The Evolution of Natural Gas Market Integration: From Regional Segmentation to Global Interconnectedness. Insights from a Literature Review.

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Abstract

This article provides a review of academic studies on natural gas market integration, tracing the shift from regional segmentation to global interconnectedness. It explores the roles of market liberalization, infrastructure development, and liquefied natural gas (LNG) trade growth in transforming the global gas landscape. By analyzing key methodological approaches, the review highlights the progression of integration in European, North American, and Asian markets. The findings underscore the increasing interconnectedness of gas markets, the challenges of achieving full global integration, and the implications for pricing, investment, and energy security.

Keywords: Gas market integration; Gas trading; LNG; European gas markets; cointegration.

JEL Classification: Q40; L95; G12; L16

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1. Introduction

The gas crisis in 2022 demonstrated that developments in gas markets in one region could significantly impact price dynamics in other parts of the world, highlighting the importance of understanding the factors driving market integration and its consequences. This trend has been driven by a combination of factors, including regulatory changes, technological progress, and the growth of liquefied natural gas (LNG) trade. The transformation of regional gas markets into an increasingly interconnected global system has profound implications for pricing mechanisms, investment decisions, and energy security.

Given these dynamic shifts, the question arises as to how this transformation is reflected in academic research and what insights scientific studies on gas market integration provide. This article aims to provide a review of the academic literature on gas market integration, spanning the period from 1994 to 2024. By analyzing studies over such an extended period, we seek to track the evolution of research approaches, identify key milestones, and capture trends in the process of gas market integration developing at the price level in the context of the law of one price. The application of various econometric techniques enables capturing the dynamics of integration processes and deriving conclusions about the factors influencing them. The reviewed studies explore developments in regional markets, the emergence of global interconnections, the impact of LNG trade, and the role of financial markets in shaping an integrated environment for natural gas trading.

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The main objective of the presented study was to identify the key methodological approaches used in the scientific literature while examining the historical development of integration processes from the liberalization of markets in the 1980s and 1990s to the present day. By emphasizing a chronological perspective, we aim to track the gradual evolution of gas market integration and identify the factors that shaped it in different periods. This approach also provides insight into the development of research tools and analytical techniques applied to this issue. Each part of this review concludes with a brief summary of the main findings, allowing the reader to quickly orient themselves to the key discoveries and their implications for the functioning of natural gas markets.

The chronological and holistic approach chosen in this literature review offers several benefits. First, it allows for mapping the development of market integration research over time, identifying turning points, and understanding the transformations in scholarly perspectives and approaches. Second, it can provide a complete picture of the various dimensions of integration processes, starting from regional dynamics and ending with emerging interconnections at the global level. Finally, by identifying key methodological approaches and the most influential articles, this review helps readers navigate the field of gas market integration research and offers a solid foundation for further scholarly work.

This article contributes to the existing literature on gas market integration in several ways. It provides an up-to-date overview of the state of knowledge in this sphere over the past three decades, identifies the main trends, milestones, and factors shaping integration processes, and summarizes the applied methodological approaches and findings. Moreover, it contributes to the discussion on the impacts of gas market liberalization in the EU and the growing role of LNG in market integration while synthesizing key common findings in the overall body of market integration research.

This analysis aims to contribute to a deeper understanding of the dynamics driving the integration of natural gas markets at both European and global levels. Its conclusions can benefit researchers seeking to develop the topics and market participants looking for solid starting points to understand the topic.

The following sections of the article address consecutively the key themes emerging from the extensive literature review. First, we present an examination of the development of integration processes at the regional level in Europe, North America, and Asia, gradually transitioning to an analysis of the formation of global gas markets convergence and the role of LNG in this process. This is followed by identifying key methodological and econometric approaches used in gas market integration research. Each subchapter concludes by summarizing the contributions of the given area to the overall understanding. The final section concludes with a summary of the main findings.

2. Methodological framework

To ensure a systematic review, articles were selected based on a search of relevant academic databases (Scopus, Web of Science, JSTOR, Google Scholar) using specific keywords.

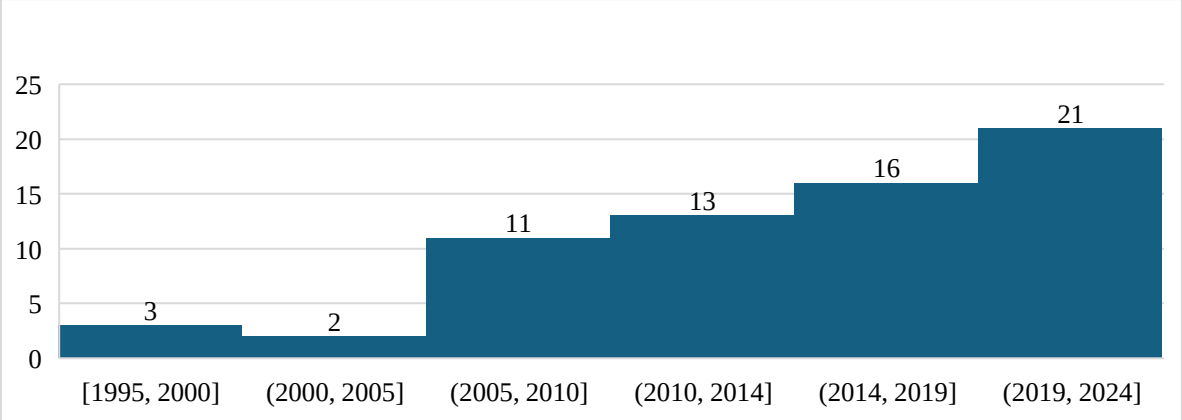
Table 1. Keyword occurrence: a cross-database analysis

Keywords / Database	gas market integration	natural gas markets	gas price convergence	gas market liberalization	LNG trade	gas price dynamics
Scopus	22	1720	3	87	343	13
Web of Science	15	389	3	25	107	10
JSTOR	58	1140	14	44	374	25
Google Scholar	792	16300	108	980	5380	434

Source: Author

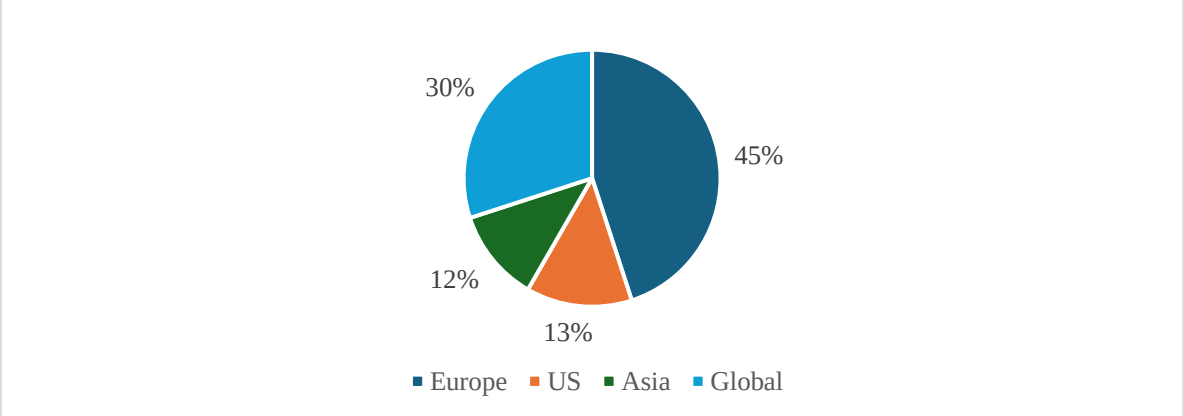
A combination of primary keywords ("gas market integration," "natural gas markets," "gas price convergence," "gas market liberalization," "LNG trade," and "gas price dynamics") and secondary keywords ("cointegration," "vector error correction model," "econometric analysis," "law of one price," "market deregulation," "spot markets," "long-term contracts") were used to capture a relevant body of literature and to refine the search results. ***Table 1*** presents the findings of the initial search.

Figure 1. Trend of published papers over five-year intervals



Source: Author

Figure 2. Regional focus of reviewed papers on integration



Source: Author

The screening and selection process involved an initial screening based on titles and abstracts, then a thorough full-text review, and a final selection of more than 60 key studies based on thematic relevance, methodological framework, and geographical coverage. ***Figure 1*** presents the number of selected articles by year of publication, which shows that the last ten years are the most reviewed period. It is worth noting that the author's professional experience in the field of energy markets provided an additional perspective during the selection process. This expertise, grounded in an understanding of the subject matter, enabled the identification of the most impactful and methodologically sound studies. Consequently, the selected studies were systematically grouped by regions given their distinctive experience with market liberalization (US, EU, and Asia) and to trace the evolution of research approaches and thematic focus over time, and were further categorized thematically (regional focus, global market integration, and LNG, methodological advances) to facilitate a structured analysis of the literature. ***Figure 2*** presents the frequency of the reviewed studies by the regional focus, showing that the studies on the EU gas market integration and the global gas market integration were the major focus in this review.

Additionally, the bibliographies of the key identified studies were also examined to label the most frequently cited sources. This procedure helped to identify studies that noticeably influenced the direction of research and shaped the professional discussion on gas market integration (such as papers by Asche et al. from 2001, 2002, 2009, 2013 or Heather from 2012, 2015). Furthermore, this article expands on the analysis by Hupka et al. (2023), focused on the role of LNG in market integration and price formation, and extends the work of Dukhanina and Massol (2018) by specifically focusing on the historical context of regional and global integration of gas markets. As a result, it provides an updated perspective enriched with the latest findings and trends in this research area.

3. Spatial integration of the gas markets

3.1 Integration of the European gas markets

The evolution of the European gas market integration from regional segmentation to global interconnectedness has been the subject of significant academic research. The process of forming a single integrated European gas market, driven by a series of EU energy packages aimed at liberalizing national markets and promoting cross-border trade, is a necessary prerequisite for effective integration and a shift away from oil-indexed gas pricing.

The first major studies that dealt with price relationships and the integration of European gas markets came from Asche et al. (2001, 2002). Their studies on French and German gas imports provided evidence of market integration, particularly among countries interconnected by pipeline infrastructure. These works were instrumental in introducing cointegration techniques to the analysis of the natural gas market and paved the way for further research. Another notable contribution to the examination of European gas market integration was the study by Neumann et al. (2006), which pointed to a trend towards price convergence between NBP and Zeebrugge, especially after the construction of the pipeline connecting the United Kingdom and Belgium. The historical perspective on the early stage of European gas market integration is also addressed in Robinson (2007), who examined gas price convergence in six EU member states in the period before market liberalization. However, the results were ambiguous, and while there were indications of convergence, it was not uniform across all the countries studied. Neumann and Cullmann (2012) provided empirical evidence of varying degrees of interconnectedness between emerging spot markets in the EU between 2009 and 2011. Of 28

possible hub pairs, only 12 exhibited integrations, with the highest degree of integration between TTF and PEG North and the lowest between TTF and Zeebrugge.

With the development of the European gas market, the evolution of gas trading hubs has become a key factor supporting integration. Heather (2012, 2015, 2019, 2023,2024) provided extensive analyses of the development of European virtual trading points, offering a detailed look at the changing dynamics of gas trading in Europe and the interconnectedness between hubs. Heather (2015) examined the development and transformation of European hubs over the previous decade. Heather used quantitative metrics and qualitative indicators to assess the maturity and functioning of various hubs. It can be stated that this is one of the most comprehensive studies capturing the development of the EU gas markets. The study identified several key factors that contribute to the development of hubs, including regulatory support, physical interconnectivity, and the presence of multiple market participants. Heather's follow-up study from 2023 examined the performance of European hubs in 2022, with a particular focus on TTF, which evolved into the most liquid market in Europe and a global benchmark for the European region. In Heather (2024) it was pointed out that markets at the main hubs returned to the correlations and convergences they had before the turbulent year 2022, albeit with some exceptions.

The works of Heather and Petrovich (2017) and Heather (2012, 2015, 2019, 2023) are particularly valuable for their methodological approach to assessing market development. By considering multiple factors beyond price relationships alone, these studies provide a more holistic view of market integration. These works, along with Asche et al. (2001, 2002, 2012, 2017), Asche, Misund, et al. (2013), and Asche, Oglend et al. (2013), are among the most cited in the field of price and market integration in the EU analysis.

As methodological approaches became more sophisticated, researchers were able to capture increasingly precise aspects of European gas market integration. Garaffa et al. (2019), Bastianin et al. (2019), Jotanovic and D'Ecclesia (2021), Schultz and Swieringa (2013), Szafranek et al. (2023), and Ribeiro et al. (2023) are examples of this trend. Schultz and Swieringa (2013) focus on price discovery processes and short-term and long-term price dynamics between physical hubs and financial futures markets in northwestern Europe. The development of European gas market integration and price convergence over a longer time horizon is addressed by Bastianin et al. (2019). The authors focused on industrial consumers in fourteen European countries from 1991 to 2017. The findings regarding the convergence of price pairs (markets) suggest that European natural gas markets have become increasingly integrated. The study also found that countries with developed gas infrastructure (including mature markets, transport capacities, and LNG terminals) exhibited faster reductions in price differentials. The question of natural gas price convergence in Europe and the identification of a reference virtual trading point is the subject of a study by Jotanović and D'Ecclesia (2021). The study covered the development of natural gas prices from 2007 to 2017 across various virtual trading points (VTPs). The results revealed significant correlations between hubs, indicating a high level of integration. Convergencies were more pronounced among established markets such as NBP, TTF, and ZEE, reflecting their higher liquidity and market activity. However, southern and central European hubs exhibited lower correlations, indicating a lower level of integration with the rest of Europe. Cointegration analysis confirmed the presence of a long-term equilibrium relationship between the main European hubs. Granger causality tests identified the Dutch TTF as the leading trading point, influencing prices in other markets. However, Broadstock et al. (2020) point to the ongoing and evolving nature of the NW EU gas markets integration, applying rolling window spillover analysis.

The impact of exogenous shocks on the integration of the European gas market and risk transmission is another important aspect explored in recent studies. Chen et al. (2022) analyzed the effects of the COVID-19 pandemic using a quantile connectedness approach, which allows the authors to capture the dynamic and asymmetric nature of market integration and risk transmission in the European gas futures market, especially during periods of extreme stress. Szafranek and Rubaszek (2023) investigated the resilience of the European natural gas market interconnectedness to exceptional shocks, such as the Russian invasion of Ukraine. The study utilizes advanced econometric techniques, including a time-varying parameter vector autoregressive model with stochastic volatility (TVP-VAR-SV), to capture the dynamic relationships and volatility between spot prices (day-ahead) and forward prices (month-ahead) of major European hubs (NBP, TTF, THE, and PSV) in the period around the Russian invasion of Ukraine. The authors also employ the Diebold-Yilmaz (DY) spillover index and Baruník-Křehlík (BK) frequency decomposition to quantify the extent of spillovers between gas markets and provide insights into how shocks of varying durations affect market interconnectedness. Their findings confirm that, despite significant shocks, market interconnectedness remains relatively robust, although there are periods of decoupling, particularly between NBP and continental hubs during the peak of the Ukrainian crisis.

To provide a more precise picture of European gas market integration, it is worth noting several other studies that offer important context on EU gas markets. Growitsch et al. (2015) examined the impact of specific regulatory reforms on the integration and efficiency of national gas markets in the context of the broader European integration process, focusing on the effects of changes in the regulation of access to the transmission network in Germany, specifically the introduction of an entry-exit system in 2007. This study highlights the importance of specific regulatory reforms in improving market integration and market efficiency. Another perspective on the integration of European natural gas markets, with an emphasis on industrial gas price convergence in six Western European countries, is provided by Renou-Maissant (2012). Using both cointegration analysis and time-varying parameter models, Renou-Maissant found evidence of integration among continental European gas markets, particularly between France and Italy. However, convergence was less "complete" between continental markets and the United Kingdom, reflecting differences in the pace of liberalization and market dynamics. Osička et al. (2018) explored the regional challenges of European gas market integration, specifically in the context of the Visegrád Four countries. This study underscores the importance of political will and regulatory harmonization in achieving effective market integration, providing a more detailed understanding of the sociopolitical aspects of market integration.

Price convergence and gas market integration in Eastern Europe, which often remains outside the mainstream of research due to the absence of liquid markets, is the subject of a unique study by Bublyk et al. (2022). The study found that although there is an overall positive price convergence after 2014, this convergence is heterogeneous across different consumer groups. The findings on the heterogeneous nature of price convergence across different consumer groups highlight gaps in the institutional mechanisms of European integration and the need for tailored regulatory policies.

The reviewed studies overall point to the increasing integration of gas prices in European markets over the past two decades. The studies consistently indicate a gradual process of integration, accompanied by a shift from oil-indexed gas pricing to market-oriented pricing based on supply and demand. From this body of research focused on EU gas markets, several key findings emerge:

1. The importance of physical infrastructure, such as the construction of interconnectors and LNG terminals, played a crucial role in facilitating market integration.
2. The role of regulatory frameworks and EU directives aimed at market liberalization has been fundamental in creating the conditions for increased market integration.
3. The emergence of key liquid hubs, such as TTF and NBP, which have become benchmarks for pricing and market efficiency in the western part of the EU.
4. Persistent regional differences between hubs in northwestern Europe and those in southern and central Europe, suggesting the need for more targeted policies to promote integration in less liberalized regions.
5. Studies have confirmed the sensitivity of market integration to external shocks, such as the COVID-19 pandemic and geopolitical tensions.
6. The gradual nature of integration, as highlighted by studies covering longer time periods, such as Robinson (2007) and Renou-Maissant (2012), emphasizes that market integration is a long-term process with periods of both convergence and divergence.

Despite the significant contributions of the presented studies, it is also necessary to critically assess their limits. Most research focuses on Western European markets, while the study of integration in Central and Eastern Europe remains more modest. Future research could focus more on these less explored regions to provide a more comprehensive understanding of the integration process across the entire European continent.

3.2 Gas prices convergence in the North American markets

The North American natural gas market, particularly in the United States, transitioned to competitive market-based pricing as early as the late 1980s and early 1990s. As described in Blanchard (2021), the deregulation of the U.S. natural gas market was a gradual process that began in 1978 with the enactment of the Natural Gas Policy Act. This law progressively removed price ceilings on natural gas and fostered the development of a competitive market. The Federal Energy Regulatory Commission (FERC) Order No. 436 (1985) enabled open access to pipelines for third parties, requiring pipeline operators to provide access to gas transportation at non-discriminatory prices. Another significant milestone was the passage of the Natural Gas Wellhead Decontrol Act in 1989, which eliminated price regulation on natural gas production. FERC Order No. 636 (1992) mandated the unbundling of gas sales from transportation for pipeline operators. By 1993, all natural gas prices were determined by market forces, free from regulatory constraints.

The evolution of the North American market provides an interesting contrast to the European experience with natural gas market deregulation. European countries began the deregulation process later, primarily in the late 1990s, and the pace of change was more gradual and less comprehensive compared to the United States (with so-called Energy Packages enacted in 1998, 2003, 2009 and 2019). Both examples demonstrate that deregulation can bring benefits in terms of increased competition, lower prices, and innovation, but it also requires careful management and regulation to ensure the reliability and security of supply.

In the period immediately following the full deregulation of the gas markets, several studies, including Doane and Spulber (1994), Walls (1995), and King a Cuc (1996), investigated the impact of regulatory changes on market efficiency and integration in the United States. These studies provide a good foundation for understanding the subsequent development of the North

American gas market, while offering an important methodological basis for studying market integration. Doane and Spulber (1994) highlighted the key role of regulatory changes in promoting market integration and efficiency. Building on this, Walls (1995) provided insight into the efficiency of the newly introduced natural gas futures market. This study is particularly interesting because it examines the integration between the spot and futures markets in the emerging gas market shortly after liberalization. Walls confirmed cointegration between spot and futures prices, indicating a long-term equilibrium relationship. King and Cuc (1996) similarly confirmed the strengthening price convergence in North American natural gas spot markets following the deregulation of natural gas prices in the mid-1980s.

Serletis and Herbert (1999) applied cointegration analysis, Granger causality, and error correction models to energy markets, setting a standard that influenced subsequent research in this area, including works such as Cuddington and Wang (2006) and Gebre-Mariam (2011). They also emphasized the importance of regulatory frameworks that support market integration and efficient pricing mechanisms. As U.S. gas markets became established and more liquid, attention was drawn not only to inter-commodity-based relationships but also to the supply chain itself. Mohammadi (2011) examined the long-term relationships and short-term dynamics of natural gas prices in the US from production to end-users, highlighting the integration of natural gas markets at different levels of the supply chain, but with asymmetric price adjustments and regime changes.

As the North American natural gas market continued to evolve, researchers focused on more detailed analyses of regional price dynamics and market structure. The works of Cuddington and Wang (2006), Gebre-Mariam (2011), Ghoddusi (2015), and Park et al. (2008) provide empirical and methodological insights into these aspects of market integration. Cuddington and Wang (2006) analyzed regional market integration following the reforms associated with "open access" to gas infrastructure. The results show significant regional segmentations in the US natural gas market and suggest the presence of significant barriers to integration between these regions, likely related to insufficient physical connectivity and capacity of transmission networks. The study emphasizes that FERC's "open access" reforms led to the creation of integrated regional markets in the eastern and central parts of the US, but a single national natural gas market remains incomplete. Park et al. (2008) examined price interactions and pricing processes among eight major North American regional natural gas spot markets, aiming to characterize the dynamic integration of these markets and explore the role each market plays in price determination. Building on this work, Gebre-Mariam (2011) confirmed the gradual interconnection between regional markets, improving efficiency and responsiveness to new information following deregulation, open access to pipelines, and the construction of pipeline infrastructure after 2000.

This section explored the evolution of the natural gas market integration in North America, highlighting the key role of regulatory reforms in driving the transition to a more competitive and efficient market structure. Earlier studies by Doane and Spulber (1994), Walls (1995), King and Cuc (1996), and Serletis and Herbert (1999) laid the foundation for understanding the impacts of deregulation and the development of financial markets on natural gas market integration in North America. They demonstrated that regulatory changes lead to rapid improvements in market efficiency and integration, a finding that may have influenced subsequent policy decisions in other regions, particularly in the EU. Subsequent studies by Cuddington and Wang (2006), Gebre-Mariam (2011), and Park et al. (2008) used more advanced methods to examine market integration, highlighting both the successes and limitations of the integration process. Several key conclusions emerge from the articles studied:

1. The significance of deregulation demonstrates the potential for policy interventions to shape the market structure.
2. The importance of physical infrastructure confirms the crucial role of physical interconnectivity in facilitating market integration.
3. The development of financial markets, as demonstrated by Walls (1995) and Gebre-Mariam (2011), played a decisive role in improving overall market efficiency and price convergence between regional markets.

The North American studies offer an interesting contrast to the European experience. While both regions have moved toward greater market integration, the process has been faster and more complete in North America, likely due to earlier deregulation efforts and a more homogeneous regulatory environment.

3.3 Gas prices convergence in the Asian region

The development of Asian market integration, particularly in the East and Southeast Asian regions, is particularly influenced by the historical dependence on long-term, oil-indexed LNG contracts. The shift towards more flexible trade agreements, the growth in spot LNG volumes, and the emergence of regional hubs make the Asian market an interesting case study in the ongoing process of regional and global gas market integration and the transition to market-oriented pricing. However, it is important to note that most studies analyze integration primarily in relation to global markets. A more detailed description of Asian markets can be found in Stern (2012).

Shi and Variam (2016) provide valuable context for understanding the development of Asian gas markets by examining the flexibility in destination clauses in East Asian gas supply contracts, focusing on the impacts on regional and global gas markets. Among the key findings of this study is that the transition to hub indexation and increased flexibility could lead to greater price convergence between the Asian and global gas markets.

The development of Asian gas market integration is also reflected in the growing research focus on the linkages between Asian markets and other regional gas markets. The work of Kim and Kim (2020) and Kim et al. (2020) reflect these trends. Kim and Kim (2020) examine how the roles of major markets in Asia have changed over time. Building on this work, Kim et al. (2020) provided a broader perspective on global gas market integration, focusing on the role of swing suppliers, particularly Qatar and Russia, and their role in linking European and Asian natural gas markets. The authors used monthly spot natural gas prices from 2000 to 2016, covering three main markets: Henry Hub, NBP, and the Japan-Korea Marker (JKM). This work highlights the key role of LNG flexibility in supporting global market integration. By demonstrating how swing suppliers can respond to price differentials between regions, Kim et al. provide insight into the mechanisms that help increase global market interconnectedness, similar to what we are accustomed to in oil markets in relation to Saudi Arabia.

In addition to the studies discussed above, for a deeper understanding of the development of Asian natural gas market integration and the transition to market-oriented pricing, it is necessary to consider other works that offer complementary perspectives on this process, such as Shi and Shen (2021) and Xiaoyi Mu and Haichun Ye (2018), or Chai et al. (2019), who found that the Chinese natural gas market exhibited a low level of integration with global markets between 2014 and 2018.

The analysis of the presented studies on the development of Asian natural gas market integration points to a market undergoing significant transformation from regional segmentation to global interconnectedness and from oil-indexed pricing to efforts towards market-oriented pricing. Several important observations emerge from these studies, contributing to the understanding of the dynamics of the Asian gas market integration process and the transition to more flexible pricing mechanisms:

1. The importance of developing liquid regional hubs
2. The role of LNG swing suppliers in supporting integration between Asian and European markets
3. The heterogeneity of Asian markets, as emphasised by Chai et al. (2019) in the case of the Chinese natural gas market, highlighting that Asian market integration is not a uniform process across all countries in the region.

The Asian experience offers an interesting contrast to both the European and North American perspectives. Although all three regions have moved towards greater market integration, Asia's progress is slower, primarily because of the historical dominance of long-term, oil-indexed contracts and the diverse regulatory environments across the region. This situation highlights the challenges in transitioning from a market structure based on long-term contracts to one that is more flexible and market-oriented. Furthermore, the studies underscore the importance of developing regional hubs and increasing the flexibility of LNG trade to support market integration and price convergence.

3.4 Global markets integration and the increasing influence of LNG

As regional markets have become more interconnected, the focus has shifted towards price convergence between these markets on a global scale. Notably, the expansion of LNG trade has played a crucial role in this global integration process, establishing physical connections between previously isolated markets and enabling price arbitrage across regions.

Siliverstovs et al. (2005) provided early evidence of the fragmented nature of global gas markets in the early 2000s and underscored the obstacles to achieving global market integration, even as regional markets (particularly in Europe) were becoming more price-aligned. One of the first studies to address the potential of LNG in supporting global gas market integration is the theoretical work of Brito and Hartley (2007), which emphasized the adaptability of LNG markets in response to evolving market conditions and participant expectations.

Neumann (2009) analyzed the role of LNG in facilitating the transition from regional segmentation to global gas market integration, providing evidence that LNG plays a role in connecting natural gas markets in the Atlantic basin. Aune et al. (2009) focused on projecting price trends and trade patterns using the FRISBEE model. The authors envisaged substantial growth in intercontinental trade, particularly with LNG, with its share in global gas production doubling by 2030 in high-demand scenarios. Their observation that regional price differences are likely to persist due to transportation costs highlights the limits of global market integration, aligning with the findings of Loureiro et al. (2023) on price convergence. This suggests that while markets may become more integrated, perfect cointegration or price convergence is improbable due to enduring structural factors. They identified the Middle East as a key player in global gas markets, significantly influencing global prices after 2020.

Erdős and Ormos (2012) contribute to the discussion on global market integration by examining price formation in international natural gas markets and their relationships with the global oil market. The authors investigated whether a globally integrated natural gas market, similar to the global oil market, has developed over the period 1992-2010. In the first half of the study period, the natural gas markets were strongly linked to the oil market and gas prices always returned to equilibrium with oil. In the second half of the period, the relationship between the oil and natural gas markets weakened. The authors conclude that a globally integrated natural gas market, comparable to the global oil market, has not yet developed. The European market exhibits the strongest degree of integration, while the North American market is the least integrated. Reference prices in Europe and Asia have remained tied to the price of oil, while the U.S. reference price has deviated from this pattern. Maxwell and Zhu (2011) focused on the dynamics of LNG trade in the context of gas prices and transportation costs. The significance of this study lies in its demonstration of the interplay between regional price differentials, transportation costs, and LNG trade flows, highlighting the potential for arbitrage opportunities that would lead to improved integration between regional markets. The evolution of contractual terms in the LNG market and their impact on gas market integration is the subject of Hartley's (2015) study. The findings on the trend towards greater volume and destination flexibility in contracts and increased reliance on short-term and spot trades indicate a shift towards a more market-oriented structure of global LNG trade, which may support further market integration.

The studies by Rosendahl and Sagen (2009) and Ritz (2014, 2019) provide important theoretical and practical insights into the role of LNG and strategic competition between pipeline and LNG transportation in shaping the dynamics of global gas markets in the context of their integration. Ritz (2014) examines why price differences persist despite the theoretical expectation of price convergence due to international trade. He explains this by the fact that LNG exporters can maintain different prices in different markets due to market power and limited arbitrage opportunities. On the other hand, Ritz (2019) examines the strategic competition between piped gas and LNG using game theory. The study analyses how differences in mobility and investment between piped gas and LNG affect market outcomes, pricing strategies, and overall competitive dynamics. Ritz (2014) points out that increased LNG exports from the US could increase competition and reduce price differentials, although existing market structures and constraints may still limit the extent of arbitrage. Ritz (2019) emphasizes that diversifying gas imports through LNG can enhance competition and lower prices and highlights the need for regulatory frameworks that facilitate infrastructure investment and market integration. Both works thus underscore the importance of addressing market power, transportation constraints, and promoting investment in LNG infrastructure to improve market efficiency and integration, which is crucial for the transition from regional segmentation to global interconnectedness.

As the integration of the natural gas market advances, Brown and Yücel (2009) and Barnes and Bosworth (2015) find that initial indications of price convergence between key trading hubs on a global scale are emerging. During the mid-2010s, the global LNG trading landscape underwent a significant shift driven by the entry of the US into the LNG export market, marking a significant change from the period before, when the US was projected to be a major importer of LNG, a trend reversed by the shale gas revolution. Building on this, Li et al. (2014) state that, although there is not yet an integrated international natural gas market, there is a clear distinction between the North American market and the rest of the world, with European and Asian markets converging. However, this trend towards integration reflects the position of LNG in market and price integration, as LNG supplies to Europe and the UK are increasingly sourced from countries that also supply the "Asian trio", creating a more direct link in prices that is

more based on contractual ties to oil prices than on market dynamics driven by inter-regional arbitrage and is therefore driven by oil market dynamics.

A comprehensive study contributing to the understanding of global gas market integration is the work of Geng et al. (2016). The authors combine the Ensemble Empirical Mode Decomposition (EEMD) method and cross-correlation analysis to reveal how different factors influence natural gas prices over different time horizons and highlight the potential for the development of LNG trade to increase the integration of regional gas markets. They suggest that a growing share of flexible LNG trade could lead to a shift from gas-to-oil indexation to gas-to-gas competition. This shift, they argue, would contribute to greater integration and efficiency of the global market. However, as shown by Loureiro et al. (2023) in more recent data, even a substantial increase in LNG trade after 2016 has not yet led to price convergence between continents. Building on this, the comprehensive view of the development of gas market integration in key world regions is offered by the study of Chiappini et al. (2019). The authors examine the impact of the growing LNG export capacities and the increasing share of spot LNG transactions on natural gas price dynamics. The study concludes that despite increasing interdependence between US and European natural gas prices, markets are not yet fully price integrated. However, the decreasing dependence on oil prices and observed asymmetries in price corrections suggest that the global natural gas market is undergoing a significant transformation towards greater flexibility, liquidity, and regional interconnectedness. This trend is further supported by the findings of Farag et al. (2023) on a 2016-2022 sample, which confirms that Asian and European prices were cointegrated, while the US benchmark was partially decoupled. Nonetheless, the degree of integration between markets varied over time and was affected by the supply - demand shocks related to the COVID-19 economic slowdown and geopolitical tensions, with each region exhibiting a specific response to these disruptive events.

Oglend et al. (2020) focused on analyzing the impact of costs on LNG shipping, which are an important barrier to integration. The potential for flexible routing of LNG supplies in supporting global gas market integration is the subject of a study by Baba et al. (2020). The authors' methodology is based on the TVAR model, which captures the dynamics of natural gas prices in Asia, North America, and Europe. The authors' findings on the significant profit potential of flexible LNG routing and the possible benefits of greater reliance on spot markets suggest that a combination of lower dependence of gas prices on oil prices and market forces driving vessel movements could potentially lead to price convergence and deepening global market integration.

Building on Li et al. (2014), Loureiro et al. (2023) use a similar methodology on more recent datasets. Outside of Europe, there is no clear evidence of gas price convergence. Convergence is observed in some shorter periods (e.g., before 2009) and is explained by temporary alignments in supply and demand across regions and practices of indexing gas prices to oil prices. After 2010, these links loosened, especially in Europe. The increase in LNG trade has not yet been sufficient to create fully integrated transnational markets. While Li et al. found convergence of Asian prices and partial convergence between Asia and Europe, current results show that Asia and Europe converge only within their own regions. In conclusion, the authors state that, to achieve true market integration, an even more substantial expansion of LNG trade and the removal of barriers to arbitrage will likely be necessary. Bernhard et al. (2024) analyze the future of LNG trade until 2040, focusing on Europe's dual goal of achieving decarbonization and ensuring energy security in the context of geopolitical tensions.

The reviewed literature points to an ongoing integration process, rather than a fully integrated market. Although LNG trade has established physical links between previously isolated regional markets, enabling price arbitrage and reducing price differentials, significant barriers to full integration remain. We can summarize the main findings as follows:

1. Ambiguous progress in global integration and persistent regional disparities are particularly evident in the divergence between North American prices and those in other regions.
2. The pivotal role of LNG in interconnecting previously segmented markets, as emphasized by Brito and Hartley (2007), Maxwell and Zhu (2011), Babu, Creti, and Massol (2020), and Oglend et al. (2020).
3. The significance of transportation costs in shaping LNG trade patterns and global price dynamics.
4. Market participants' strategic behavior influences global natural gas trade patterns.
5. The ongoing evolution of contractual structures in the LNG market towards greater flexibility, reflecting changing market conditions and participant preferences, as noted by Hartley (2015).

The development towards a more integrated global natural gas market, largely driven by LNG trade, represents a significant shift in global energy policy. However, this process is ongoing and complex, influenced in the future by a wide range of factors, including infrastructure development, regulatory changes, technological advancements, and shifting geopolitical dynamics.

4. Gas Markets Integration Methodological Framework and Evolution of the Econometric Methods Used

The application of cointegration techniques, convergence models, and related econometric methods in a significant portion of the analyzed studies represents a notable methodological contribution to the research on natural gas market integration. These analytical tools, including Johansen cointegration tests, vector error correction models (VECM), and time-varying parameter (TVP) models, enable the testing and quantification of long-term equilibrium relationships between price time series in various regional markets. These methodological approaches not only quantify the degree of market integration, but also allow tracking its evolution over time, thus providing a robust empirical basis for analyzing historical trends and projecting potential future scenarios for the development of the EU gas market. In the **Appendix** we present the overview of every paper by methodology and data applied, while in this section we outline historical development of the application of the econometric methodology.

Cointegration analysis became a fundamental methodology in studies of natural gas market integration. This approach, introduced in gas market studies by researchers such as Walls (1995), King and Cuc (1996), and Asche et al. (2001, 2002), allows for the examination of long-term equilibrium relationships between prices. Asche et al. (2001) used the Johansen cointegration test to explore long-term relationships and revealed strong links between the French, German, and Belgian markets. In a follow-up study, Asche et al. (2002) extended their analysis to the German natural gas market. This study examined the integration of the German

market and determined whether there were significant price differences between gas from different exporting countries. The study focused on long-term "take-or-pay" contracts governing gas exports to Germany from Norway, the Netherlands, and Russia from 1990 to 1998. Using the Johansen cointegration test and examining the law of one price, the authors found that import prices from Norway, the Netherlands, and Russia were cointegrated. These works inspired subsequent studies on natural gas market integration and demonstrated the ability of cointegration to reveal long-term price relationships and market dynamics. However, it is important to note that while cointegration analysis provides insight into long-term equilibrium relationships, it may not capture short-term dynamics or structural changes in the market.

Building on cointegration analysis, a significant portion of studies utilize vector error correction models (VECM) to capture long-term equilibrium relationships while also accounting for short-term dynamics in natural gas markets. This approach allows for a more detailed understanding of how markets adjust to deviations from long-term equilibrium. An example is the application of VECM in the analysis of the natural gas market by Siliverstovs et al. (2005). Among more recent studies, the article by Kim and Kim (2019), which focuses on the dynamic relationships between Asian and European natural gas markets, is worth mentioning. It focuses on identifying structural changes resulting from significant events such as the entry of Russia and Qatar into the Asian market as swing suppliers after 2009, the large earthquake in Japan in 2011 and the subsequent increase in LNG imports, and the significant increase in natural gas imports by China after 2011. Kim and Kim used cointegration analysis (Johansen test) and an error correction model (VECM) to analyze monthly spot natural gas prices from January 2000 to December 2017. They applied the Bai-Perron test to identify potential structural breaks. The results of their study revealed significant changes in market dynamics over time. Before March 2011, the Asian market (represented by JKM prices) led the natural gas markets, suggesting that the Asian market was more "informative" and slower to adjust to shocks. However, after March 2011, which coincided with the identified structural break, the European market (represented by NBP prices) became the leading market. The Asian market became the main adjuster following price shocks in Europe. The long-term equilibrium relationship also changed significantly – the impact of European prices (NBP) on Asian prices (JKM) increased significantly after March 2011. The study by Kim and Kim demonstrates how cointegration models and tests for structural breaks can provide a more accurate picture of evolving market relationships.

The aforementioned studies underscore the value of VECM in providing a more dynamic representation of market integration. By capturing both long-term relationships and short-term adjustments, VECM offers a more comprehensive perspective on market dynamics compared to cointegration analysis alone. However, it should be noted that VECM assumes linear adjustments to equilibrium, which may not always reflect the complex reality of natural gas markets, for example, due to structural breaks.

With the rise of research on the dynamic nature of natural gas markets, there has also been a shift toward the need for more flexible modeling of relationships between gas prices. Time-varying parameter models, often implemented using Kalman filter techniques, have gained popularity. We encounter them in articles such as King and Cuc (1996) and Neumann et al. (2006). As natural gas market research progressed, researchers have employed increasingly advanced econometric techniques to capture market dynamics. These methods often build upon or combine previous approaches, providing new insights into market integration processes. An example of this trend is the study by Papież et al. (2022), which uses a vector autoregression model with time-varying parameters and stochastic volatility (TVP-VAR-SV) to examine the

integration of European natural gas markets. Papież et al. used daily spot natural gas prices from 2013 to 2022 for four European gas hubs: NBP, TTF, NCG, and PSV. The use of the TVP-VAR-SV model allowed the authors to capture time-varying coefficients as well as changing volatility patterns, providing a highly flexible framework for analyzing market dynamics. The TVP-VAR-SV model is capable of capturing various types of nonlinearities. The Diebold-Yilmaz (2009, 2012, 2014) connectedness approach used in this study measures total spillovers, net spillovers for individual markets, and pairwise net spillovers between different markets. This methodology provides a detailed view of how shocks in one market affect others and how these relationships evolve over time. The study's results revealed increasing interconnectedness among European natural gas markets during the period examined. The authors identified TTF and NCG as the main markets, transmitting shocks to other hubs. The role of NBP changed significantly, becoming the largest net recipient of shocks, which the authors attribute to Brexit and the loss of this hub's importance in favor of TTF. This study demonstrates the power of advanced econometric techniques in providing more accurate insights into market integration processes.

5. Conclusion

The evolution of natural gas market integration from regional segmentation to global interconnectedness is a multidimensional process encompassing both physical and price integration. Physical integration refers to the development of interconnected infrastructure, such as pipelines and LNG terminals, that enables gas flow between different markets. Price integration, on the other hand, refers to the convergence of prices across different markets, driven by arbitrage opportunities and the alignment of supply and demand fundamentals.

This review of articles published over three decades reveals significant progress in price-level market integration in the context of the law of one price, particularly within regions and increasingly on a global scale. The key drivers of this integration have been regulatory changes, infrastructure development, the growth of hubs, and the expansion of LNG trade, creating links between previously isolated regional markets. Several important observations emerge from this body of scientific articles:

1. Studies focused on European, North American, and Asian markets demonstrate increased integration within these regions, although at different paces. The EU exhibits strong integration, followed by North America, while Asia's integration is largely driven by oil-indexed pricing and the emergence of the JKM benchmark.
2. Although full global integration has not yet been achieved, there is growing evidence of linkages between regional markets, supported predominantly by LNG trade. However, significant price differences persist, particularly between North America and other regions.
3. The growth of LNG trade has been a key factor in facilitating global market convergence, creating physical links between previously isolated markets, and enabling price arbitrage. The development of flexible LNG contracts and spot trading has further supported this trend.
4. The transition from oil-indexed pricing to gas-on-gas competition, particularly in Europe, has been a major theme in the literature, with hub-based pricing becoming increasingly prevalent. However, oil-indexation remains significant in Asia, and the pace of transition varies across regions.

5. The development of futures markets has played an important role in increasing market efficiency and price discovery since the beginning of liberalization.
6. Exceptional events, such as the Fukushima disaster, the shale gas revolution, geopolitical tensions, or the COVID-19 pandemic, can significantly alter market dynamics and patterns of integration, highlighting the need for resilient and adaptable market structures.
7. The increasing sophistication of econometric techniques employed in market integration research, such as time-varying parameter models and connectedness analysis, has provided more nuanced insights into the dynamic nature of gas market relationships and the transmission of shocks across markets.

As market integration progresses and global interconnectedness increases, the resilience of natural gas markets to supply disruptions, geopolitical events, and economic shocks will be increasingly important. Developing a deeper understanding of the factors influencing market integration, transmission of price shocks, and effectiveness of policy interventions will be essential to foster stable, efficient, and sustainable natural gas markets in the future.

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Appendix

Table 2. Review of the relevant papers by econometric methodology and data

Author	Year	Econometric Methodology	Data
Asche et al.	2001	Johansen cointegration tests	Border prices of natural gas from Norway, Netherlands, and Russia to France, Germany, and Belgium, 1990–1997
Asche et al.	2002	Cointegration	Norwegian, Dutch, and Russian gas export prices to Germany, 1990–1998
Asche et al.	2012	Johansen cointegration tests	Monthly gas prices from Norway, Netherlands, and Russia for Europe, 1990–1997
Asche et al.	2013	Johansen cointegration tests, VECM, exogeneity tests	Monthly UK, Belgium, Netherlands gas and German contract prices 1999-2010, Brent oil
Asche et al.	2013	Regime-switching model with time-varying transition probabilities	Weekly UK NBP and Brent oil prices 1998-2011
Asche et al.	2017	Regime-switching model with periodic decoupling from oil prices (VECM for linear price adjustments)	UK NBP and Brent oil prices, 1997–2014
Aune et al.	2009	Numerical partial equilibrium model (FRISBEE)	Assumes liberalized integrated markets, varies economic growth, export constraints, cartelization

Author	Year	Econometric Methodology	Data
Baba et al.	2020	Threshold Vector Autoregression (TVAR), Generalized Impulse Response Functions (GIRF), Monte Carlo simulations	LNG prices across Asia, Northern America, and Europe; simulation of future price trajectories
Barnes & Bosworth	2015	Gravity model for natural gas trade	Trade volumes of LNG and CNG, distance-based trade data
Bastianin et al.	2019	Cointegration analysis, convergence tests, pairwise convergence tests	Half-yearly natural gas prices for industrial consumers in 14 European countries, 1991–2017
Brito & Hartley	2007	Stylized model based on Diamond search and matching	Simulated data
Broadstock et al.	2020	Extended spillovers index method with rolling window and importance-weighting	Daily NBP, ZEE, TTF prices 2005-2018
Brown & Yücel	2009	Cointegration tests, VECMs, causality tests	Weekly Henry Hub, NBP, WTI, Brent prices 1997-2008
Bublyk et al.	2022	Standard deviation detection method for price convergence	Bi-annual gas prices for households and industry 2007-2020 from Eurostat
Cai & Wu	2020	Bootstrap rolling window Granger causality test	Monthly Japan, Europe, US gas and oil prices 1992-2017
Chai et al.	2019	DCC-GARCH to measure linkages between gas markets; NARDL and ARDL for international price effects on China	Spot gas prices for regions and China/Japan LNG prices 2014-2018
Chen et al.	2022	Quantile connectedness approach to measure market integration	Gas futures market data focusing on the European market under COVID-19 impacts
Chiappini et al.	2019	Gregory-Hansen and Maki cointegration tests with breaks, Enders-Siklos TVECM	Daily gas prices at EU hubs (NBP to Gaspool) and Henry Hub 2004-2018
Cuddington & Wang	2006	Cointegration tests, speed of price adjustment tests	Daily spot prices for natural gas at 76 U.S. market locations, 1993–1997
Erdős & Ormos	2012	Unit root, cointegration, causality tests, FMOLS	Monthly oil and regional gas prices 1992-2010
Farag et al.	2023	Asymmetric ECMs, threshold cointegration, time-varying Granger causality	Daily Henry Hub, TTF, East Asia Index futures 2016-2022
Garaffa et al.	2019	Linear and non-linear ECMs for price transmission	Daily German, Belgian, Dutch gas prices 2013-2014
Gebre-Mariam	2011	Unit root, cointegration, causality, efficiency tests	Daily US regional spot and futures gas prices 1998-2004
Geng et al.	2016	Ensemble Empirical Mode Decomposition (EEMD) to extract multi-scale components; cross-correlation analysis	Monthly regional gas prices and factors 1992-2013
Ghoddusi & Emamzadehfard	2017	Vector Error Correction Model (VECM), cointegration tests, impulse response, variance decomposition	U.S. natural gas market, Henry Hub, wellhead prices, 1997-2007
Growitsch et al.	2015	Johansen cointegration, Kalman filter state space model, ECM for efficiency	Daily NCG, Gaspool, TTF prices 2007-2011
Hartley	2015	Theoretical contracting model with take-or-pay and spot trading options; calibration and sensitivity analysis	Representative LNG project costs, spot prices and volatilities

Author	Year	Econometric Methodology	Data
Heather	2015	Correlation and convergence analyses of European gas prices, five key element analysis	Price data from European gas hubs including TTF, NBP, ZEE, 2005–2014
Heather	2023	Price convergence, correlation, and volatility analyses	Traded gas hubs data from 2021–2023 across Europe
Heather	2024	Market trend analysis, churn rate comparison, correlation analysis	European traded gas hubs data and LNG volumes, 2022-2023
Jotanovic & D'Ecclesia	2021	Cointegration tests, Granger causality, GARCH (1,1) Dynamic Conditional Correlation	Spot and forward gas prices from European hubs, 2007–2017
Kim & Hamori	2020	2-stage structural VAR for oil vs gas supply and demand shocks; regressions on US macro variables	Monthly oil, gas prices, production, economic activity 1973-2019; quarterly US GDP and CPI
Kim & Kim	2020	Price discovery framework, Vector Error Correction Model (VECM), cointegration	Asian and European natural gas markets, price data from 2000–2017
Kim & Tamvakis	2019	VAR and Granger causality of positions and forward curve slope by trader type	Weekly energy futures prices and trader positions 1995-2015
Kim et al.	2020	Engle-Granger cointegration tests and ECM on price series and subsamples	Monthly US (HH), Europe (NBP), Japan (LNG) prices 2000-2019
King & Cuc	1996	Time-varying parameter (Kalman filter) model for price convergence	Monthly bid-week spot prices for North American hubs 1990s
Li et al.	2014	Phillips-Sul convergence test; Kalman filter for time-varying coefficients	Monthly LNG prices for Japan, Korea, Taiwan, UK NBP, US HH 1997-2011
Loureiro et al.	2023	Phillips-Sul convergence test; Kalman filter pairwise convergence	Monthly regional gas and Brent prices 2001-2020
Maxwell & Zhu	2011	Granger causality, variance decomposition, impulse response analyses, VAR model	U.S. LNG imports and natural gas prices from Henry Hub and UK, 1997–2007
Mohammadi	2011	Cointegration, causality tests, impulse response, asymmetric adjustments	U.S. natural gas prices from wellhead to end-use markets, 1990–2010
Mu & Ye	2018	Time-varying coefficient model, Phillips-Sul convergence test	Weekly LNG prices from East Asia, Iberia, Northwest Europe, South America, and UK NBP, 2010–2015
Neumann	2009	Kalman filter for time-varying price convergence	Daily spot prices at Henry Hub, NBP, Zeebrugge 1999-2008
Neumann & Cullmann	2012	Kalman filtering technique, time-varying cointegration tests	Daily gas prices from EU hubs (ZEE, NCG, TTF) over 2009-2011
Neumann et al.	2006	Kalman filter for time-varying price convergence	Daily spot prices at NBP, Zeebrugge, Bunde 2000-2005
Oglend et al.	2020	Time-varying parameter model and Phillips-Sul convergence	Weekly European, Asia and South America LNG prices and NBP 2010-2015
Osička et al.	2018	Discourse network analysis, stakeholder analysis, network analysis	Interviews and qualitative data from stakeholders in V 4 countries on gas market integration
Papież et al.	2022	Time-varying spillover analysis with DY connectedness approach and TVP-VAR	Daily TTF, NBP, NCG, PSV prices 2013-2022
Park et al.	2008	Vector Error Correction Model (VECM), directed acyclic graphs	Daily natural gas prices from eight North American hubs, 1998–2007
Renou-Maissant	2012	Johansen cointegration tests, Kalman filter model	Biannual industrial gas prices for European countries 1991-2009
Ribeiro et al.	2023	Spearman correlation, hierarchical clustering, VAR-VECM	Panel data on 34 countries 2007-2022

Author	Year	Econometric Methodology	Data
Ritz	2014	Pricing model of LNG exporter with market power in segmented markets	Illustrative data on LNG costs and price elasticities
Ritz	2019	Game-theoretic model of pipeline vs LNG supplier competition	Global gas trade and price data
Robinson	2007	Beta-convergence test, cointegration, Nahar-Inder test	Annual industrial gas prices for 6 EU countries 1978-2003
Rosendahl & Sagen	2009	3-node model and numerical simulations with FRISBEE model	Demand, supply, infrastructure and cost projections to 2035
Schultz & Swieringa	2013	Price discovery regressions and Hasbrouck information share with high-frequency data	Intraday spot and futures prices at NBP, ZEE, TTF, ICE 2008-2011
Serletis & Herbert	1999	Unit root and Engle-Granger cointegration tests, ECMs and Granger causality	Daily Henry Hub, NYC gas, PJM power and NY fuel oil prices 1996-1997
Shi & Shen	2021	SVAR with macroeconomic uncertainty, supply-demand analysis	Monthly gas prices, uncertainty, fundamentals for US, Japan, Germany 2000-2016
Shi & Variam	2016	Nexant World Gas Model linear cost minimization for scenarios	Country-level supply, demand, infrastructure data and projections 2015-2035
Siliverstovs et al.	2005	Principal components analysis and Johansen cointegration tests	Monthly gas import prices for Europe, US, Japan 1993-2004
Stern	2014	Historical and conceptual analysis of oil-linked vs hub-based pricing	Monthly prices 2007-2013; discussion of key events and trends
Szafranek & Rubaszek	2023	Constant and time-varying coefficient SVAR models	Monthly US, EU gas and oil prices 1993-2022
Szafranek et al.	2023	Time-varying parameters VAR model with stochastic volatility (TVP-VAR-SV), spillover measures	Daily gas prices from four major European hubs (TTF, NBP, THE, PSV), 2021–2022
Walls	1995	Cointegration tests for futures market efficiency at multiple locations	Monthly NYMEX gas spot and futures prices at different nodes 1990-1994
Zwickl-Bernhard & Neumann	2024	GAMS linear optimization model for global LNG market from European perspective	Infrastructure, cost data; demand and capacity projections (IEA, BP); CCS costs

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