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Are European and U.S. natural gas futures markets integrated? Insights from network-connectedness and cross-herding analysis

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Abstract
This paper investigates the connectedness as well as the cross-herding behavior among the U.S. and European natural gas futures markets. Daily data of U.S. and European natural gas futures prices for maturities ranging from 1 to 60 months were used. The network-connectedness analysis emphasizes a weak level of integration between these two geographically distinct natural gas futures markets, while revealing much more pronounced magnitude of connectedness among the different maturities within each of them. The dynamic total connectedness results reveal a relatively higher and more stable level of integration within the European market. The static, as well as dynamic, cross-herding analyses show the absence of herding behavior between the two considered markets, reflecting that investors' behavior in one market is not sensitive to conditions in the second market.

Keywords: natural gas futures markets, network-connectedness, cross-herding, Europe, United States
JEL Classification Codes: G15, G41, C58

1. Introduction

The global importance of natural gas has witnessed a notable increase in recent years. In lights of escalating concerns over climate change and the push to decarbonize industries, natural gas has risen to prominence in the global energy supply due to its environmental and economic

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benefits. As a form of relatively clean-burning energy source[1], natural gas has two main advantages (Geng et al., 2016; Yoon et al., 2018; Szafranek et al., 2023). First, it serves as a more carbon-efficient energy source than coal. Second, the high dispatchability of gas-fired power plants makes them an excellent complement for the unstable renewables from wind and solar. According to statistics provided by the International Energy Agency (IEA), while fossil fuel electricity generation is on a downward trend, the proportion of electricity generated by natural gas plants in OECD countries in July 2023 stands at nearly 35% (327 697.1 GWh), marking a substantial surge from the 25% share (235 074.2 GWh) recorded in July 2010.

The natural gas market is highly sensitive not only to structural changes associated to the ongoing energy transition, but also to extreme events (e.g., the COVID-19 pandemic) as well as political and geostrategic uncertainties (e.g., the ongoing Russian-Ukrainian war). During the global COVID-19 pandemic, and for the first time since the subprime crisis, global demand for natural gas contracted slightly in 2020 (-1.2% in 2020 compared to 2019, according to IEA data) but later in 2021 rebounded in tandem with the global economic recovery.[2] Nevertheless, the Russian-Ukrainian war triggered a global crisis, particularly in the energy sector, causing the natural gas price volatility to increase substantially (McWilliams et al. 2023). According to IEA statistics, Russia's natural gas exports fell by 34% in 2022. Between February 28, 2022, and March 7, 2022, the TTF gas prices, a Europe-wide natural gas price benchmark, surged to €227.2 per MWh following the outbreak of the Russia-Ukraine war. Furthermore, the announcement of the Nord Stream shutdown pushed TTF prices to a record high of €330 per MWh on August 26, 2022. In the United States, the Henry Hub spot price, a key benchmark for U.S. natural gas prices, rose each month in the first half of 2022 due to increased domestic consumption and exports. In June 2022, the average natural gas spot price at the Henry Hub exceeded $7.7 per MMBtu, compared to $4.69 per MMBtu in February 2022.

A substantial amount of the literature has thoroughly explored the integration level of natural gas spot markets. For instance, Nakajima and Toyoshima (2019) and Kan et al. (2019) show that the natural gas market is geographically segmented into at least three regional markets (America, Europe, and Asia). These markets are relatively isolated from each other primarily due to transportation costs and the presence of heterogeneous institutional structures (Szafranek et al. 2023). Scarcioffolo and Etienne (2019) analyze data from seven U.S. natural gas spot markets, along with one Canadian spot market located on the U.S.-Canada border, to assess the integration level within U.S. regional natural gas markets. While their findings indicate that the U.S. natural gas market is well integrated, they report a noticeable decline in connectedness from 2012 onwards, concomitant with the unconventional shale gas boom era. Szafranek and Rubaszek (2024) investigate the decoupling of U.S. and European natural gas prices from crude

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[1] Since burning natural gas results in fewer emissions of almost all types of air pollutants and significantly less CO_2 compared to coal or petroleum products for the same amount of energy, the U.S. Energy Information Administration (EIA) considers it an efficient, relatively clean-burning, and economical energy source. https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php

[2] https://www.iea.org/reports/natural-gas-information-overview/demand

oil prices using a time-varying parameters structural vector autoregressive (TVP-VAR) model. Their results indicate that oil prices are barely impacted by shocks in natural gas markets. However, over the long term, European natural gas prices are significantly influenced by oil shocks. As for the European gas market, many studies show that it has become increasingly integrated in recent years (Chen et al., 2022; Papież et al., 2022; Szafranek et al., 2023), with a slight drop in connectedness during the COVID-19 period (Chen et al. 2022) and following the outbreak of war in Ukraine (Szafranek et al. 2023).

While the existing literature provides insights into the global and regional integration or segmentation of spot natural gas markets, it lacks a comprehensive analysis of futures markets. Thus, this study investigates the integration of natural gas futures markets in the United States and Europe, followed by a cross-market herding analysis to assess the impact of investor behavior in one market on the decisions made in the other.

The network-connectedness analysis indicates geographic segmentation between the U.S. and European natural gas futures markets, while revealing a high level of integration within each of them. The dynamic total connectedness shows a higher and more stable integration level within the European market. Notably, the U.S. market exhibits greater sensitivity to the war in Ukraine. The static and dynamic cross-herding analyses reveal that investors' behavior in one market is not influenced by conditions in the second market.

The contribution of this paper is twofold: (i) to the best of our knowledge, it is the first to investigate the network connectedness among two major geographically distinct natural gas futures markets, namely the U.S. Henry Hub and the European Dutch TTF markets; (ii) while a significant bulk of the literature examine herding within a single geographical market (e.g., Stavroyiannis and Babalos, 2017; Kumar et al., 2021), our study examines dynamic cross-herding between the U.S. and European natural gas futures Markets.

The paper is structured as follows: Section 2 describes the data used as well as the empirical methodology; Section 3 analyzes the results; Section 4 concludes and provides practical implications.

2. Data and methodology

2.1. Data

Our dataset consists of daily prices of U.S. Henry Hub [**NG**] and Dutch TTF [**TZT**] natural gas futures for different maturities ranging from 1 to 60 months. These commodities are traded on the NYMEX (for **NG**) and the Dutch TTF[3] (for **TZT**). All prices are in U.S. dollars. The data are sourced from Bloomberg and span from October 7th, 2013, to October 4th, 2023. This period is informative in terms of market development as it covers the pre-COVID-19 period, the COVID-19 period, the pre-Russia-Ukraine war period, and the war period. The daily return of a natural gas futures contract i for a given maturity M is computed as $r_{M,t}^{i} = \ln\left(P_{M,t}^{i}\right) - \ln\left(P_{M,t-1}^{i}\right)$, where $P_{M,t}^{i}$ is the daily closing price of a given natural gas futures contract i for maturity M on day t. Table 1 depicts the Bloomberg tickers of each of the indices considered.

[3] The Dutch TTF is the most liquid natural gas hub in Europe (Papież et al., 2022).

Table 1. Summary of commodity futures markets

Commodity	Exchange	Contract size	Prices quotation	Delivery months	Tickers
US Natural gas	NYMEX	10000 MMBtu	U.S.$ per MMBtu	F G H J K M N Q U V X Z	**NG**
EU Natural gas	TTF	1 MW	Euros per MWh	F G H J K M N Q U V X Z	**TZT**

Source: own elaboration
Note. F, G, H, J, K, M, N, Q, U, V, X, and Z stand for Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, and Dec, respectively.

2.2. Methodology

We use a combination of statistical methods to investigate the extent to which the U.S. and European natural gas futures markets are integrated or segmented. First, we use network-connectedness framework to (i) measure the independence level among the considered markets and (ii) visualize the network plot. Then we investigate the cross-herding among the U.S. and European natural gas futures markets to assess whether the behavior of investors in one market influences the decisions of investors in the other.

2.2.1. Network-connectedness methodology

To construct the connectedness network among the considered natural gas futures markets, we first estimate a k-variables vector autoregressive (VAR) model as follow: $w_t = \sum_{i=1}^{n} \tau_i w_{t-i} + \varepsilon_t$, where $w_t = \left(r_{1,t}^{US}, r_{2,t}^{US}, \ldots, r_{N,t}^{US}, r_{1,t}^{EU}, r_{2,t}^{EU}, \ldots, r_{N,t}^{EU}\right)$ represents the vector of endogenous variables, n the integration order of the model, $\tau_1, \tau_2, \ldots, \tau_n$ are the coefficient matrices, and $\varepsilon \sim (0, \Sigma)$ is the vector of *iid* errors, such that $E(\varepsilon_t) = 0$, $E(\varepsilon_t \varepsilon_t') = \Sigma$ and $E(\varepsilon_t \varepsilon_{t-s}) = 0$. The moving-average representation for this process is expressed as: $w_t = \sum_{i=0}^{\infty} B_i\, \varepsilon_{t-i}$, where the $k \times k$ coefficient matrices B_i follow the recursion $B_i = \tau_1 B_{i-1} + \tau_2 B_{i-2} + \cdots + \tau_n B_{i-n}$, with B_0 being a $k \times k$ identity matrix and $B_i = 0$ for $i < 0$ (Wold, 1954). Then, the generalized forecast error variance decomposition (Koop et al., 1996; Pesaran and Shin, 1998) is employed to compute an overall connectedness index among the considered futures markets (Diebold and Yilmaz, 2012). The total connectedness index is defined as:

$$C = \frac{\sum_{i,j=1, i\neq j}^{k} \tilde{\gamma}_{ij}^{G}(H)}{k} \cdot 100 \quad \text{with } \tilde{\gamma}_{ij}^{G}(H) = \frac{\gamma_{ij}^{G}(H)}{\sum_{j=1}^{k} \gamma_{ij}^{G}(H)} \tag{1}$$

where $\tilde{\gamma}_{ij}^{G}(H)$ represents directional connectedness from natural gas futures market j to natural gas futures market i at horizon H. After obtaining the directional connectedness metrics, we rely on Jacomy et al. (2014) to produce the connectedness network plot. The construction of this plot involves the consideration of nodes (where each node represents a natural gas futures market), edges (an edge from node j to node i represents directional connectedness from futures market j to futures market i), and weights (the thickness of an edge from node j to node i reflects the magnitude of directional connectedness from market j to market i). Indeed, the ForceAtlas2 algorithm reaches a stable state by balancing the forces of repulsion and attraction among nodes; while nodes repulse each other, edges act as forces of attraction, bringing them closer together. In other words, nodes will be positioned on the plot in a way that natural gas futures markets with strong connectedness will be close to each other, while weakly connected markets will be farther apart.

2.2.2. Cross-herding methodology

To investigate the cross-herding among the considered natural gas futures markets, we first compute the cross-sectional absolute deviation (Chang et al., 2000) as follows:

$$CSAD_t^i = \frac{1}{N}\sum_{M=1}^{N}\left|r_{M,t}^i - r_{m,t}^i\right| \quad (2)$$

where $r_{m,t}^i$ is the equally weighted average returns of all maturities at time t for the natura l gas futures contract i. $N = 60$ is the number of maturities. We then build on Chang et al. (2000), Galariotis et al. (2015) and Benkraiem et al. (2021) to investigate the cross-herdi ng behavior between the U.S. and European natural gas futures markets. Specifically, we consider the following regressions:

$$CSAD_t^{US} = \alpha + \beta\left|r_{m,t}^{US}\right| + \gamma_1\left(r_{m,t}^{US}\right)^2 + \gamma_2\left(r_{m,t}^{EU}\right)^2 + \varepsilon_t \quad (3)$$

$$CSAD_t^{EU} = \alpha + \beta\left|r_{m,t}^{EU}\right| + \gamma_1\left(r_{m,t}^{EU}\right)^2 + \gamma_2\left(r_{m,t}^{US}\right)^2 + \varepsilon_t \quad (4)$$

In the presence of cross-herding, the coefficient γ_2 should be significantly negative, indicating that herding behavior in the first market is influenced by market conditions in the second one.

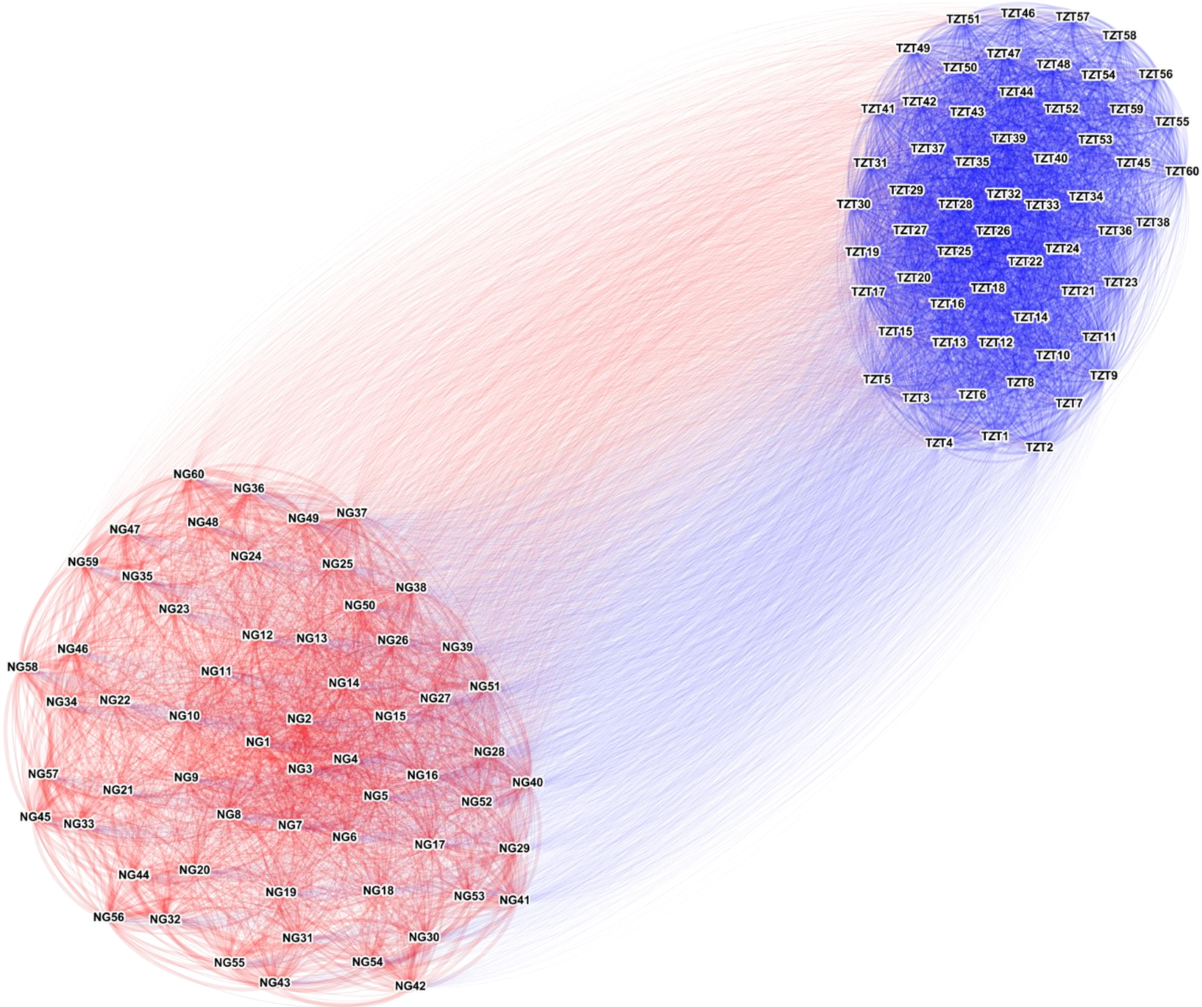
3. Results

This section investigates (*i*) the network-connectedness among the U.S. and European natural gas futures markets as well as (*ii*) the cross-herding dynamics between these two distinct markets.

3.1. Network-connectedness analysis

Figure 1 depicts the directional connectedness network among the considered natural gas futures markets (Henry Hub [**NG**] for the Unites States and Dutch TTF [**TZT**] for Europe) across various maturities (ranging from one to 60 months), based on the average estimate of the full sample. The connectedness network plot reveals a clear geographical clustering of connectedness. Specifically, the natural gas futures market is geographically segmented, that is, the U.S. and European natural gas futures markets weakly affect each other. The relatively low level of cross-integration between the two markets can be attributed to two main complementary factors: (*i*) the geographical separation of production sites in the U.S. and Europe (Szafranek et al., 2023), and (*ii*) the technical challenges involved in transporting natural gas over long distances (Petrovich, 2013; Scarcioffolo and Etienne, 2019). Unlike many other energy commodities that can be transported using various means, natural gas can only be transmitted through pipelines or in liquefied form via specially designed infrastructures. This makes it costly and technologically challenging to transport natural gas over long distances.

Figure 1. Directional connectedness network among U.S. and European natural gas futures markets

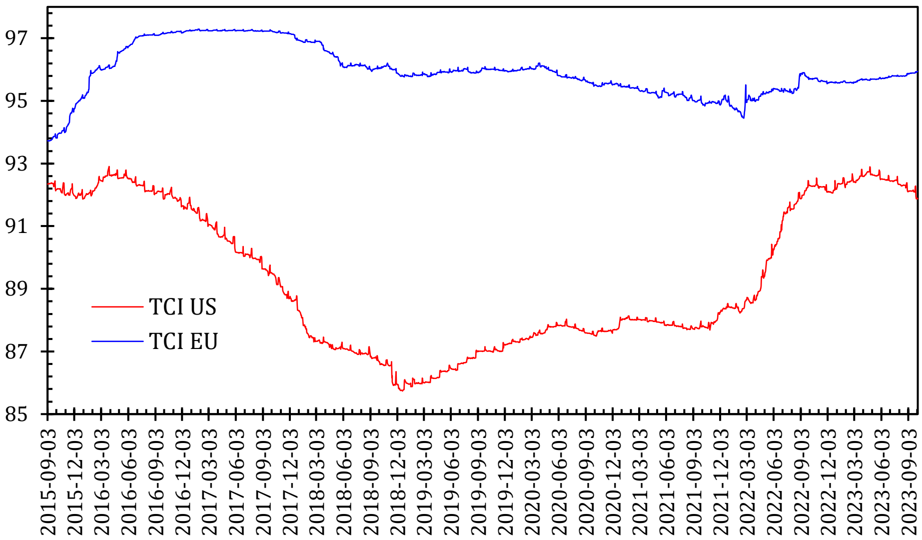


Source: own elaboration
Note. The red colour represents U.S. futures contracts, while the blue colour represents European futures contracts. The ForceAtlas2 algorithm was used to construct this network plot. This algorithm positions nodes in the plot such that natural gas futures markets with strong connections are close to each other, while weakly connected markets are farther apart. The connectedness table is available upon request.

Consequently, the geographical distance between the two markets increases transportation and transaction costs, leading to a lower level of market integration. However, the connectedness plot also demonstrates that the level of integration within each of the two markets is quite high, with the European market being relatively more integrated: the nodes representing the different maturities are more concentrated (respectively dispersed) on the European market (respectively on the U.S. market). Indeed, the relatively low integration level between these geographically separated markets, combined with a well-connected pipeline infrastructure within each region, explains why the natural gas market tends to be more concentrated within each region (Broadstock et al., 2020). This regional concentration is further reinforced by the fact that local supply and demand conditions, regulatory environments, and market structures vary significantly between the U.S. and Europe, contributing to localized market behaviors and, consequently, distinct market dynamics in each region (Szafranek et al., 2023).

Since the U.S. and the European natural gas futures markets are highly segmented, we now estimate the dynamic connectedness within each of the two considered markets. This estimation is performed using a 500-day drifting window and ten-day-ahead forecast horizon.

Figure 2. Time-varying connectedness indices



Source: own elaboration
Note. "TCI US" and "TCI EU" stand for Total Connectedness Index for U.S. and European natural gas futures markets, respectively. The estimation is based on the methodology of Diebold and Yilmaz (2012). A VAR model of order one was used to estimate the TCIs. The integration order of the VAR model is defined based on the Bayesian information criterion (BIC).

Figure 2 depicts the dynamic total connectedness for the U.S. (**TCI US**) and European (**TCI EU**) natural gas futures markets, respectively. The estimation was conducted separately for each of the two markets. Specifically, the estimation of the connectedness was performed between the 60 maturities of natural gas futures contracts selected in each market (U.S. and European). This plot indicates that the European market is relatively more integrated than the U.S. market throughout the entire period. Moreover, the level of integration across maturities in the European market (**TCI EU**) is more stable over time than that in the U.S. market (**TCI US**), with the latter displaying relatively substantial variations over time. Interestingly, the U.S. market reacted significantly to the war in Ukraine, while the European market displayed very low sensitivity to this conflict.

3.2. Cross-herding analysis

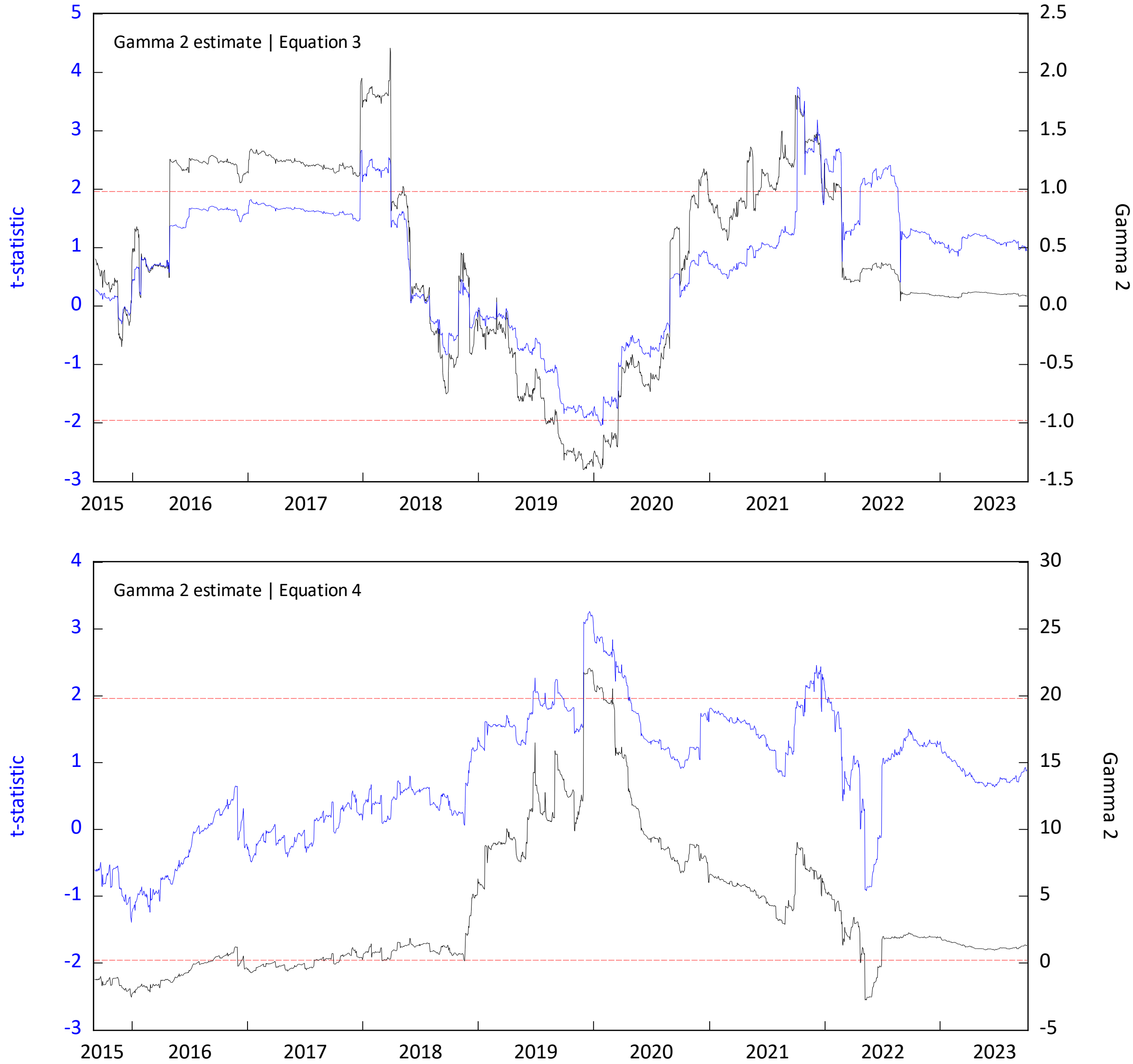
Table 2 reports the estimate of herding behavior within each of the considered natural gas futures markets (γ_1) as well as the cross-herding behavior between them (γ_2).

Table 2. Cross-herding between US and EU natural gas markets

Commodity	α	β	γ_1	γ_2	Adj. R^2
US Natural gas	0.0029***	0.5247***	-2.8875***	0.3200**	0.1692
EU Natural gas	0.0032***	0.3258***	0.5449	5.2605***	0.3202

Source: own elaboration
Note. *** and ** denote statistical significance at the 1% and 5% levels, respectively.

Figure 3. Time-varying estimate for γ_2



Source: own elaboration
Note. The dashed red lines represent the significance level limits at 5%.

It uncovers several results that can be summarized as follows. First, it reveals the presence of herd behavior in the U.S. market. More interestingly, it shows the absence of cross-herding behavior between the U.S. and European natural gas futures markets. Indeed, the significant positive values of γ_2 coefficients reflect that herding behavior in one market is not impacted by conditions in the other market and that investors consider only the information related to the market in which they operate. This result confirms the previous network-connectedness analysis showing that the two markets are highly segmented.

Despite the interesting results provided in Table 2, the static estimates may not fully capture the evolution of cross-herding behavior over time. Thus, to better understand the time-varying cross-herding behavior between the two considered natural gas markets, we now estimate the dynamic values of γ_2 in equations 3 and 4, by using a 500-day rolling window, as in Babalos and Stavroyiannis (2015).

Figure 3 displays the estimated time-varying values for γ_2 (in black) along with their t-statistics (in blue). The results confirm the absence of cross-herding between the U.S. and European markets. Indeed, for both markets, we do not identify any time periods where γ_2 coefficients are simultaneously negative and significant at the 5% level. This result suggests the absence of cross-herd behavior among the U.S. and European natural gas markets, that is, investors in one market are insensitive to the information related to price dynamics in the other market. These findings are consistent with the previous static cross-herding analysis (Table 2) and align with the network-connectedness analysis (Figure 1).

4. Concluding remarks

This article contributes to the existing literature on the linkages among commodity markets and introduces new perspectives and highlights regarding the connectedness and cross-herding between the U.S. and European natural gas futures markets. Gaining clarity on the segmentation or integration of natural gas futures markets is crucial for effective portfolio diversification and the implementation of robust hedging strategies.

Our findings emphasize a weak magnitude of integration between these two geographically distinct natural gas futures markets, while revealing much more pronounced magnitude of connectedness among the different segments (i.e., maturities) within the same geographical market. Moreover, the static and dynamic cross-herding analyses both reveal the lack of herd behavior between the U.S. and European markets, suggesting that investor behavior in one market is highly insensitive to the conditions prevailing in the second market.

The empirical findings of this research carry diverse implications, particularly for investors seeking to enhance their risk management, portfolio construction, and hedging strategies. Indeed, a better understanding of the integration level of the natural gas futures markets would enable to make more informed decisions, fine-tune portfolios and positions, all while mitigating global systemic risk.

There are numerous promising avenues for future empirical investigations. One limitation of our study is its exclusive focus on just two natural gas futures markets: the U.S. and European markets. Future investigations could broaden the scope by including an extended range of natural gas futures markets, thereby providing a more in-depth and all-encompassing insight into the network connectedness structure. Furthermore, it would be interesting to study the potential impact of emerging natural gas markets on the integration dynamics among developed natural gas futures markets, as these emerging players could reshape the global landscape.[4] Furthermore, future research could use connectedness and cross-herding results to explore the optimal portfolio structure for investors in the natural gas market.

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