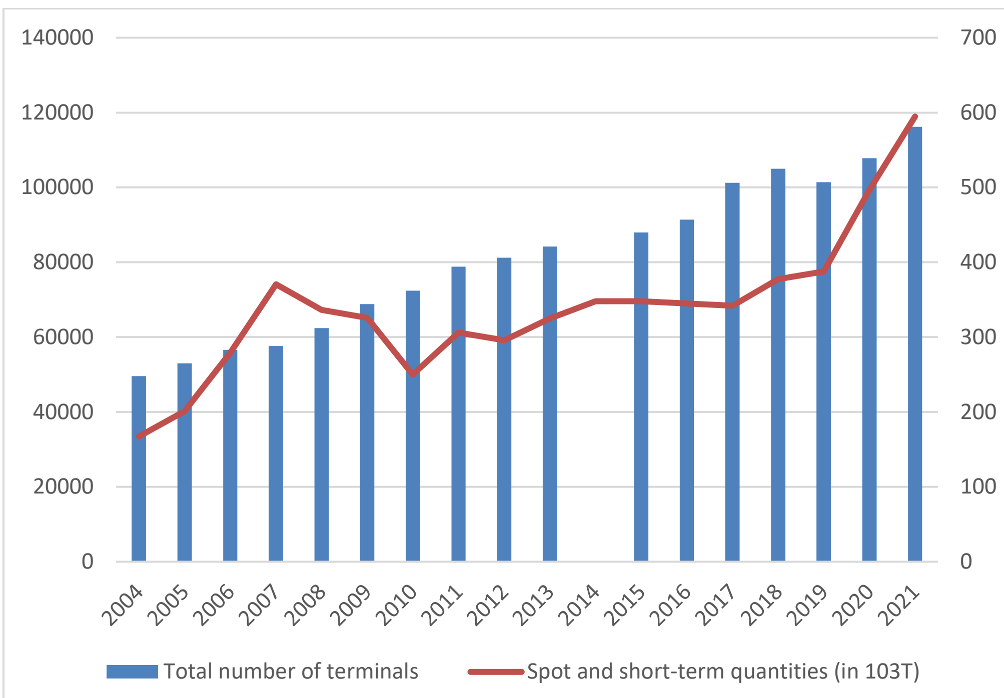


Table 3: Correlations between Capacity and Short-Term Contracts

This table shows the correlations between regasification capacity, number of terminals and spot trading. As shown, th correlations are high, with 99.57% between regasification capacity and number of terminals, and 78.08% between number of terminals and spot trading.

	Total Regasification Capacity (MTPA)	*Total number of terminals*	*Spot and short-term quantities (in 10^3T)*
Total Regasification Capacity (MTPA)	1		
Total number of terminals	0.9957	1	
Spot and short-term quantities (in 10^3T)	0.7808	0.7884	1

4. MARKET INTEGRATION

While there is a plethora of academic studies examining NG, there are few studies focusing on LNG. This is likely because large-scale international LNG market development and intercontinental arbitrage has only taken place over the last couple of decades. In response, many early works interchangeably consider NG and LNG. As LNG hubs have become more prevalent in recent years, and with them LNG transportation, research specific to LNG has become more common.

Additionally, NG and petroleum products have historically been viewed as close substitutes. In North America, power generators often alternated between fuel oil and NG depending on whichever was least expensive. Price movements between the two fuels were therefore closely related. An early NG price rule-of-thumb ratio was 10:1, meaning that one barrel of WTI crude oil was priced at roughly ten times one million British thermal units (MMBtu) of NG. It was not until the late 1990s that this rule-of-thumb was changed to a 6:1 ratio, which more accurately reflected the Btu energy conversions.

Table 5 summarizes the academic articles described in detail, and Figure 3 presents the data sample ranges used in the cited studies in this section.

Table 4: Key Characteristics of Section 4 Literature

No.	Name	Author(s)	Year	Journal	ABDC	Google Scholar Citation	Data Freq.
1	Co-integration and error correction:	Engle and Granger	1987	Econometrica	A*	46,101	-

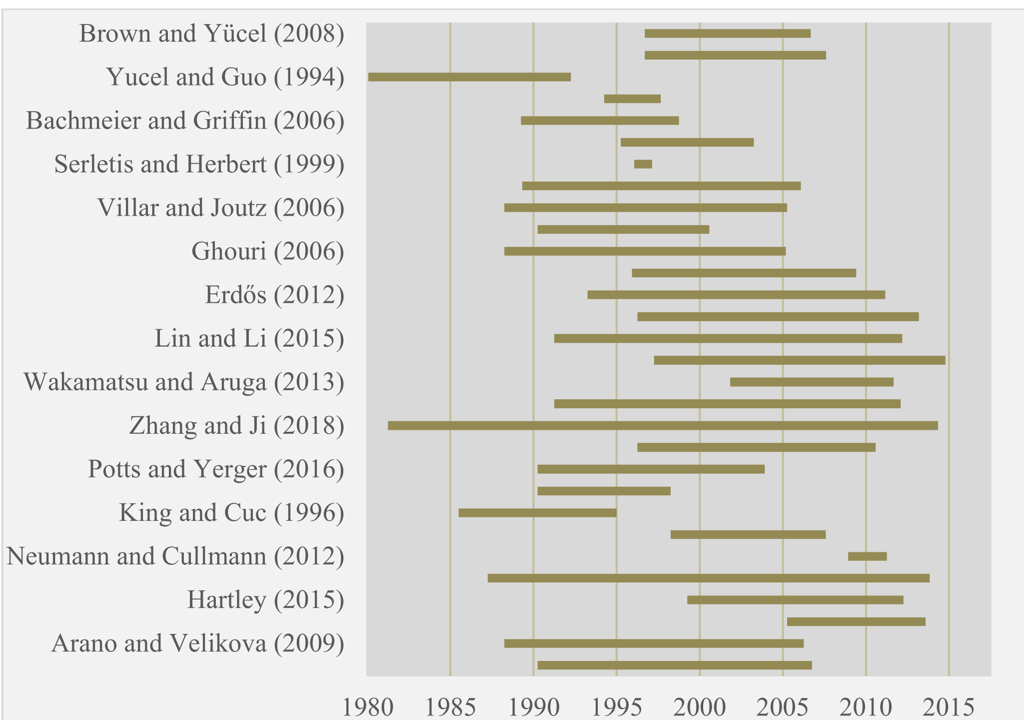
	Representation, estimation, and testing						
2	Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models	Johansen	1991	Econometrica	A*	14,699	-
3	Asymptotic properties of residual based tests for cointegration	Phillips and Ouliaris	1990	Econometrica	A*	2,588	-
4	What drives natural gas prices?	Brown and Yücel	2008	The Energy Journal	A	386	Weekly
5	Market arbitrage: European and North American natural gas prices	Brown and Yücel	2009	The Energy Journal	A	90	Weekly
6	Fuel taxes and cointegration of energy prices	Yucel and Guo	1994	Contemporary Economic Policy	B	45	Annual
7	The UK market for natural gas, oil and electricity: Are the prices decoupled?	Asche et al.	2006	The Energy Journal	A	245	Monthly
8	Testing for market integration crude oil, coal, and natural gas	Bachmeier and Griffin	2006	The Energy Journal	A	302	Daily
9	Oil and gas markets in the UK: Evidence from a cointegrating approach	Panagiotidis and Rutledge	2007	Energy Economics	A*	226	Monthly
10	The message in North American energy prices	Serletis and Herbert	1999	Energy Economics	A*	182	Daily
11	The relationship of natural gas to oil prices	Hartley et al.	2008	The Energy Journal	A	240	Monthly
12	The relationship between crude oil and natural gas prices	Villar and Joutz	2006	EIA: Office of Oil and Gas	-	277	Monthly
13	Testing for common features in North American energy markets	Serletis and Rangel-Ruiz	2004	Energy Economics	A*	150	Daily
14	Forecasting natural gas prices using cointegration technique	Ghouri	2006	OPEC Review	C	16	Annual
15	Gas versus oil prices the impact of shale gas	Asche et al.	2012	Energy Policy	A	143	Monthly
16	Have oil and gas prices got separated?	Erdős	2012	Energy Policy	A	118	Weekly
17	The long-run oil-natural gas price relationship and the shale gas revolution	Caporin and Fontini	2017	Energy Economics	A*	57	Monthly
18	The spillover effects across natural gas and oil markets: Based on the	Lin and Li	2015	Applied Energy	A	97	Monthly

	VEC-MGARCH framework						
19	The impact of the North American shale gas revolution on regional natural gas markets: Evidence from the regime-switching model	Geng et al.	2016 a	Energy Policy	A	56	Daily
20	The impact of the shale gas revolution on the U.S. and Japanese natural gas markets	Wakamatsu and Aruga	2013	Energy Policy	A	70	Monthly
21	The U.S. shale gas revolution and its effect on international gas markets	Aruga	2016	Journal of Unconventiona l Oil and Gas Resources	-	57	Monthly
22	Further evidence on the debate of oil-gas price decoupling: A long memory approach	Zhang and Ji	2018	Energy Policy	A	42	Monthly
23	International natural gas market integration	Li et al.	2014	The Energy Journal	A	54	Monthly
24	Marcellus shale and structural breaks in oil and gas markets: The case of Pennsylvania	Potts and Yerger	2016	Energy Economics	A*	10	Monthly
25	U.S. natural gas exports and their global impacts	Arora and Cai	2014	Applied Energy	A	67	-
26	Are regional oil markets growing closer together?: An arbitrage cost approach	Kleit	2001	The Energy Journal	A	82	Weekly
27	Price convergence in North American natural gas spot markets	King and Cuc	1996	The Energy Journal	A	132	Monthly
28	Linking natural gas markets - Is LNG doing its job?	Neumann	2008	The Energy Journal	A	127	Daily
29	What's the story with natural gas markets in Europe? Empirical evidence from spot trade data	Neumann and Cullmann	2012	9th International Conference	-	25	Daily
30	Global LNG pricing terms and revisions: An empirical analysis	Agerton	2017	The Energy Journal	A	11	Monthly
31	The future of long-term LNG contracts	Hartley	2015	The Energy Journal	A	72	Annual
32	Strategic model of LNG arbitrage: Analysis of	Ikonnikova et al.	2009	Association for Energy	-	5	-

	LNG trade in Atlantic Basin						
33	Price discrimination and limits to arbitrage: An analysis of global LNG markets	Ritz	2014	Energy Economics	A*	38	Monthly
34	Trade with endogenous transportation costs: The case of liquified natural gas	Oglend et al.	2016	Energy Economics	A*	25	Monthly
35	Time commitments in LNG shipping and natural gas price convergence	Oglend et al.	2020	The Energy Journal	A	30	Monthly
36	Price convergence in natural gas markets: City-gate and residential prices	Arano and Velikova	2009	The Energy Journal	A	16	Monthly
37	Convergence of European natural gas prices	Bastianin et al.	2019	Energy Economics	A*	20	Frequency

Figure 2: Section 4 Sample Ranges

This figure illustrates the sample ranges of data for the studies listed in Table 5. The studies are listed in order as they are discussed in this section. The start date of Yucel & Guo (1994) is truncated for brevity.



4.1 PRICING SYSTEMS AND EMPIRICAL METHODOLOGIES

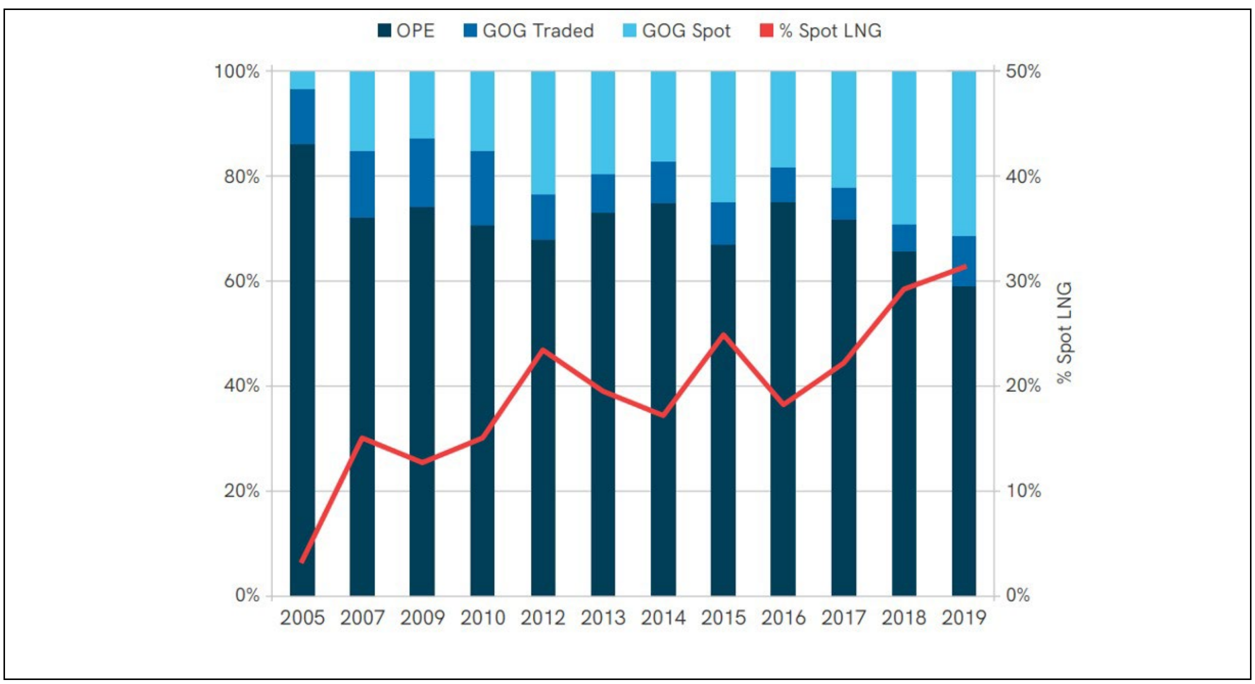
Over the last decades, regulatory changes, infrastructural changes, and trading developments have curtailed the ability to substitute fuels easily. This has led to alternative pricing mechanisms, each with its own set of advantages and disadvantages. Generally speaking, NG has faced three main pricing mechanisms:

- Hub pricing known as 'gas-on-gas' competition;
- Government regulated prices; and
- Oil-indexation.

Gas-on-gas (GOG) pricing indexes the NG price to market spot prices, which are determined by supply and demand factors. These factors often widely vary across hubs, with each exhibiting its own set of dynamics. Therefore, GOG pricing reflects the prevailing market equilibrium occurring at an individual hub location.

Figure 3: World Price Formation – LNG Imports

This figure is from the International Gas Union (IGU) Wholesale Price Survey (2020). This figure illustrates how more countries are straying away from oil price indexation (OPE) as a pricing mechanism and adopting gas-on-gas (GOG) and more spot trading instead.

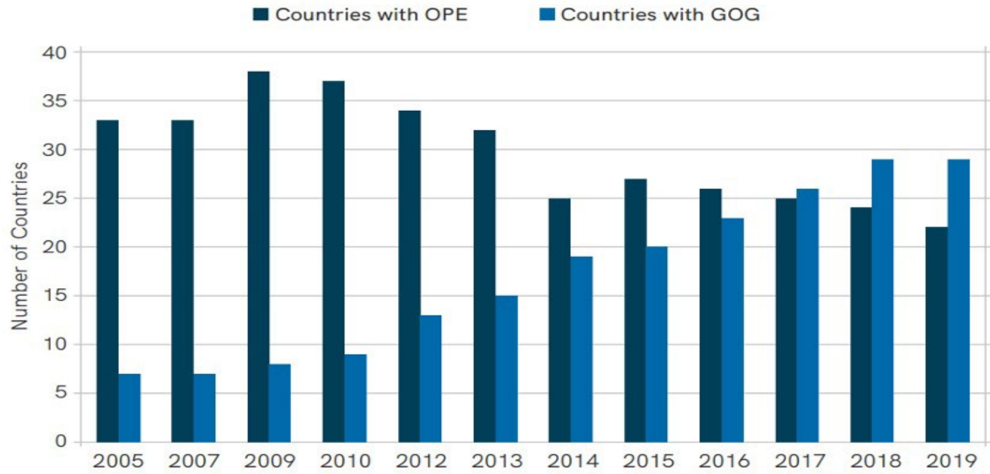


Source: (IGU, 2020). *https://www.cmegroup.com/education/articles-and-reports/is-oil-indexation-still-relevant-for-pricing-natural-gas.html*.

Historically, oil-indexed (OI) pricing has been the most widely used. Under OI, contractual NG prices are set in relation to netback values, using a formula to calculate the point of sale value minus transportation costs and profit margin. Such formulas are contract specific. These contracts are traditionally viewed as 'long-term', lasting upwards of 20-25 years. OI pricing relies upon a number of suppositions such as crude oil and NG are near perfectly substitutable fuels, the oil market is too big to be manipulated, and international oil prices provide a 'price-anchor' to limit substantial regional price gaps. These suppositions are quite strong. Determining which pricing mechanism is most efficient, GOG or OI, requires additional investigation into each. Nonetheless, the global trend has strongly favored a movement toward GOG pricing. Figure 4 illustrates global trends in GOG and OI pricing. As shown, a greater number of countries now use a comparatively higher proportion of GOG pricing.

Figure 4: Number of Countries by Price Formation

This figure is from the International Gas Union (IGU) Wholesale Price Survey (2020). This figure illustrates how more countries are straying away from oil price indexation (OPE) as a pricing mechanism and adopting gas-on-gas (GOG) instead.



Source: (IGU, 2020). *https://www.cmegroup.com/education/articles-and-reports/is-oil-indexation-still-relevant-for-pricing-natural-gas.html*.

The strongest supposition is the substitutability principle. Contractual OI efficiency requires a long-term relationship between crude and NG prices. Without a strong relationship, a hub-based pricing mechanism would more closely reflect NG market fundamentals. Prices would also be able to respond more quickly to gas market specific changes and disruptions. Academics have proposed a wide variety of methods for determining the strength of the oil-gas relationship. Widely proposed methods include:

- Cointegration;
- Ordinary least squares (OLS) and simple regression;
- Vector auto regressive (VAR);
- Generalized auto-regressive conditional heteroskedasticity (GARCH);
- Time-series smoothing models; and
- Various alternative approaches.

Each of these methods presumes a time-series relationship between NG and oil prices, consistent with the long-run nature of contracts. Each method also presents a different framework for how the long-run pricing relationship is formed. As these methods all have their own set of characteristic benefits and drawbacks, it is impractical to consider which is optimal. Nonetheless, the most widely used methodology is cointegration.

4.2 COINTEGRATION MODELS

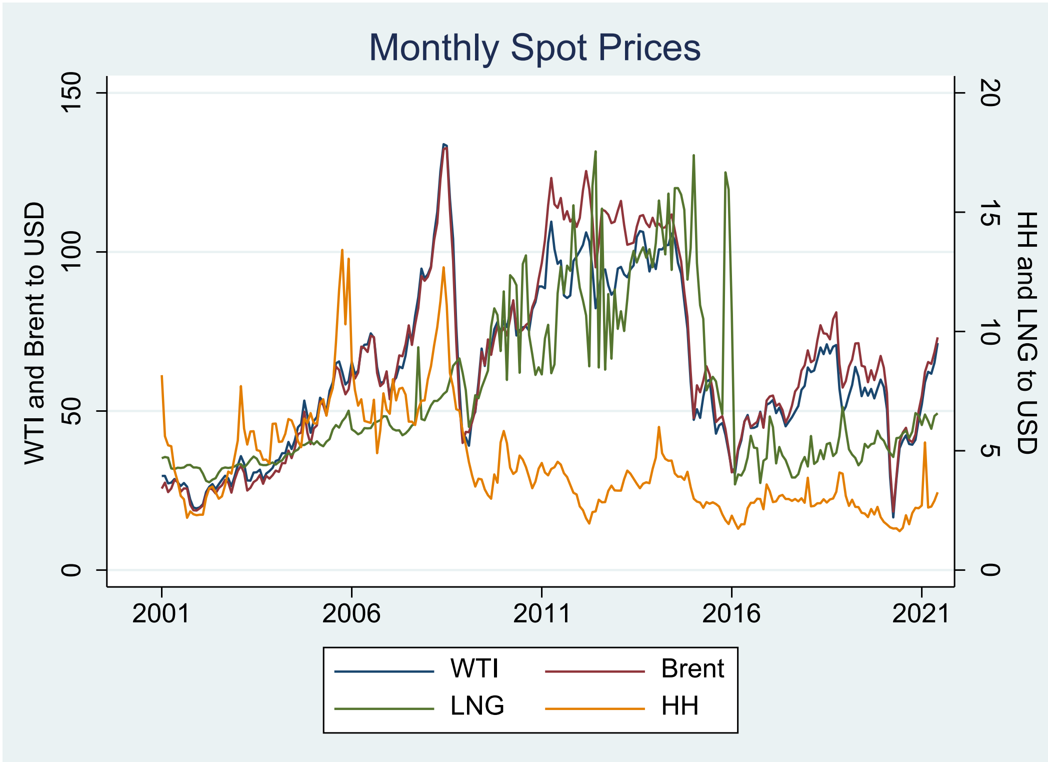
4.2.1 WHAT IS COINTEGRATION?

Cointegration techniques test for long-run correlating relationships between time series processes. Prior to cointegration, researchers relied upon linear regressions and detrending techniques. These methods were prone to finding spurious correlations, leading to misleading statistical results. In 1987, economists Robert F. Engle and Clive Granger formalized the multiple cointegrating vector approach. While several advancements have been made since, their approach still provides the foundation for numerous contemporary works. This includes a significant portion of energy market research.

Most macroeconomic data are non-stationary, meaning they exhibit stochastic trends and drifts over time. Non-stationary variables are therefore 'unstable', making long-term characteristics difficult to define. To aid in interpretation, economists often convert such variables into stable 'stationary' forms by differencing the data into higher orders. For example, first differenced data is referred to as $I(1)$. Twice differenced is $I(2)$. Generally, differencing is conducted until the data is stationary where the mean, variance, and autocorrelation does not change over time.

Figure 5: Monthly Spot Prices

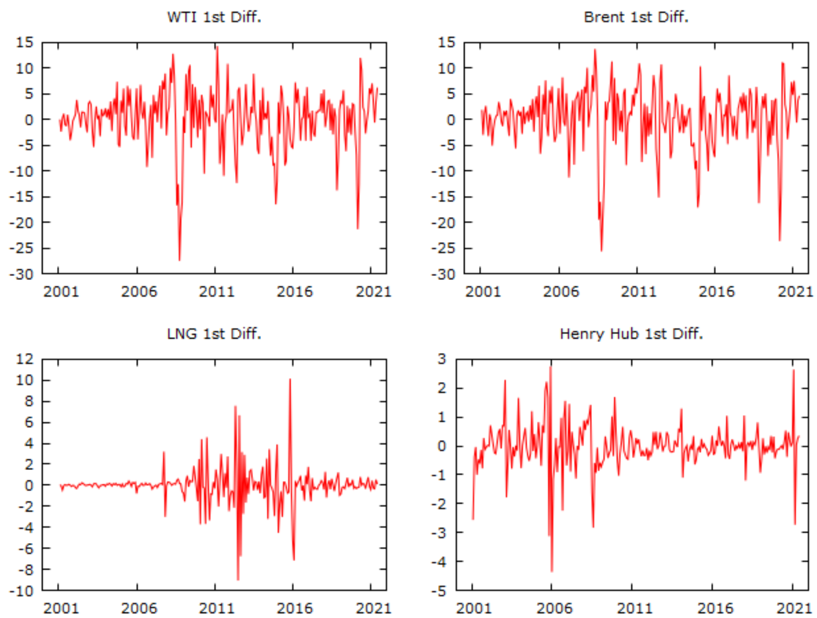
This figure plots the monthly spot prices for WTI, Brent, LNG, and Henry Hub NG over 2001 to 2021. WTI and Brent are plotted on the left-hand axis and LNG and Henry Hub NG are plotted on the right-hand axis.



Trend features for West Texas Intermediate (WTI) crude oil, Brent crude oil, Henry Hub (HH) NG, and LNG export prices are presented as levels in Figure 6, and first-differenced (*I(1)*) in Figure 7. All price level series are of order $I(1)$, reflecting that they are stationary when first differenced. When two non-stationary variables are stationary of the same order, meaning they can be made stationary by differencing an equal number of times, they are considered integrated. Specifically, we find that both WTI and LNG prices are $I(1)$, meaning a cointegrating relationship can be estimated.

Figure 6: Time Series Plots of First Differentials

This figure plots the first-differenced prices for WTI, Brent, LNG, and Henry Hub NG over 2001 to 2021.



Cointegration exploits this statistical relationship by creating a linear combination of the differenced series. This combination essentially 'cancels out' their individual stochastic elements, leaving only their shared long-run trends. When this occurs, the two variables are referred to as being cointegrated. Commonly, there are three tests to confirm the presence of a cointegrating relationship:

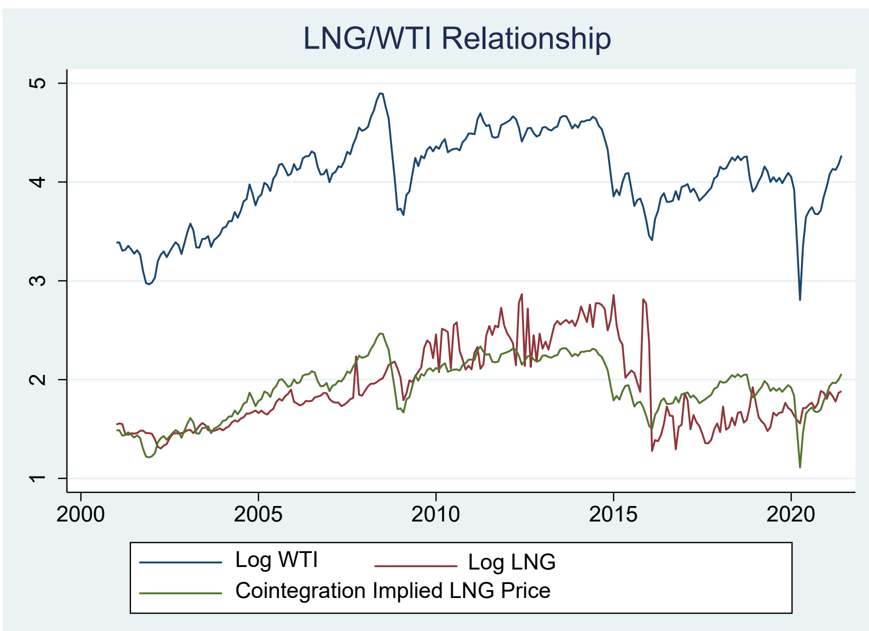
1. Engle-Granger Two Step Method (Engle and Granger, 1987): This method tests the residuals generated from a regression for the presence of stationarity (i.e., unit roots). If the two non-stationary time series are cointegrated, then cointegration is confirmed by the residuals being stationary. This test has some limitations. For example, if there are two or more non-stationary variables then the method will reflect two or more cointegrated relationships. Nonetheless, this method continues to be the most widely employed.
2. Johansen Trace Test (Johansen, 1991): Often used for testing cointegration between three or more time-series simultaneously. It overcomes the single relationship limitation of the Engle-Granger method by declining to make one of the series a dependent variable. Instead, the Trace Test opts for a vector approach. However, the test requires a large sample size to avoid false positive results. The Johansen test takes two common forms of a Trace test and Maximum Eigenvalue test and is often used in conjunction with the Engle-Granger tests to provide greater context.

3. Phillips-Ouliaris Test (Phillips and Ouliaris, 1990): A set of statistical tests with different assumptions, formulations, critical values, and implications. Although it is referred to as a single test, formally it consists of four distinct tests. Two are similar to the Engle-Granger test, using a Phillips & Perron-like approach. The other two use variance-ratio approaches. The test is a residual-based unit root test, looking for stability in the long-run equation residuals. When there is no cointegration the tests stabilize and when there is cointegration, they diverge. Resultant asymptotic residual distributions are known as Phillips-Ouliaris distributions. While a main method of determining cointegration, the Phillips-Ouliaris test is quite uncommon to the literature.

We apply the Engle-Granger and Johansen tests to LNG and WTI data from January 2001 to June 2021. Figure 8 shows a plot of each log price series, as well as the implied price of LNG given the long-run cointegration relationship with WTI.

Figure 7: Log LNG, Log WTI, and Cointegrating Relationship

This figure illustrates the log price series from 2001 to 2021 for WTI and LNG, as well as the implied price of LNG given the long-run cointegration relationship with WTI.



4.2.2 VECTOR ERROR CORRECTION MODELS (VECM)

Essentially, a cointegrating path is the mean long-run relationship left after filtering out the cyclical components and short-run deviations. This implies that although short-run deviations may occur, there always tends to be a reversal to the mean relationship. The short-run corrections back to the mean (i.e., mean reversion), known as an adjustment path, is of considerable importance to practitioners and researchers alike. Vector Error Correction Models (VECM or ECM) estimate the adjustment path by representing each series deviations in an auto-regressive vector form. Within the literature, VECM estimation often follows once a cointegrating relationship is confirmed and estimated.

4.2.3 THE EARLY GAS-OIL RELATIONSHIP

Due to the scarcity of LNG specific research and its' synonymous consideration with NG, it is necessary to address the prevailing literature across all NG prices. The authors Brown and Yücel provide seminal studies of the cointegrating relationships between oil and NG prices. They also interchangeably utilize the terminology. Brown and Yücel (2008), their most widely cited study, examines weekly HH and WTI prices from June 1997 through June 2007. Additionally, they include heating and cooling degree days to account for demand changes due to weather and seasonality, gas storage to account for supply constraints, and a series of control variables in the cointegrating equation. They find strong evidence of oil and NG cointegration, both with and without the use of control variables. Further, the relationships causality implies that oil is the determining factor of NG prices, and not vice-versa. ECM results indicate that deviations from the long-run path are corrected at a rate of 6% to 12% per week, with 90% adjustment occurring within 12 weeks.

Brown and Yücel (2009), expand their work to include European markets. They find evidence that the NBP and Brent crude prices are cointegrated. Integrated relationships are also found between HH and NBP prices, suggesting that North American and European markets are integrated. Price determination is shown to run from North America to Europe, with WTI being the driving factor of both HH and NBP. Additionally, HH prices are a determining factor of NBP, with mean adjustment occurring at 4.8% to 14.1% per week, respectively. Conversely, Brent exhibits no such causal relationship on HH prices. They also find strong evidence of Cross-Atlantic GOG arbitrage opportunities, such that coordination of NG prices could be facilitated through movements with crude-oil prices.

The early literature evidence points to a strong cointegrating relationship between NG and crude oil prices, which widely holds throughout the 1980s, 1990s, and early 2000s. However, the exact reasons for the relationship's strength are widely debated.

Yucel and Guo (1994) provide one of the earliest cointegration studies, finding North American oil and NG prices to be strongly integrated over the years 1975-1990. They suggest this is mainly due to the perceived substitutability of gas and oil in energy markets.

Asche et al. (2006) find evidence of energy price cointegration within the U.K. market during the years of 1995-1998. This period exhibited heavy deregulation. After the opening of the Interconnector in 1998, the U.K. market became integrated with global oil prices. In each case, oil prices were the leading factor for NG price determination. In addition, they conclude that changes in regulatory structures and capacity constraints can make prices appear to be more or less cointegrated. These results are broadly supported by the work of Panagiotidis and Rutledge (2007).

Bachmeier and Griffin (2006) come to similar conclusions for U.S. regional markets. Using daily prices, they find HH and WTI prices to be strongly integrated in the long-run and suggesting strong evidence of market integration. They find global oil prices to be integrated as well, with WTI being a leading factor across four global oil markets of Brent, ANS, Dubai, and Arun (Indonesia). Their results show that oil price shocks quickly reverberate around the world while NG prices, although integrated, respond much slower. Serletis and Herbert (1999) show the North American market NG integration extends to NYMEX fuel oil. However, the integration was strongest in U.S. North American Electric Reliability Council (NERC) regions where fuel-switching capability was greater (Hartley et al., 2008).

Villar and Joutz (2006) support the presence of a significant and stable long-run cointegrating relationship between the WTI and HH when using a time trend. Although they find evidence of short periods of price decoupling, the adjustment speed parameter is 0.19, indicating 19% of the difference is recovered in the following period. Further, the effect of oil prices on NG demand is dominant in the short-run with every 10% increase in oil prices leading to a 2.6% increase in NG price. They conclude that short-run supply and demand factors are the driving force for cross-commodity price changes.

Presumably, technological changes also played a role in the early formation of integrated relationships. Hartley et al. (2008) show the emergence of combined cycle NG power plant reduced costs, increasing the demand for NG. They determine that technological factors explain the trend (drift) in the long-run gas-oil relationship. Therefore, disequilibria in long-run gas-oil prices were driven not only by random shocks to the international crude oil market but also technological factors influencing the relationships drift. Variables such as weather, inventories, and seasonal factors had, and continue to have, significant influence on short-run price adjustment dynamics, with extended periods counteracting adjustment back to long-run equilibrium.

4.2.4 DATING THE STRUCTURAL BREAK

Even in the early literature, evidence was building that the strong relationship between NG and oil prices was beginning to decay. Serletis and Rangel-Ruiz (2004) examine the impact of a series of North American regulatory changes on HH and WTI prices using daily data from January 1991 to April 2001. Particularly, they focus upon the U.S. Natural Gas Policy Act of 1978, Natural Gas Decontrol Act of 1989, FERC Orders 486 and 636, the Free Trade Agreement (FTA) of 1988, and the North American Free Trade Agreement (NAFTA) signed in 1993. These policies fundamentally changed the environment of the North American energy industry by promoting efficiency through deregulation. Their analysis finds that although a common oil-gas nexus could not be rejected, the strength of the relationship had significantly weakened in post-policy periods of deregulation.

It is important to note that energy price decoupling was reasonably unexpected, both regionally and globally. Using the cointegrating relationship from 1989-2005, Ghouri (2006) predicted regional gas and oil prices would continue to be linked in the long-run. He suggested the linkages were primarily due to gas trade contract price formulas being oil based. Further, he forecasted that limited gas production and growing demand would push prices higher. The highest prices were expected to be in Asia Pacific regions, such as Japan and Korea, where long-distance transportation would cause increased trade frictions.

While technological advancement, gas infrastructure development, and deregulation were clearly factors driving decoupling, it was seemingly that shale had the greatest impact. Asche et al. (2012)

was one of the earliest papers to consider the shale impact. Although they find evidence of a stable long-run oil-gas relationship, their Chow test results do not find evidence of a structural break. However, the model employed is not robust and the data is quite limited, ending in 2010. In all likelihood, such a sample would not have ample observations to statistically find post-shale changes; an issue they themselves note when discussing significant future supply changes stemming from increasing U.S. production.

Erdos (2012) expands upon the work of Brown and Yücel (2009) by testing the regional and global gas-to-gas and oil-to-gas relationships. He considers changes in NBP, WTI, and HH equilibrium relationship over time, by restricting subsamples and re-estimating the relationship. Controls for exogenous demand and supply shocks are additionally included in the vector error correction model. Interestingly, his results for the 1997 to 2008 period find strong short- and long-term integration, aligning with findings of previous authors. He attributes this to higher U.S. prices attracting LNG exports to the U.S. on a netback basis, lowering the potential supply in Europe thereby triggering cross-Atlantic price adjustment and integration. Atlantic arbitrage flows from the U.S. to Europe, due to shale oversupply, should have led to a stable price relationship of relatively lower U.S. gas prices. However, this arbitrage did not 'work' due to a lack of liquefying and export capacity in the U.S. Therefore, North American gas prices decoupled from their global counterparts in Europe and Asia around 2009.

The overwhelming consensus of the literature is that 'shale gas revolution' occurred between 2008 and 2009. Caporin and Fontini (2017) specifically test for the presence of structural breaks in the cointegrating equation. They utilize an expanded dataset from 1997 to 2013, which results in two major implications. First, they show HH and WTI prices to be non-stationary. As stationarity is a pre-requisite of a cointegrating relationship, this result suggests an end to linearly related prices. Secondly, although initial Perron tests find changes in the oil-gas relationship around 2007, with the impact of oil prices on gas prices more than doubling. They attribute such inter-period effects to transitory factors including market anticipation, tight oil production, and delayed global market impacts. Most importantly, they cease to find a long-run relationship from 2009 onward and refrain from making generalized claims due to the shortness of the monthly post-2009 subsample. Additional vector error correction research by Lin and Li (2015) offers additional support.

4.3 ALTERNATIVE MODEL EVIDENCE

A number of authors have investigated the decoupling result using a variety of alternative (non-cointegration) models. Geng, Ji, and Fan (2016a) analyze the impact of the shale gas revolution using a Markov switching model, showing that HH prices decoupled from oil after 2008. They suggest that a relative lack of LNG infrastructure limited early NG exports from North America, while in the future large quantities of North American shale gas were apt to be exported to other countries. Additionally, they believe the European gas market to be vulnerable to external supply shocks due to its heavy reliance on imported gas.

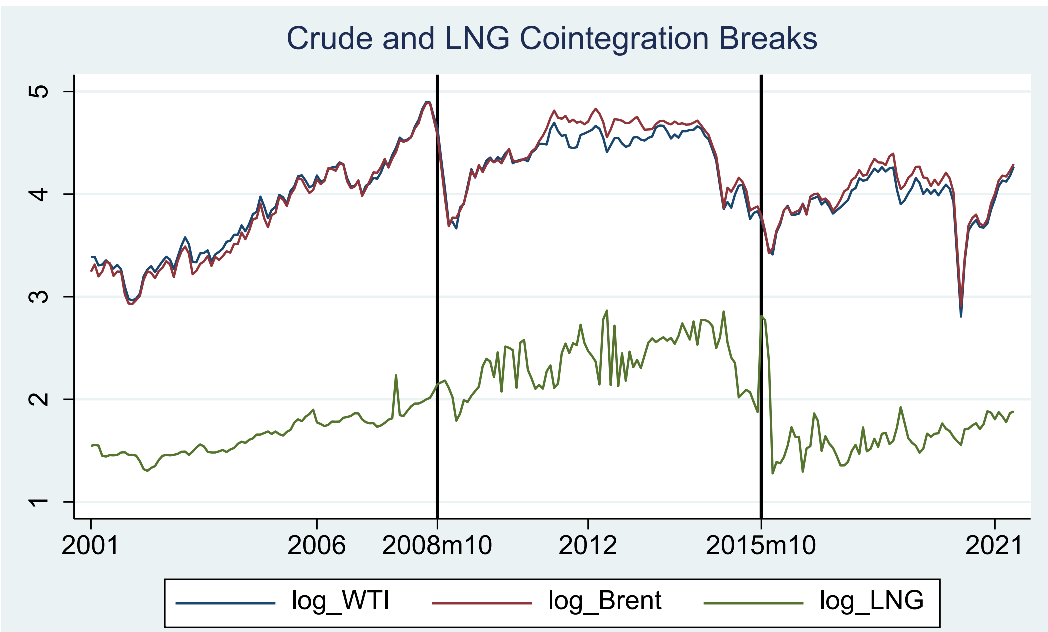
Wakamatsu and Aruga (2013) estimate the impact of shale on the Japanese NG market. Using a Bai-Perron test, they find two structural breaks in the Japanese market to have occurred in 2005 and 2009. The first break is attributed to gas consumption changes, while the second break is due to price and income shocks. Market impacts are also estimated using a vector auto regressive (VAR) impulse response model. VAR results show a one-sided influence of gas prices from the United States toward Japan prior to 2005, after which the influence ceases.

Aruga (2016) extends Wakamatsu and Aruga (2013) to include shale impacts across both Japanese and European markets. These findings are qualitatively similar, with a key difference of determining the break date to have been in August 2006. Again, U.S. NG prices are shown to decouple and no longer influence international markets.

Similar results are found across a variety of other models including long-memory ordinary least squares (Zhang & Ji, 2018), Philips-Sul and Kalman Filters (Li et al., 2014), multi-variate threshold testing (Potts & Yerger, 2016), and global multi-sector general equilibrium models (Arora & Cai, 2014). Considered together, the North American shale revolution is the primary factor for U.S. LNG and NG prices decoupling from global oil prices. At the same time, global NG prices have not yet fully decoupled from global oil. While there is minor variation in the exact date by region, the North American break is strongly suggested to have occurred in late 2008/early 2009 while global breaks, when present, range between 2005-2009.

Two key empirical issues prevail throughout much of the literature. First, there is a shortage of recent evidence utilizing updated data. Most gas research, especially the most highly cited research, uses data from the 1990s or 2000s. Second, empirical examinations predominantly consider only the NG to oil relationship and not the specific LNG to oil relationship. We briefly address this by employing a Gregory-Hansen structural break test on the Engle-Granger cointegrating relationship between LNG and WTI prices. We also utilize the most current data (January 2001 to June 2021) taken from EIA. In the following figure, we show the structural break in the LNG-WTI cointegrating relationship to occur in August 2008. For LNG-Brent the break date is October 2015. Across both crude to LNG relationships, all test statistics conclude a strong cointegrating relationship prior to the break date and no relationship after. Although these results are from a simplified model and require significant further examination, they fall well within the generalized findings of the literature.

Figure 8: Crude Oil and LNG Cointegrating Relationship Break Tests



Gregory-Hansen test break dates in the cointegrating relationships,after which they are no longer related.
WTI and LNG break: August 2008
Brent and LNG: October 2015

4.4 CONVERGENCE TOWARD A NO-ARBITRAGE RELATIONSHIP?

Natural gas has become a key fossil fuel for power, industrial, and residential sectors. Natural gas demand has also seen an increase in all regions of the world. Such trends have not only created upward pressure on prices, but also triggered competition between formerly segmented regions.

Traditionally, pipeline NG has supplied nearby regional markets, which have historically had their own supply-demand balances, contractual structures, and gas price formation mechanisms. Historical price series analysis suggests that both inter-market and inter-hub price differentials have created opportunities for LNG arbitrage. The growth of LNG supply to regional markets, and improved destination flexibility from hub development, have increased LNG trade to the point of playing an important role in interconnecting markets.

Historically, LNG prices have been indexed to crude oil. The plethora of cointegration literature has measured whether LNG and crude oil markets were linked, a signal for arbitrage. Overall, the cointegration research has found that early gas-oil relationships were strong and arbitraged, while after the shale revolution, such relationships waned. Similar results have been found for regional oil markets as well (Kleit, 2001).

A separate literature has examined whether regional gas markets are linked and arbitraged across regions. While early cointegration methods were able to estimate whether long-run relationships existed, the methodology had not developed enough to estimate the strength of the relationship. Therefore, early papers modeled the speed and degree of convergence using a variety of time series filters. King and Cuc (1996) apply a Kalman Filter to analyze price convergence in North American NG markets. Their results suggested that regional gas markets were not only becoming increasingly connected, but also that regional market price convergence was becoming stronger. Increasing convergence was particularly occurring within larger North American regions, with an 'east-west' split characterized by western basins being more strongly linked with each other than eastern ones. They attribute the growing convergence to the development of pipelines and interconnectors driven by price deregulation.

Not long after North America experienced major changes to HH integration, international NG markets went through similarly substantial periods of deregulation and infrastructure during the early 2000s. Neumann (2008) examines the integration between U.K. NBP, Zeebrugge, and HH pricing. The authors argue that the U.K. followed a similar path to the U.S., with a delay of around half a decade. For example, in 1986 the U.K. ended the British gas monopoly, opening competition and a truly competitive European gas market. Although trailing behind, continental Europe similarly opened market competition with the EU Acceleration Directive and the Dutch TTF hub. The newly restructured global LNG market featured a high proportion of spot trading and generally shorter contracts. Using the Kalman Filter methodology, he finds evidence of convergence to the law of one price, independent of fuel oil prices. The strength of the convergence is shown to be increasing over time, and to be seasonally stronger in winter months. Further, cross Atlantic LNG arbitrage, in response to short-term supply and demand imbalance, is theorized to be the driving force behind the convergence.

Neumann and Cullmann (2012) continue this line of research, testing for convergence across 26 European hub pairs. Interestingly, within region convergence is found in only 12 of the pairs. They speculate that introducing spread contracts and reducing the number of European market areas would 'harmonize' services, providing control over short-term trade incumbents and pricing structures. Importantly, they note that capacity allocation and congestion management mechanisms would have to be efficiently managed for such benefits to take place. Considering events surrounding recent European NG crises, additional investigations are needed to see if such conclusions hold.

A key drawback of the Kalman Filter methodology is that it 'smooths out' long-term relationships between prices. Therefore, it omits potential for discrete changes, such as global events, which structurally change the prior relationship. Additionally, Kalman Filter research tends to come from earlier decades. While contemporary works occasionally employ filter methods, more often than not it is to contextualize the results of more robust methodologies. Many newer methodologies not only allow for structural breaks, but also incorporate robust time-variant dynamics such as asymmetric positive and negative responses, regime shifts, and non-linearity.

Agerton (2017) examines the convergence of gas prices across 16 global import-export pairs, allowing for structural breaks in the equation. Although a co-integration framework is employed, the allowance of multiple in-model structural breaks circumvents the issue of not being able to examine convergent relationship magnitudes. He finds that although LNG prices appear strongly oil-linked, LNG-oil relationships are asymmetric within importing countries. Moreover, structural breaks are found to be quite common in Asian markets, occurring in two out of four Korean series and both of the two Taiwanese series, due to heterogeneous portfolios of long-term contracts. However, there are fewer breaks per relationship as only one (South Korea-Indonesia) has more than a single break. While import-export prices would be expected to normally correspond to single contracts, changes to portfolios that include large numbers of contracts are shown to induce structural breaks. It is unsurprising that global markets exhibit such changes as contract terms have become more flexible over time (Hartley, 2015; Ikkonikova et al., 2009). While increased flexibility is not new to global markets, Asian markets have featured relatively more contract pricing changes. The analysis finds that Japan has had the most contract term revisions, followed by South Korea, Spain, Malaysia, and Taiwan. A mismatch of LNG pricing is also found following the mid-2000s, due to tightening of LNG markets. While a variety of region-specific convergence breaks exists, two periods stand out. The first is 2008-2009, where a cluster of structural breaks corresponds to oil price volatility and the global financial crisis. The second is the Fukushima disaster of 2011, where Japanese LNG import prices markedly increased in response. However, the LNG-oil relationship did not respond, consistent with long-term contracts providing a form of insurance against unexpected energy shocks. Interestingly, after 2011 fewer structural breaks are found. In general, Asian markets have been less prone to convergence than their global counterparts have, likely due to the continuing ubiquity of long-term oil-linked contracts.

There is some dissent to the global convergence argument. Ritz (2014) builds a theoretical model of LNG market arbitrage. He finds that price differentials arise due to exporter market power. He concludes that this assures that global LNG prices will never converge, even after considering transportation costs. However, no corresponding empirical examination is provided to support the model results. However, his work highlights the importance of contextualizing convergence trends under prevailing production and transportation infrastructure factors.

Oglend et al. (2016) and Oglend et al. (2020) concur that transportation costs provide a missing link to determining price convergence. Using a more recent sample, these studies find that shipping costs are endogenous to regional LNG price spreads. However, they also find initial evidence of increasing price spreads, a hallmark of divergence, once capacity and transport limitations are included the spreads become negligible.

Convergence has been found to be increasing between city-gate and residential prices as well. Using a sample of 50 U.S. state level data from 1989 to 2007, Arano and Velikova (2009) find evidence that residential and city-gate prices were increasingly cointegrated, implying that various industry segments have moved toward a long-run competitive equilibrium over the last few decades. They argue that increasing retail unbundling, market liberalization, and customer choice have provided benefits both down the supply chain and to residential customers.

Overall, the global LNG price convergence has been found to be increasing. However, it must be noted that this conclusion is highly heterogeneous across region, import export pairs, and subsample analysis. The more recent and dynamic models, which take into account key trade frictions and regional pricing determinants, ostensibly agree on the presence of a general trend toward long-run LNG market convergence. However, Bastianin et al. (2019) suggests this may be limited to price-growth convergence as opposed to price-level convergence. Bastianin et al.'s results additionally predict an inevitable tightening of cross-country LNG prices. Particularly due to existence of trading hubs and rising degree of interconnection.

Improved convergence implies benefits for both consumers and producers. The ability for consumers to access energy at the lowest prices while producers obtain the best prices, regardless of their respective locations, improves overall market welfare. Increasing price integration also implies that the markets have become more competitive due to a growing number of participants. As a result, the potential for a few players to dominate the market is reduced. However, regional variation and corresponding arbitrage opportunities remain across regional markets. Conversely, within-region long-run price convergence has become increasingly omnipresent.

It is unclear if or for how long such convergence will last, especially when considering regional price differences. The previous literature has shown structural changes can often occur quickly and for a wide variety of reasons. Contracts, infrastructural development, transportation advances, and changing regulatory settings have all shown to be important factors of both long and short-run price relationships. If anything, the prevailing literature emphasizes the need for timely and informed analysis to provide a robust picture of current global LNG market.

5. CONCLUSION

TBD

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