

Vulnerability of European electricity markets: A quantile connectedness approach[☆]

Helena Chuliá^{a,b}, Tony Klein^{c,*}, Jorge A. Muñoz Mendoza^{d,e}, Jorge M. Uribe^f

^a Departament D'Econometria, Estadística I Economia Aplicada, Universitat de Barcelona (UB), Spain

^b RISKcenter, Institut de Recerca en Economia Aplicada (IREA), Universitat de Barcelona (UB), Spain

^c Queen's Business School, Queen's University Belfast, UK

^d Department of Business Management, University of Concepcion, Chile

^e School of Economics, University of Barcelona, Spain

^f Open University of Catalonia, Barcelona, Spain

ARTICLE INFO

JEL classification:

C22

L94

L95

Q4

Keywords:

Energy prices

Energy poverty

Markets distress

Market vulnerability

Spillovers

ABSTRACT

The most recent dramatic increases in European Gas and Electricity prices demonstrate how vulnerable Europe is to energy supply shocks. We investigate the transmission of shocks from natural gas prices to local electricity prices in 21 European electricity markets. Using a quantile connectedness model, we find that the vulnerability of electricity markets in Europe varies both over time and across quantiles. Natural gas price shocks have a significant and nearly symmetrical impact on extreme quantiles of electricity prices. However, for moderate price changes, there is a disconnection between electricity and natural gas markets. We also identify the European countries that are most and least vulnerable to shocks in natural gas prices, which is due to differing energy mixes for electricity production. This novel vulnerability index has implications for the development of country-specific regulations and energy policies aimed at reducing the reliance on natural gas in European economies, combating energy poverty, and promoting the growth of renewable energy sources.

1. Introduction

Natural gas plays a significant role in electricity generation, particularly in gas-fired power plants, which contribute to a substantial portion of the electricity supply mix. Compared to other power plant types, such as coal or nuclear energy, these gas-fired power plants are very flexible in their electricity production and output can be adjusted to demand relatively easily. The integration of gas-fired power plants into the electricity supply mix inevitably creates interdependencies between gas and electricity markets and it is essential that these dependencies are actively planned and managed over different time horizons (Chaudry et al., 2014; Sheikhi et al., 2015). Fluctuations in gas prices then directly affect the operational and economic viability of gas-fired power plants and their load management via the merit order scheme, in which the last fuel source for generation is the main determinant for the price of generated electricity. This way, natural gas prices have a significant influence on electricity prices due to interactions between gas and

electricity markets (Alexopoulos, 2017). Gas prices affect the cost of electricity generation, which impacts wholesale electricity prices. The bi-directional relationship between natural gas prices and electricity markets needs to be taken into consideration in any decision-making regarding efforts of carbon emission reduction or neutrality (Johnson and Keith, 2004; Chevallier et al., 2019). Wang et al. (2022) highlight the importance of natural gas as a technological catalyst on the way to scalable cost-effective renewable energy. With the established connection of gas prices and electricity prices, it remains to analyse if and to what extent the degree of price impact depends on the energy mix. In this study, we focus on European countries and analyse country-specific transmission intensities of shocks in natural gas prices, or more generally, in natural gas supply, to local electricity prices. Hence, we implicitly differentiate between different energy mixes and regulations and, in view of the most recent volatile periods of both natural gas and European electricity markets, find major differences in spillover and vulnerability across countries.

[☆] We appreciate the valuable comments of the participants of the 23th International Finance Conference (Durango, Mexico). We also thank the Editor and three anonymous referees for their valuable suggestions.

* Corresponding author.

E-mail addresses: hchulia@ub.edu (H. Chuliá), t.klein@qub.ac.uk (T. Klein), jormunozm@udec.cl (J.A. Muñoz Mendoza), juribeg@uoc.edu (J.M. Uribe).

<https://doi.org/10.1016/j.enpol.2023.113862>

Received 30 June 2023; Received in revised form 3 October 2023; Accepted 18 October 2023

Available online 31 October 2023

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This work addresses this interdependence in light of the recent and unprecedented increase in natural gas prices, or more generally, their extreme volatility, all over Europe. The inevitable link to the energy mix and subsequent change in electricity prices in each country differs significantly, translating to country-specific impacts and responses. However, this price fragmentation is not new and has been outlined in research already, albeit for price changes of less extreme manifestation. [Cassetta et al. \(2022\)](#) find that electricity prices do not converge despite regulatory harmonization and that the E.U. remains clustered in its price distribution. This is in line with previous findings of dispersion, for example in [Telatar and Yasar \(2020\)](#). One of the reasons for this recent inversion of price convergence is given as differing climate and energy policies on a national level [Cassetta et al. \(2022\)](#), which also plays a significant role in the present research. This work aims to address the vulnerability of the E.U. to natural gas price fluctuations and supply shocks with regard to electricity prices. In our sample, this supply shock is represented by the reduction of imported natural gas from Russia and the subsequent supply change to liquefied natural gas and natural gas from other sources in the vicinity of Europe. Securing this supply is still an ongoing challenge.

Our contributions to existing literature on the link of electricity and natural gas markets is threefold. Firstly, we adapt a novel methodology of [Ando et al. \(2022\)](#) to assess the connectedness of these markets. With this quantile vector autoregression, we provide robust evidence that changes of natural gas prices affect the electricity price distribution differently across quantiles, in particular for periods of substantial in- and decreases. Secondly, we derive a measurement for vulnerability of European electricity markets to changes in natural gas markets and show that clustering is present. For example, the Netherlands, Italy, and the United Kingdom have the most vulnerable electricity markets with regard to natural gas price fluctuations. On the other hand, Spain, Portugal, and Germany show the least vulnerability. These findings are of utmost importance for energy poverty and increasing price pressure on consumers and producers. Having identified countries with elevated vulnerability, targeted and country-specific policies can be derived. Furthermore, this vulnerability index allows for an objective analysis of different countermeasures taken by individual countries to combat these price increases. This differentiation might further improve the effectiveness of future measures. In a wider sense, the vulnerability index might also be consulted in view of inflation measures and should inform decision makers on the potential of proposed actions. Thirdly, we show that there is a significant time-variation of these spillover effects. In recent years, this spillover increased dramatically. This increased spillover highlights that, at differing degrees, European countries have recently experienced a higher exposure to gas supply shock risks and that long-term security of supply as well as price stability via market measures are of essential importance. These tasks are particularly challenging in view of Western sanctions on Russia and the discontinuation of direct gas imports via Nord Stream, for example, which are contributing factors to the increase in vulnerability.

Addressing energy poverty based on our results offers multiple insights. Especially in urban areas, a high natural gas dependency is source of vulnerability to extreme electricity price periods. However, flexible energy production with natural gas might also alleviate energy poverty, especially in more rural areas ([Pereira and Marques, 2023](#)). Furthermore, within community energy systems, particularly in thermal energy communities, subsidies on natural gas prices have proven to be more effective in ensuring energy security levels compared to other mechanisms such as CO₂ taxes ([Fouladvand et al., 2022](#)).

All three contributions of this study are highlighting the importance to derive policy and regulatory actions to address this increased dispersion not only on a price level (e.g. [Telatar and Yasar, 2020](#); [Cassetta et al., 2022](#)) but also with regard to time-varying spillover and diverging vulnerability across E.U. member countries. This study offers a comprehensive analysis in differing vulnerability and its possible effects on energy poverty.

The remainder of this study is organised as follows. Section 2 provides an overview of the employed methodology and links our advances to existing literature. Section 3 describes out data selection in detail and motivates our focus on 21 European electricity markets. Section 4 presents our results and offers a discussion with regard to differing vulnerability and implications thereof. Section 5 concludes.

2. Methodology

The empirical literature on connectedness in energy and financial markets is extensive, encompassing a variety of methodologies. Key approaches include Vine copulas ([Sukcharoen and Leatham, 2017](#)), Multivariate generalized autoregressive heteroskedasticity (MGARCH) models ([Karali and Ramirez, 2014](#)), Time-varying parameter vector autoregressive (TVP-VAR) models ([Jebabli et al., 2014](#); [Gong et al., 2020](#)), time-frequency connectedness ([Naeem et al., 2020](#); [Geng et al., 2021](#)), and least absolute shrinkage and selection operator vector autoregressive (LASSO-VAR) models ([Barbaglia et al., 2020](#); [Chuliá et al., 2023](#)). Many of these approaches have adapted the classical methodology developed by [Diebold and Yilmaz \(2012, 2014\)](#) to compute mean-conditional connectedness between financial time series. This adaptation provides significant advantages for international portfolio decisions and regulatory design in energy markets, as it helps identify specific pathways for shock transmission. However, these methods typically disregard the nature of connections at the extreme tails of the variable distribution.

In response to this limitation, several studies have focused on analysing extreme event connectedness, employing a quantile approach to compute linkage measures ([Saeed et al., 2021](#); [Bouri et al., 2022](#); [Luo et al., 2023](#); [Pham et al., 2023](#)). The primary advantage of quantile connectedness approaches lies in their ability to assess spillover intensity under different scenarios. This provides more detailed information for portfolio decisions and policy formulation compared to traditional methods that rely solely on mean-conditional connectedness. For instance, [Pham et al. \(2023\)](#) conducted an empirical analysis using returns quantile connectedness between the natural gas market and the stocks of the ten largest utilities companies in the United States, applying the framework of [Diebold and Yilmaz \(2012\)](#) through QVAR estimates. Their findings indicated that market dependence is dynamic across time and quantiles, with greater intensity observed at the extreme tails of the return distribution. This study exemplifies the advantages of the quantile connectedness approach in identifying shock transmission channels between markets and opportunities for international diversification at different quantiles. Furthermore, the quantile connectedness approach can facilitate the construction of vulnerability indicators that quantify a specific market's response to systemic shocks.

To assess the interconnectedness between electricity prices in various European markets and natural gas prices, we employ the quantile connectedness method introduced by [Ando et al. \(2022\)](#). This approach builds upon the conventional framework proposed by [Diebold and Yilmaz \(2012, 2014\)](#), but incorporates a quantile vector autoregression model, referred to as QVAR(p), under the following baseline structure:

$$y_t = \mu(\tau) + \sum_{j=1}^p \Phi_j(\tau)y_{t-j} + u_t(\tau), \quad (1)$$

where y_t and y_{t-j} are $k \times 1$ dimensional vectors that contain the endogenous variables in t and $t-j$, respectively. In our case, the QVAR(p) model is bivariate since it contains $k = 2$ endogenous variables, that is, the natural gas prices and the electricity prices of a specific market. In addition, the quantile of interest $\tau \in [0, 1]$, p is the autoregression order of the QVAR model, $\mu(\tau)$ is a $k \times 1$ dimensional conditional mean vector, $\Phi_j(\tau)$ is a $k \times k$ matrix that contains the coefficients of the QVAR system while $u_t(\tau)$ is a $k \times 1$ dimensional vector with a variance-covariance matrix of dimension $k \times k$, denoted by $\Sigma(\tau)$.

The equation-by-equation quantile approach of the VAR system can be written as:

$$y_{st} = \Phi'_s(\tau)z_t + u_{st}(\tau), \quad (2)$$

where $s = 1, 2, \dots, k$ and z_t indicates the $(kp+1) \times 1$ vector of all regressors including the intercept. The vector Φ_s contains the corresponding autoregressive coefficients at τ th-quantile and, naturally, the residuals $u_{st}(\tau)$ adhere to the conditional quantile restriction $Q_\tau(u_{st}(\tau)|z_t) = 0$, where Q_τ indicates the τ conditional quantile function of y_{st} .

According to [Koenker and Hallock \(2001\)](#), the autoregressive coefficients for a specific quantile τ can be estimate by solving the problem:

$$\min_{\Phi_s(\tau)} \sum_{t=1}^T (\tau - \mathbf{I}[y_{st} \leq \Phi'_s(\tau)z_t]) (y_{st} - \Phi'_s(\tau)z_t), \quad (3)$$

where $\mathbf{I}[\cdot]$ is the indicative function taking the value of 1 when $y_{st} \leq \Phi'_s(\tau)z_t$ and 0 otherwise, and T is the number of observations in the sample.

In order to compute the connectedness measures originally formulated by [Diebold and Yilmaz \(2012, 2014\)](#) using Wold's Theorem within the QVAR framework, we can express Equation (1) as an infinite moving average representation $QVMA(\infty)$ as follows:

$$y_t = \mu(\tau) + \sum_{i=0}^{\infty} \psi_i(\tau)u_{t-i}, \quad (4)$$

where the $k \times k$ dimensional coefficients matrix, denoted by $\psi_i(\tau)$, is defined as:

$$\psi_i(\tau) = \begin{cases} 0 & , i < 0 \\ \mathbf{I}_k & , i = 0 \\ \Phi_1\psi_{i-1}(\tau) + \Phi_2\psi_{i-2}(\tau) + \dots + \Phi_p\psi_{i-p}(\tau) & , i > 0 \end{cases} \quad (5)$$

According to [Diebold and Yilmaz \(2012\)](#), the moving average representation is relevant to understand system dynamics and connectedness statistics. To achieve order-invariant variance decompositions of the QVAR system, these connectedness measures employ the methodological framework proposed by [Koop et al. \(1996\)](#) and [Pesaran and Shin \(1998\)](#), hereinafter KPPS. Therefore, for $H = 1, 2, \dots$, we denote the KPPS H -step-ahead forecast error variance decomposition as:

$$\theta_{ij}^g(H) = \frac{\Sigma(\tau)_{ii}^{-1} \sum_{h=0}^{H-1} (e'_i \psi_h(\tau) \Sigma(\tau) e_j)^2}{\sum_{h=0}^{H-1} (e'_i \psi_h(\tau) \Sigma(\tau) \psi_h(\tau) e_i)}, \quad (6)$$

where $\Sigma(\tau)_{ii}$ is the standard deviation of the error of the i -th equation in the quantile τ , and e_i is a selection vector with value one at the i -th element and zero otherwise. As the sum of the elements of each row in Equation (6) is not equal to 1 ($\sum_{j=1}^k \theta_{ij}^g(H) \neq 1$), in order to get a unit sum of each row of the variance decomposition matrix, the following normalization must be done for each entry:

$$\tilde{\theta}_{ij}^g(H) = \frac{\theta_{ij}^g(H)}{\sum_{j=1}^k \theta_{ij}^g(H)}, \quad (7)$$

where by construction $\sum_{j=1}^k \tilde{\theta}_{ij}^g(H) = 1$ and $\sum_{i,j=1}^k \tilde{\theta}_{ij}^g(H) = k$. Equation (7) thus constitutes a natural measure of the pairwise directional spillover from variable j to variable i . Next, the total directional spillover received by variable i from all other variables j is:

$$S_{i \leftarrow}^g(H) = \sum_{\substack{j=1 \\ j \neq i}}^k \tilde{\theta}_{ij}^g(H), \quad (8)$$

Similarly, the total directional spillover transmitted by variable i to other variables j is:

$$S_{i \rightarrow}^g(H) = \sum_{\substack{j=1 \\ j \neq i}}^k \tilde{\theta}_{ji}^g(H). \quad (9)$$

This measure of connectedness plays a pivotal role in understanding the vulnerability of European electricity markets concerning the natural gas market. In our case, the bivariate QVAR model, represented by Equation (9), allows us to compute the directional spillover from the natural gas market to a specific electricity market for a given quantile. This directional spillover indicator can naturally be interpreted as a vulnerability index and can be used as a high-frequency tool for assessing the exposure of electricity markets to natural gas price dynamics.

The net spillover from variable i to the remaining variables j is given by:

$$S_i^g(H) = S_{i \rightarrow}^g(H) - S_{i \leftarrow}^g(H). \quad (10)$$

This measure of net connectedness can be understood as the net influence variable i has on the remaining variables j . Finally, using the KPSS variance decomposition, the adjusted total spillover or system-wide connectedness of [Chatziantoniou and Gabauer 2021](#), [Gabauer 2021](#) which ranges between $[0, 1]$, can be represented by:

$$S^g(H) = \frac{\sum_{i,j=1}^k \tilde{\theta}_{ij}^g(H)}{k-1}. \quad (11)$$

This spillover measure quantifies the contribution of the shocks of the k variables to the forecast error variance ([Diebold and Yilmaz, 2009](#)). Usually, this measure is used as a proxy for market risk, therefore, in our case, a higher $S^g(H)$ shows a higher degree of interconnectedness between the variables in the QVAR system.

3. Data

We use data from Bloomberg and the European Network of Transmission System Operators for Electricity (ENTOS-E) covering the period from January 1, 2015, to December 30, 2022, for a comprehensive set of 21 European electricity markets. This dataset encompasses the electricity prices of the following countries: Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, the Netherlands, Norway, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the UK. The dependence of these markets on natural gas prices coupled with the recent supply restrictions imposed by Russia have configured a scenario of unprecedented energy stress, whose effects on local electricity prices have accentuated the risk of energy poverty and hindered the transition process to renewable energy. This unique scenario, along with the heterogeneous energy matrix due to weather and generation differences across countries, provides an exceptional opportunity to analyse the impact of natural gas prices on European electricity prices. It also allows us to establish an empirical framework for the design of policies and regulations aimed at alleviating the energy crisis in the region. Additionally, the dataset incorporates natural gas prices represented by the Title Transfer Facility (TTF) and National Balancing Point (NBP) indices. Our dataset includes a total of 2084 transaction days for each time series, providing us with a large sample and complete records spanning eight years, which is crucial for accurately estimating spillover effects of natural gas on various quantiles of electricity price returns in each country.

[Fig. 1](#) depicts the dynamics of electricity prices in each country in relation to the TTF natural gas price. Notably, the energy crisis in

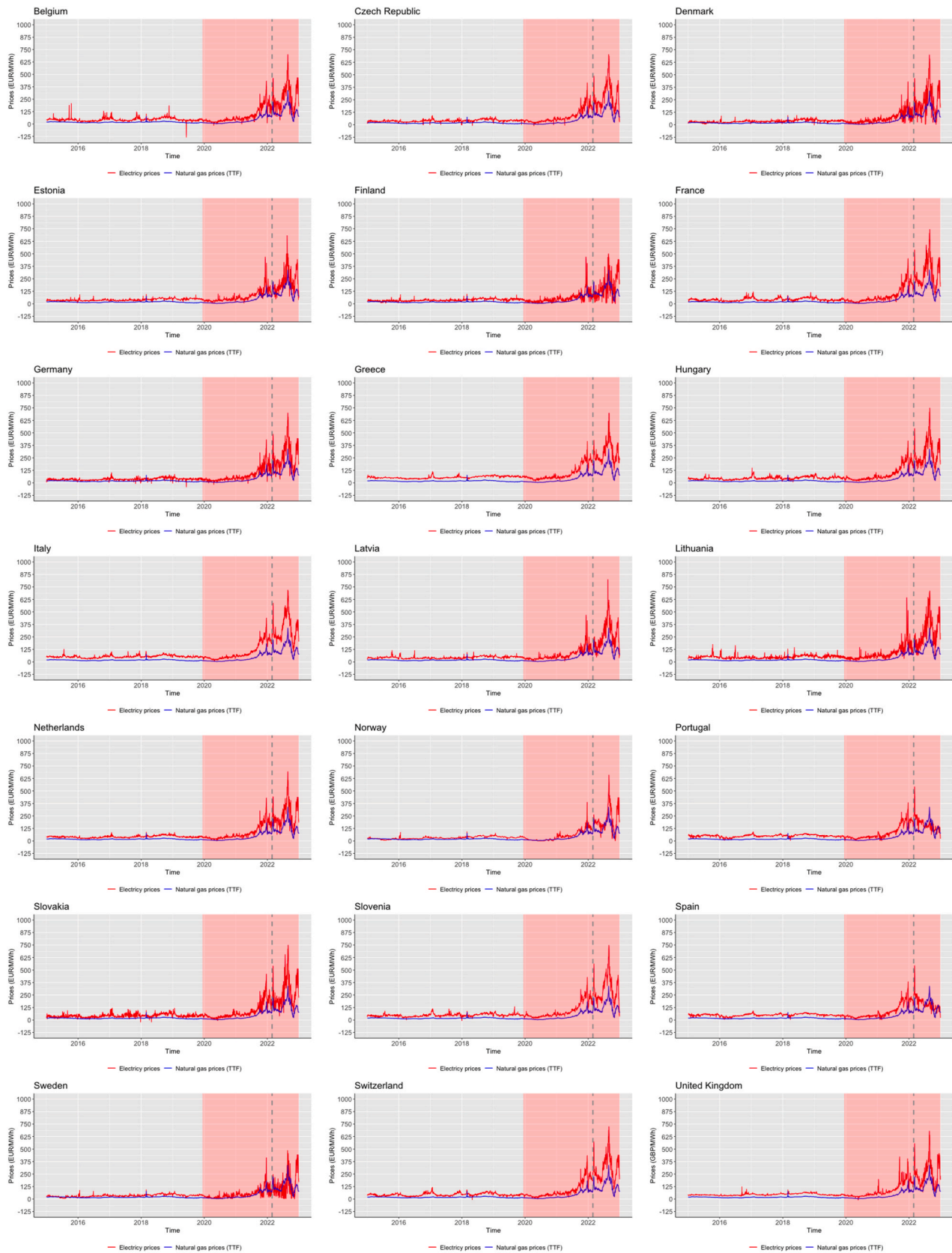


Fig. 1. Electricity and natural gas prices.

Note: The sample period spans from January 01, 2015, to December 30, 2022. The units of electricity prices are in EUR/MWh, except for the UK, which is in GBP/MWh. TTF natural gas prices are measured in EUR/MWh, while NBP natural gas prices are denoted in GBP/therm. The gray vertical dashed line indicates the date of the Russian invasion of Ukraine (February 24, 2022). The red shaded area represents the period encompassing the Covid-19 pandemic (since December 2019).

Europe, which began in the third quarter of 2021, marked a significant turning point in the behaviour of these markets. Prior to this period of energy stress, local electricity prices in Europe typically ranged from 29.4 euros per MWh (in Norway) to 54.7 euros per MWh (in Greece), while natural gas prices averaged 16.4 euros per MWh for the TTF index and 41.3 GBP/therm for the NBP index. However, after the third quarter of 2021, local electricity prices experienced a substantial increase, primarily driven by the surge in natural gas prices. This trend became even more pronounced in the wake of the Russian invasion of Ukraine, with the exception of Spain and Portugal, which exhibited different dynamics. During this period, local electricity prices ranged from an average of 119.1 euros per MWh (in Sweden) to 264.5 euros per MWh (in Italy). Simultaneously, natural gas prices climbed to average values of 102.1 euros per MWh for the TTF index and 80.2 GBP/therm for the NBP index. The supply restrictions imposed by Russia on the major European markets were a primary driver behind the increase in electricity prices and exacerbated the region's energy crisis in light of the heightened energy demand observed since the beginning of 2022. These circumstances prompted European markets to implement a series of measures aimed at mitigating the impacts of rising natural gas prices, with a particular focus on reducing dependence on this energy source and fostering the development of renewable energy.

Table 1 displays the descriptive statistics of the daily returns for electricity and natural gas prices. Panel A illustrates that the daily electricity prices fluctuate between 0.77% (Greece) and 4.58% (Lithuania), with the exception of Belgium (10.97%), Denmark (14.63%), Finland (16.61%), Sweden (18.37%), and Slovakia (183.42%), which have experienced significant periods of heightened volatility, registering the highest variability in their price movements. The excess kurtosis values and rejection of the Shapiro-Wilk test indicate that the electricity prices in each country do not follow a normal distribution. Furthermore, the ADF test results suggest that the time series of electricity prices in each country exhibit stationarity, which is a crucial characteristic for estimating the QVAR model. Panel B shows that the mean of the returns for both natural gas price indices is approximately 0%, and similar to the electricity prices, they do not follow a normal distribution. According to the ADF test, the daily returns of both the TTF and NBP indices exhibit stationarity.¹

4. Empirical results and discussion

4.1. Natural gas and electricity prices connectedness between extreme quantiles

Fig. 2 shows the total connectedness between the natural gas and electricity price returns for each European market across time and for different quantiles distribution.² Results are based on a 250-days rolling-window QVAR(1)³ and a 20-step-ahead forecast. This window length provides a suitable timeframe to capture the spillover dynamics between natural gas and electricity returns over one year.

Fig. 2 reveals four key insights that are of special interest for analyzing energy policy in European markets. First, total spillovers between natural gas and electricity price returns vary over time as well as

across quantiles. This dynamic and asymmetric connectedness between natural gas and electricity prices highlights differences in vulnerability levels of electricity markets and underscores the need for tailored energy policies to address natural gas shocks. Second, we observe strong connectedness between natural gas and electricity prices in scenarios of high and low returns for all countries of the sample, dynamic that changes over time and for some periods of energy stress such as the Russian invasion of Ukraine. Empirically, this finding supports the conclusions of Uribe et al. (2022) highlighting that dependence between electricity and natural gas prices is more substantial during episodes of stress in energy generation and naturally deserve closer monitoring by energy authorities. Our results show that spillovers are particularly pronounced for negative returns (quantiles below 20%) and positive returns (quantiles above 80%). Across all countries, we find that the spillover in this bivariate system is at least 40% in these extreme quantiles. Undoubtedly, within these scenarios, the transmission of price changes from natural gas to local electricity prices becomes more pronounced. This result heightens the potential risks of energy poverty in countries that rely heavily on natural gas, such as the Netherlands, Italy, and the United Kingdom, while also potentially impeding their progress in renewable energy development policy.

Third, natural gas and electricity price returns are practically disconnected in quantiles close to the median. Generally, within the 20%–80% quantiles, we observe a consistent and rapid weakening of spillovers that holds over time. Consequently, under normal conditions, European electricity markets do not exhibit significant vulnerability to natural gas shocks, making the need for stabilization mechanisms less relevant. However, the degree of interconnection between these markets varies across countries and is particularly influenced by the role of natural gas in their energy source mix. Indeed, the range of daily returns defining the 'lack of connectedness zone' between the 20% and 80% quantiles differs significantly among countries. For instance, in countries like Slovakia (with returns ranging between -20.44% and 24.77%), Finland (between -17.68% and 21.47%), Denmark (ranging from -17.56% to 21.78%), and Germany (with returns between -16.89% and 17.25%), the wider ranges indicate a greater resilience, suggesting that their respective electricity markets appear less susceptible to disruptions in the natural gas market. A common characteristic among these countries is their limited reliance on natural gas, which constitutes less than 15% of their total energy sources.⁴ Conversely, countries with a higher share of natural gas in their energy mix exhibit narrower ranges of returns between the 20% and 80% quantiles. For example, the United Kingdom (with returns ranging from -6.33% to 6.67%), Greece (between -6.78% and 7.32%), Portugal (ranging from -8.06% to 8.37%), and Spain (with returns between -8.18% and 8.63%) have smaller return ranges, indicating that their electricity markets are more vulnerable to natural gas shocks. In these cases, natural gas comprises between 25% and 39% of their total energy sources. These findings highlight the importance of considering a country's energy matrix when implementing price stabilization mechanisms for European electricity markets. Such mechanisms can effectively mitigate price pass-through, particularly in markets with a higher risk of energy poverty that are exposed to swifter transmission channels from the natural gas market.

Finally, we observe periods where spillovers either disappeared or intensified, regardless of the returns quantile. On one hand, during 2018, we note a weakening of spillovers in most markets (except for Belgium, Netherlands, and the United Kingdom). This could be attributed to systemic factors influencing the dynamics of natural gas and electricity markets. On the other hand, the Russian invasion of Ukraine resulted in intensified spillovers in markets such as France, Hungary, Italy, Portugal, Spain, Switzerland, and the United Kingdom. These

¹ The majority of electricity price series exhibit stationarity, whereas some of them, along with the natural gas price series, display non-stationary behaviour. Consequently, we opted to employ daily returns to ensure stationarity for all variables. Nevertheless, given that a substantial portion of the electricity price series are stationary, it can be inferred that there is no a common trend in prices.

² The TTF index serves as the benchmark for natural gas prices for all estimations. However, we also conducted the same estimations using the NBP index as a reference for natural gas prices, and we obtained similar results.

³ The order of the QVAR model was determined using the Bayesian Information Criterion (BIC).

⁴ We are using 2020 as the reference year for the data. For more details see the Our World in Data web site at www.ourworldindata.org.

Table 1
Descriptive statistics for the daily returns of natural gas and electricity prices.

Variable	Obs.	Mean	St. Dev.	Min	Max	Skewness	Kurtosis	SW test	ADF test
<i>A. Electricity markets</i>									
Belgium	2084	10.97	327.71	-548.04	14,760.00	43.82	1969.13	0.03***	-12.58***
Czech Republic	2084	1.89	117.4	-2263.62	3380.45	14.06	568.30	0.11***	-12.25***
Denmark	2084	14.63	205.88	-792.88	7882.23	30.71	1098.06	0.11***	-12.47***
Estonia	2084	2.75	27.2	-80.7	387.39	4.85	57.02	0.71***	-13.25***
Finland	2084	16.61	197.22	-98.36	7701.54	29.88	1117.35	0.13***	-11.33***
France	2084	2.99	33.42	-86.09	995.92	13.91	382.26	0.52***	-13.75***
Germany	2084	3.51	77.07	-1696.03	978.89	-5.06	167.66	0.39***	-13.35***
Greece	2084	0.77	12.05	-50.34	106.34	1.17	10.39	0.91***	-15.22***
Hungary	2084	1.91	21.94	-74.18	446.77	5.24	88.56	0.77***	-14.35***
Italy	2084	0.9	13.3	-56.54	85.35	1.04	7.29	0.94***	-14.61***
Latvia	2084	2.29	23.91	-80.7	387.39	4.25	51.86	0.75***	-13.46***
Lithuania	2084	4.58	35.41	-73.25	408.27	3.36	26.22	0.76***	-11.89***
Netherlands	2084	2.06	23.97	-69.76	385.7	6.01	79.91	0.67***	-11.68***
Norway	2084	2.5	49.61	-92.73	2065.80	34.95	1438.70	0.16***	-12.85***
Portugal	2084	3.48	55.7	-91.2	2050.99	26.68	915.63	0.19***	-11.97***
Slovakia	2084	183.42	8083.13	-684.34	369,000.00	45.58	2079.82	0.01***	-12.63***
Slovenia	2084	1.99	44.56	-587.52	1743.01	27.65	1133.86	0.23***	-12.83***
Spain	2084	3.38	51.83	-91.16	1893.15	25.6	874.81	0.22***	-11.81***
Sweden	2084	18.37	172.73	-96.38	4633.52	16.47	356.86	0.18***	-10.21***
Switzerland	2084	1.22	26.04	-772.71	269.3	-11.35	384.42	0.54***	-13.01***
United Kingdom	2084	0.79	18.06	-369.4	211.63	-2.2	112.84	0.61***	-12.98***
<i>B. Natural Gas indices</i>									
TTF	2084	0.28	6.72	-63.82	96.51	2.69	45.45	0.69***	-13.00***
NBP	2084	0.77	18.07	-98.55	647.52	23.02	799.79	0.28***	-12.28***

Note: Sampled period extends from January 01, 2015 to December 30, 2022. The TTF natural gas prices are measured in EUR/MWh, and NBP natural gas prices are measured in GBP/therm. Units of electricity prices are measured in EUR/MWh, except for the UK, which is in GBP/MWh. SW refers to the Shapiro-Wilk test for the null of normality. ADF corresponds to the Augmented Dickey-Fuller unit root test (the alternative hypothesis is a stationary process with intercept but without trend). Superscripts ***, **, * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

intensified spillovers can be attributed to the supply restrictions of Russian natural gas to these markets, and the subsequent increase in local electricity prices experienced by most European markets (European Commission, 2022). These findings are also further supported by Fig. 3, which depicts the total spillovers for high quantiles (90% and 95%), low quantiles (10% and 5%), as well as for the 50% (median) quantile of natural gas and electricity returns. Specifically, the returns at the 50% quantile exhibit time-varying spillovers, generally lower than 5%. However, for the most extreme return quantiles, we observe more intense spillovers between the natural gas and electricity markets, indicating a heightened level of interdependence between these markets. These findings underscore the necessity for energy policies capable of adapting to systematic events that may exacerbate energy poverty in European countries. Furthermore, these findings accentuate the vulnerability of electricity markets, particularly in countries with less diversified energy sources. Figures A1 and A2 in the appendix describe similar results using a 125-days rolling-window, respectively.

Fig. 4 shows the directional spillover from the natural gas market to the electricity market in each country for high quantiles (90% and 95%), low quantiles (10% and 5%), as well as for the 50% (median) quantile of the return's distribution. This spillover serves as an indicator of the vulnerability of European electricity markets to natural gas price shocks. The vulnerability index quantifies the degree to which changes in natural gas prices influence variations in electricity prices during market distress scenarios. It serves as a high-frequency tool for assessing the susceptibility of electricity markets to natural gas price dynamics. A higher index value indicates a greater vulnerability of the power market to these shocks. Consequently, this index provides policymakers with a means to not only monitor market developments during periods of market distress and heightened volatility, such as those caused by disruptions in natural gas supply but also to evaluate the impact of various policies aimed at mitigating the transmission of price fluctuations from fuel markets to power markets. These policies may include subsidies, price caps, and other interventions. Indeed, variations in the transmission of volatility and the effectiveness of different policies can account for differences in both the level and the trajectory of these indices.

Our results indicate that the vulnerability index is time-varying, and in nearly all cases, it remains below 40%, with an average spillover of 30%. In other words, around 30% of the 20-days-ahead forecast error variance decomposition of electricity price returns can be attributed to shocks originating from the natural gas market. Furthermore, the results demonstrate that directional spillovers at quantile 50% are close to 0%, while they are higher for extreme return quantiles. Notably, there is a certain symmetry in the response of electricity prices to natural gas price shocks between the extreme quantiles. For instance, the directional spillovers for the 5% and 95% return quantiles exhibit striking similarity, as do the 10% and 90% quantiles. This finding indicates that the vulnerability of European electricity markets exhibits an almost symmetrical response in extreme quantiles, while remaining nearly zero in mean quantiles. This emphasizes the importance of addressing these scenarios through policies designed to stabilize prices. Nevertheless, the directional spillover dynamics differ across countries, a phenomenon clearly attributed to idiosyncratic factors inherent to each market. Hence, it is desirable to tailor the energy policy to not only the specific return scenarios but also to the unique energy conditions prevalent in each country. Figure A3 in the appendix shows similar results using a 125-days rolling-window. Lastly, Fig. 5 illustrates the net spillover for electricity price returns, revealing mixed and varying results across time and quantiles. Notably, we observe the net receiver nature of certain electricity markets after the Russian invasion of Ukraine, including the Czech Republic, Greece, Italy, Portugal, Slovenia, Spain, Switzerland, and the United Kingdom. This finding holds across quantiles. Figure A4 in the appendix shows similar results, using a 125-day rolling window.

4.2. Vulnerability of the electricity markets

The previous section established the dynamic nature of directional spillovers from the natural gas market to various electricity markets across Europe. These spillovers exhibit temporal fluctuations and distinct patterns across quantiles. These measures of interconnectedness arise as a valuable tool in energy policy, as they serve as dynamic vulnerability indicators for individual electricity markets, gauging their

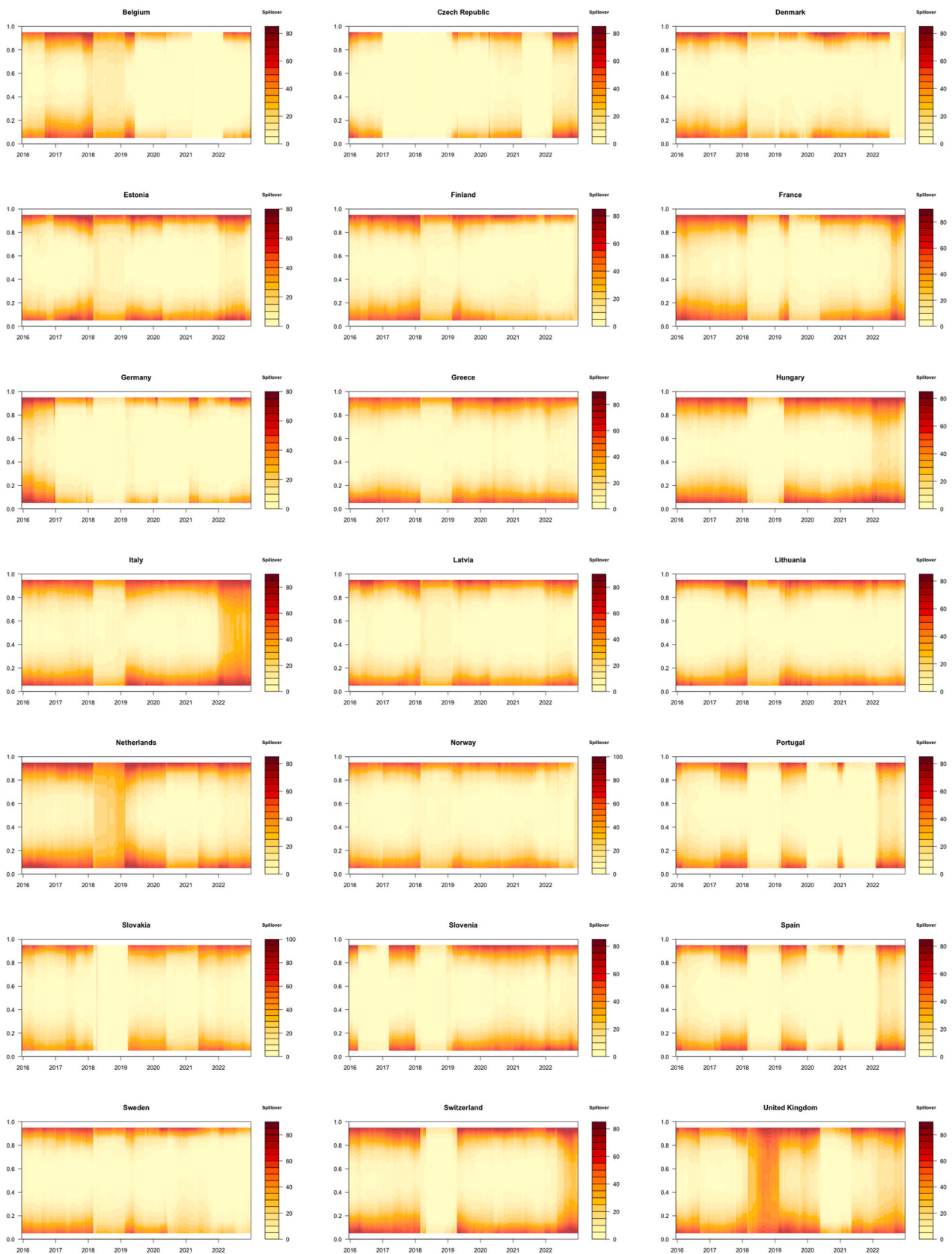


Fig. 2. Total connectedness between electricity and natural gas price returns across time and quantiles. *Note:* The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 250 days and a 20-step-ahead forecast error variance decomposition.

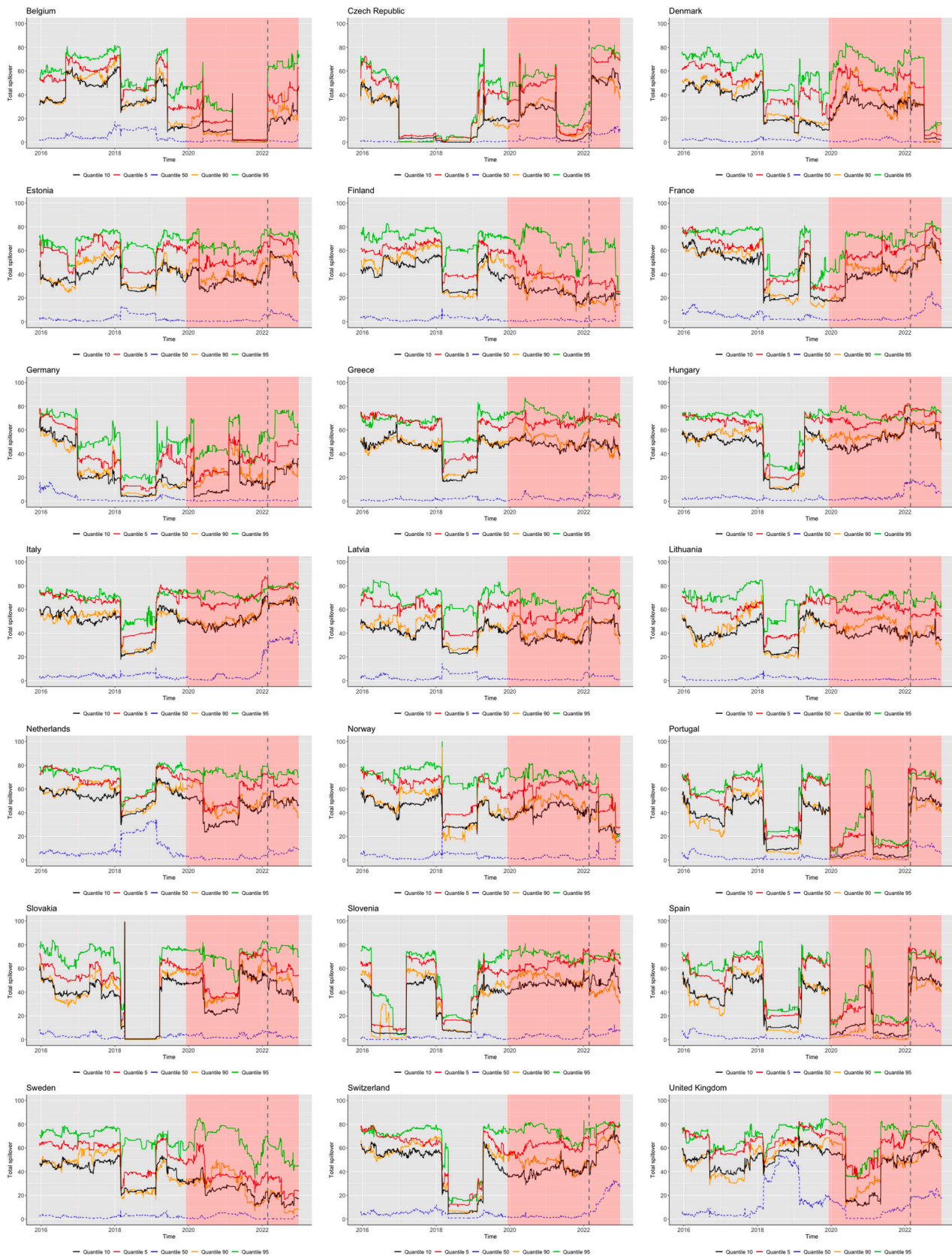


Fig. 3. Total connectedness index between electricity and natural gas price returns (quantiles 5, 10, 50, 90 and 95).
Note: The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 250 days and a 20-step-ahead forecast error variance decomposition. The gray vertical dashed line indicates the date of the Russian invasion of Ukraine (February 24, 2022). The red shaded area represents the period encompassing the Covid-19 pandemic (since December 2019).

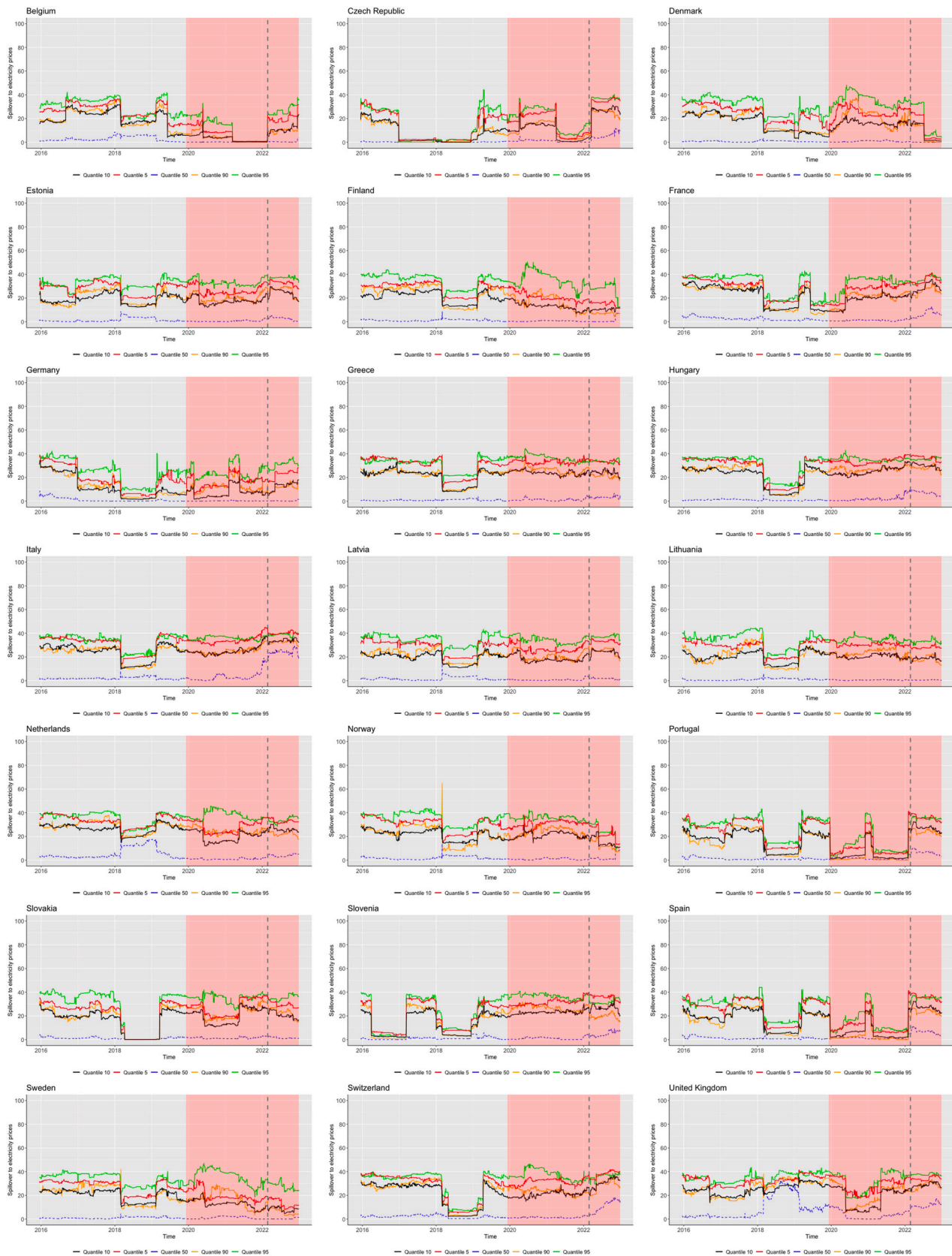


Fig. 4. Total directional connectedness from natural gas price returns to electricity prices (quantiles 5, 10, 50, 90 and 95).
 Note: The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 250 days and a 20-step-ahead forecast error variance decomposition. The gray vertical dashed line indicates the date of the Russian invasion of Ukraine (February 24, 2022). The red shaded area represents the period encompassing the Covid-19 pandemic (since December 2019).

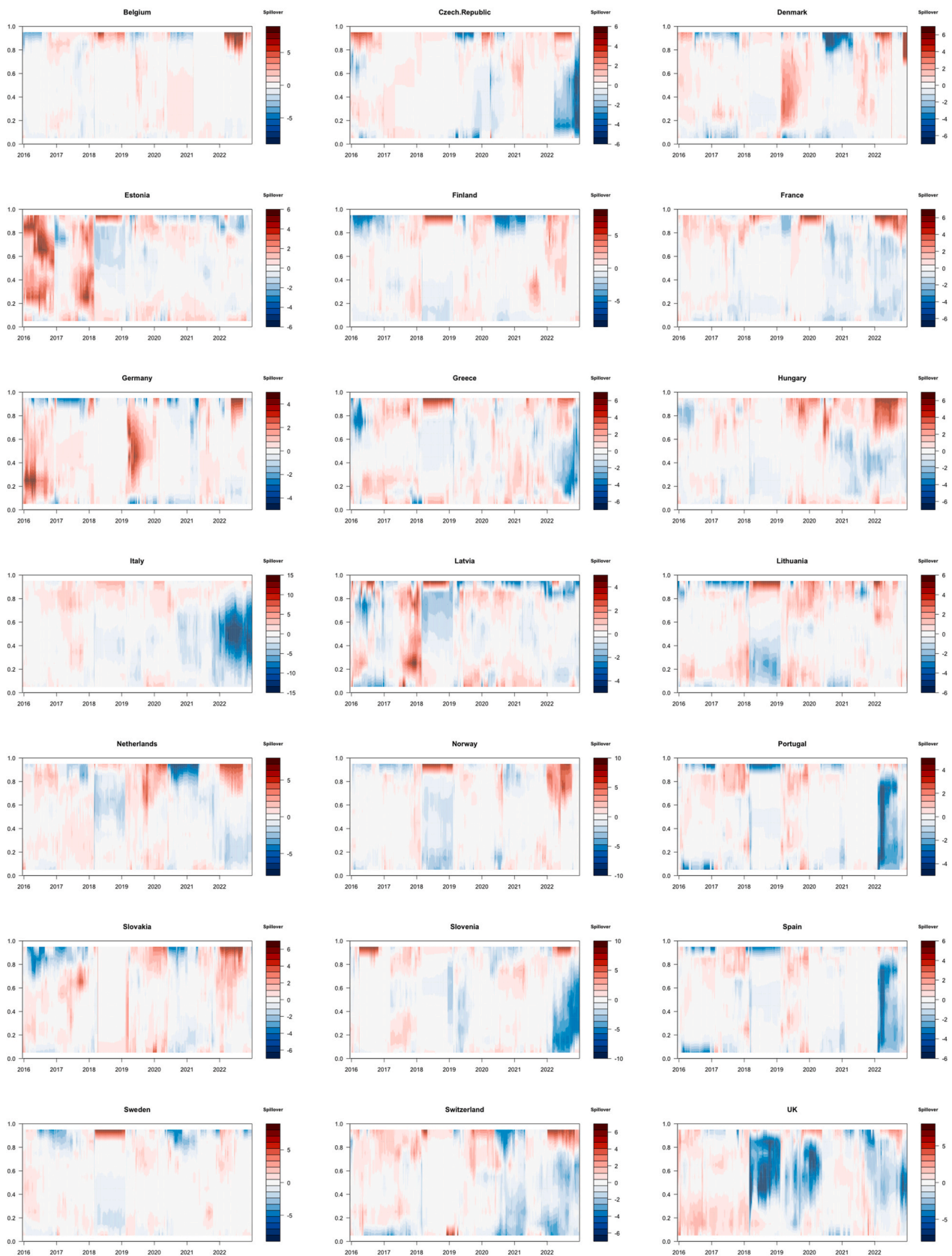


Fig. 5. Net total directional connectedness in electricity markets across time and quantiles.
Note: The sample period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 250 days and a 20-step-ahead forecast error variance decomposition.

susceptibility to shocks originating from the natural gas market. Consequently, they can provide valuable guidance for tailoring energy policies to address diverse scenarios and market characteristics.

In this section, we present an average measure of a country’s electricity market vulnerability over the entire analysis period. This measure is derived from the simple average of the directional spillover index from the natural gas market to a particular electricity market. Fig. 6 illustrates the average directional spillover, revealing two key findings. First, there is a similarity in the magnitude of vulnerability between extreme quantiles. The average spillover for high positive returns (95% quantile) is 30%, while the vulnerability to negative return scenarios (5% quantile) stands at 26%. Between the 90% and 10% quantiles, the average directional spillovers are 20% and 19% respectively. Contrary to the findings of Uribe et al. (2022), this indicates a certain degree of symmetry in the response of electricity markets to shocks transmitted by the natural gas market (at extreme quantiles). This finding holds significant implications for the energy policy in European markets, as it underscores the consistent and strong connection between these markets and the natural gas market during periods of both high and low returns. Consequently, energy authorities can strategically allocate their efforts to mitigate the transmission of natural gas price fluctuations to local electricity prices, with a primary focus on scenarios characterized by higher volatility.

Second, the average response of electricity markets to natural gas disruptions varies significantly among countries. This suggests that while efforts to address the energy crisis in Europe should primarily target the extremes of the return distribution, the design of energy policy must also consider the unique characteristics of each country. Consequently, identifying the electricity markets that are most and least vulnerable to shock transmission from the natural gas market becomes

essential.

The Netherlands, Italy, the United Kingdom, and Switzerland emerge as the most vulnerable markets to natural gas price shocks across both high returns (95% and 90% quantiles) and negative returns (5% and 10% quantiles). In the case of the 95% quantile of returns, we observe that in the Netherlands, Italy, the United Kingdom, and Switzerland, an average of 36.17%, 34.65%, 34.41%, and 32.73%, respectively, of the 20-day-ahead forecast error variance decomposition of electricity price returns can be attributed to shocks transmitted from the natural gas market. A similar pattern emerges for the 5% quantile of returns, with these figures being 31.67%, 33.36%, 31.48%, and 29.80%, respectively. The comparison between the 90% and 10% quantiles reveals a comparable situation. Although Fig. 6 depicts slight positional shifts among countries across different quantiles, the analysis identifies these markets as particularly susceptible to both high and low returns scenarios. Given this higher sensitivity to the natural gas market, these countries should establish regulatory mechanisms to mitigate the transmission of shocks from the natural gas market and promote the transition to renewable energy sources to reduce dependency.

Third, the least vulnerable electricity markets are accurately identified as well. The Czech Republic, Germany, Belgium, Portugal, and Spain demonstrate lower vulnerability across different extreme quantiles. In these cases, the average vulnerability index for the 95% quantile of returns varies from 18.43% (Czech Republic) to 25.42% (Germany), whereas for the 5% quantile of the returns distribution, the spillover ranges from 16.49% (Czech Republic) to 22.89% (Spain). The 90% and 10% quantiles of the return distribution reveal a similar pattern. While there may be minor variations in the rankings, the magnitude of the average spillover is not significantly affected. Similar results, using a 125-day rolling window, are presented in Figure A5 of the Appendix.

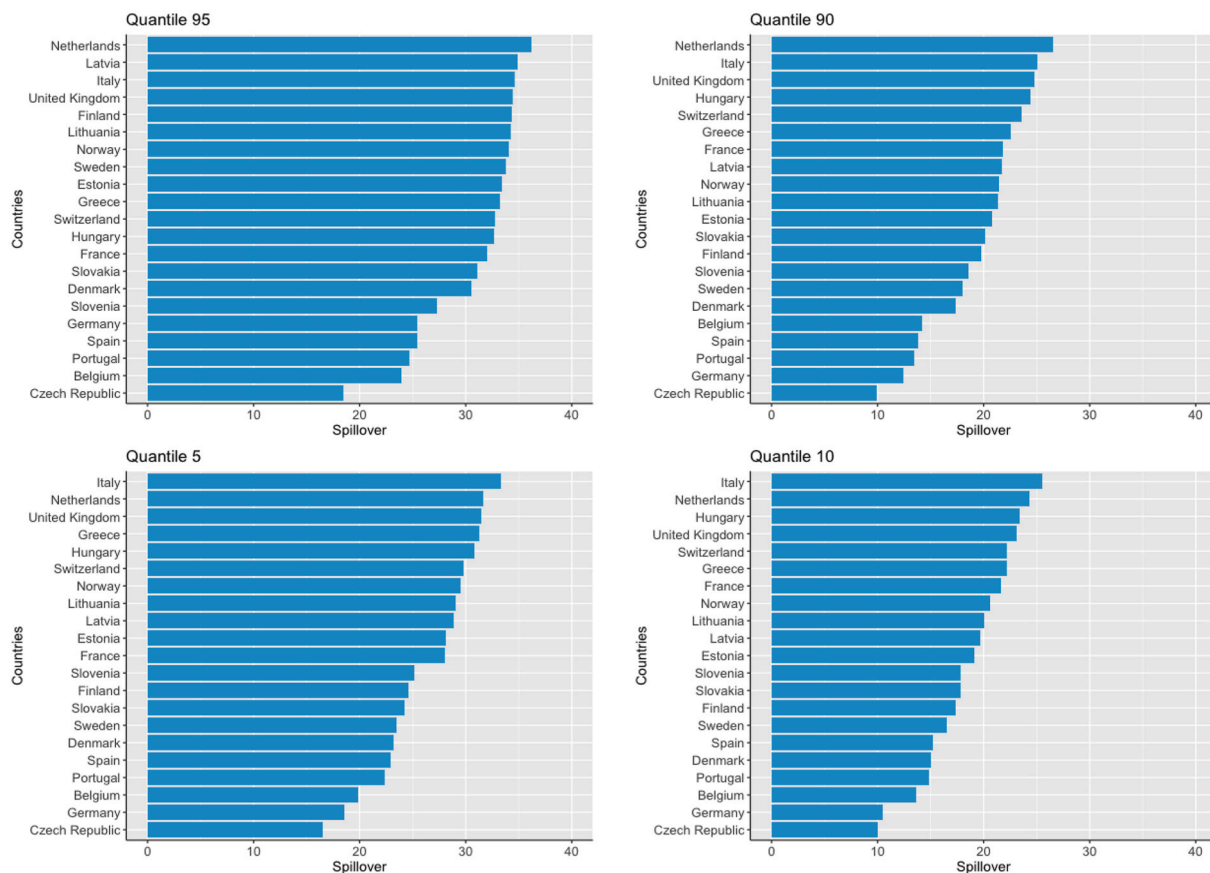


Fig. 6. Average directional connectedness from natural gas to electricity price returns.

Note: Average directional connectedness from natural gas to electricity price returns. The sample period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 250 days and a 20-step-ahead forecast error variance decomposition.

Before concluding, it is essential to recognize that the role of natural gas in addressing energy poverty has a dual nature. In urban areas, natural gas can pose a source of vulnerability, potentially disrupting the smooth operation of electricity markets and adversely affecting prices, especially for the most vulnerable consumers. Conversely, in less densely populated towns, suburbs, and rural areas it serves as a means to alleviate energy poverty (Pereira and Marques, 2023). Furthermore, within the framework of community energy systems, particularly in thermal energy communities, subsidies on natural gas prices have proven to be more effective in ensuring energy security levels compared to other mechanisms such as CO₂ taxes (Fouladvand et al., 2022). In summary, our findings underscore the vulnerability natural gas presents in urban areas with centralized electricity dispatch mechanisms, while in other contexts, a nuanced analysis is necessary to consider the positive impacts of natural gas provision. Interventions should always be tailored to the specific context.

5. Conclusions and policy implications

This study contributes to the existing literature on electricity market policies by employing a novel approach based on quantile vector autoregressions to analyse the vulnerability of these markets to natural gas price shocks. The findings of this study have relevant implications for policymakers and risk analysts across the European Union.

First, the study demonstrates that natural gas price shocks impact different segments of the electricity price distribution. Specifically, extreme quantiles of the distribution, corresponding to periods of substantial electricity price increases or decreases, are particularly sensitive to natural gas price fluctuations. This emphasizes the need for increased market monitoring during these episodes, as they are associated with heightened market turmoil and volatility. Governments and regulatory authorities should pay special attention to these extreme quantiles to ensure market stability and protect vulnerable consumers from sudden price spikes.

Furthermore, the study highlights the risks associated with the strong interdependence between natural gas and electricity markets, particularly during periods of market turmoil. When electricity demand exceeds supply from renewable or nuclear sources, natural gas prices become crucial for meeting the demand, leading to a transmission of fuel market volatility to electricity markets. This indicates the necessity to decouple electricity markets from natural gas prices, as fuel markets are known for their volatility and susceptibility to financialization. Maintaining a strong connection between the two markets during market turmoil can indirectly impact the stability of electricity markets.

Importantly, the research findings underscore the time-varying nature of spillover effects from natural gas to electricity. Recent times have witnessed relatively high spillover effects, suggesting the need for continuous monitoring and proactive risk management strategies. Moreover, the analysis reveals that certain European markets, such as Spain, Portugal, Italy, and Slovenia, act as net givers of shocks to the system, in recent years, while others like Hungary, the Netherlands, Belgium, and Switzerland continue to be net receivers, particularly during scenarios of high positive electricity returns, indicating their

greater vulnerability. Our study also provides a ranking of countries' vulnerability throughout the sample period. Italy and Netherlands emerge as the most vulnerable market according to our summary statistics of vulnerability, while the Czech Republic and Germany are shown to be the least vulnerable (followed closely by Spain, Portugal and Belgium).

Energy poverty arises when households cannot afford essential energy services necessary for an adequate standard of living and good health, such as proper heating, cooling, lighting, and essential electrical appliances. This situation is typically the result of a combination of three factors: low income, high energy expenses, and inefficient energy use. Our research introduces innovative indicators, specifically our time-varying vulnerability indicators, to address the second factor in the energy poverty equation.

We argue that unexpected energy price shocks, which disproportionately affect the high-energy expenses of vulnerable households with very limited access to credit, should be a primary focus in tackling energy poverty. Our indicators offer improved tools for monitoring this critical aspect of energy poverty, providing real-time insights into the impact of policies aimed at stabilizing electricity prices, such as those implemented by Spain in response to the Russian-Ukrainian conflict in 2022–2023.

In this context, a complete shift away from natural gas for electricity generation may not be immediately feasible. Consequently, it may be worth considering subsidies and price caps for natural gas in wholesale markets, while carefully evaluating their effects on the overall electricity market. Our findings highlight a previously underappreciated vulnerability in urban areas relying on centralized electricity distribution systems, particularly when exposed to fluctuations in natural gas prices. These price fluctuations can significantly contribute to the challenge of energy poverty in such areas. It is imperative to tailor interventions to specific circumstances when addressing this issue in different contexts.

CRedit authorship contribution statement

Helena Chuliá: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Tony Klein:** Conceptualization, Investigation, Writing – original draft, Validation, Writing – review & editing, Project administration. **Jorge A. Muñoz Mendoza:** Methodology, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Jorge M. Uribe:** Methodology, Formal analysis, Writing – original draft, Visualization, Writing – review & editing.

Declaration of competing interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability

Data will be made available on request.

Appendix

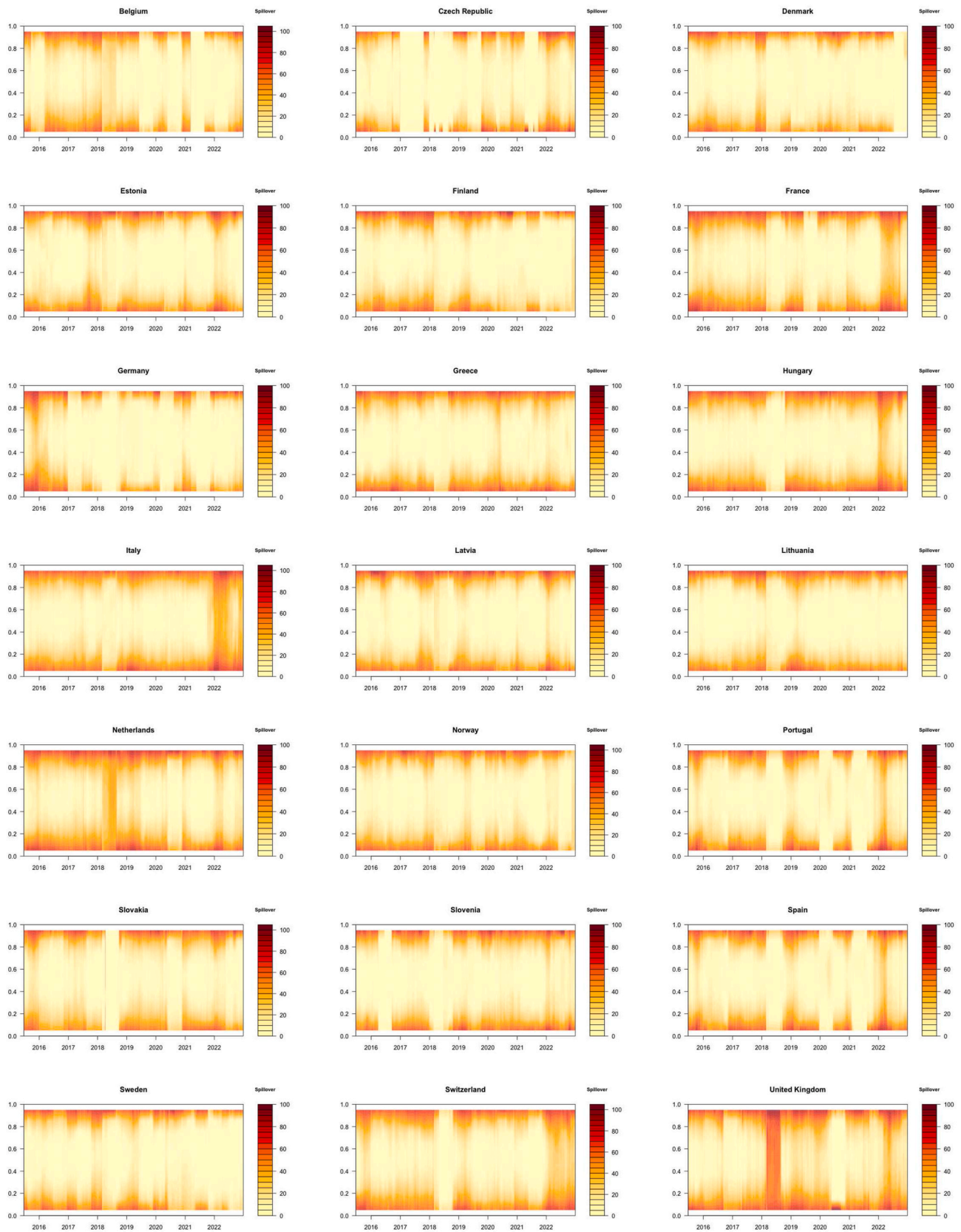


Fig. A1. Total connectedness between electricity and natural gas price returns across time and quantiles. *Note:* The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 125 days and a 20-step-ahead forecast error variance decomposition.

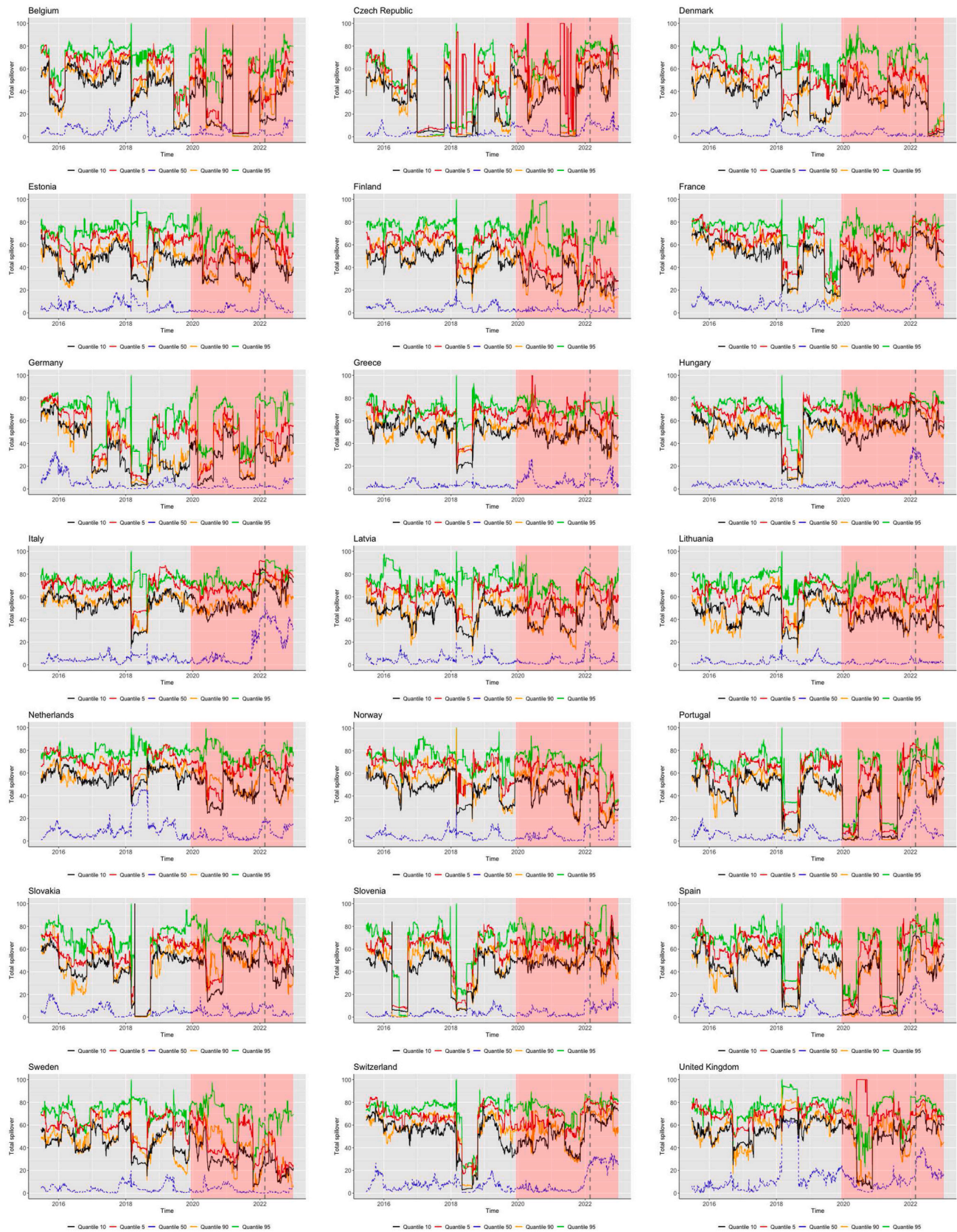


Fig. A2. Total connectedness index between electricity and natural gas price returns (quantiles 5, 10, 50, 90 and 95).
 Note: The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 125 days and a 20-step-ahead forecast error variance decomposition. The gray vertical dashed line indicates the date of the Russian invasion of Ukraine (February 24, 2022). The red shaded area represents the period encompassing the Covid-19 pandemic (since December 2019).



Fig. A3. Total directional connectedness from natural gas to electricity price returns (quantiles 5, 10, 50, 90 and 95).

Note: The sampled period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 125 days and a 20-step-ahead forecast error variance decomposition. The gray vertical dashed line indicates the date of the Russian invasion of Ukraine (February 24, 2022). The red shaded area represents the period encompassing the Covid-19 pandemic (since December 2019).

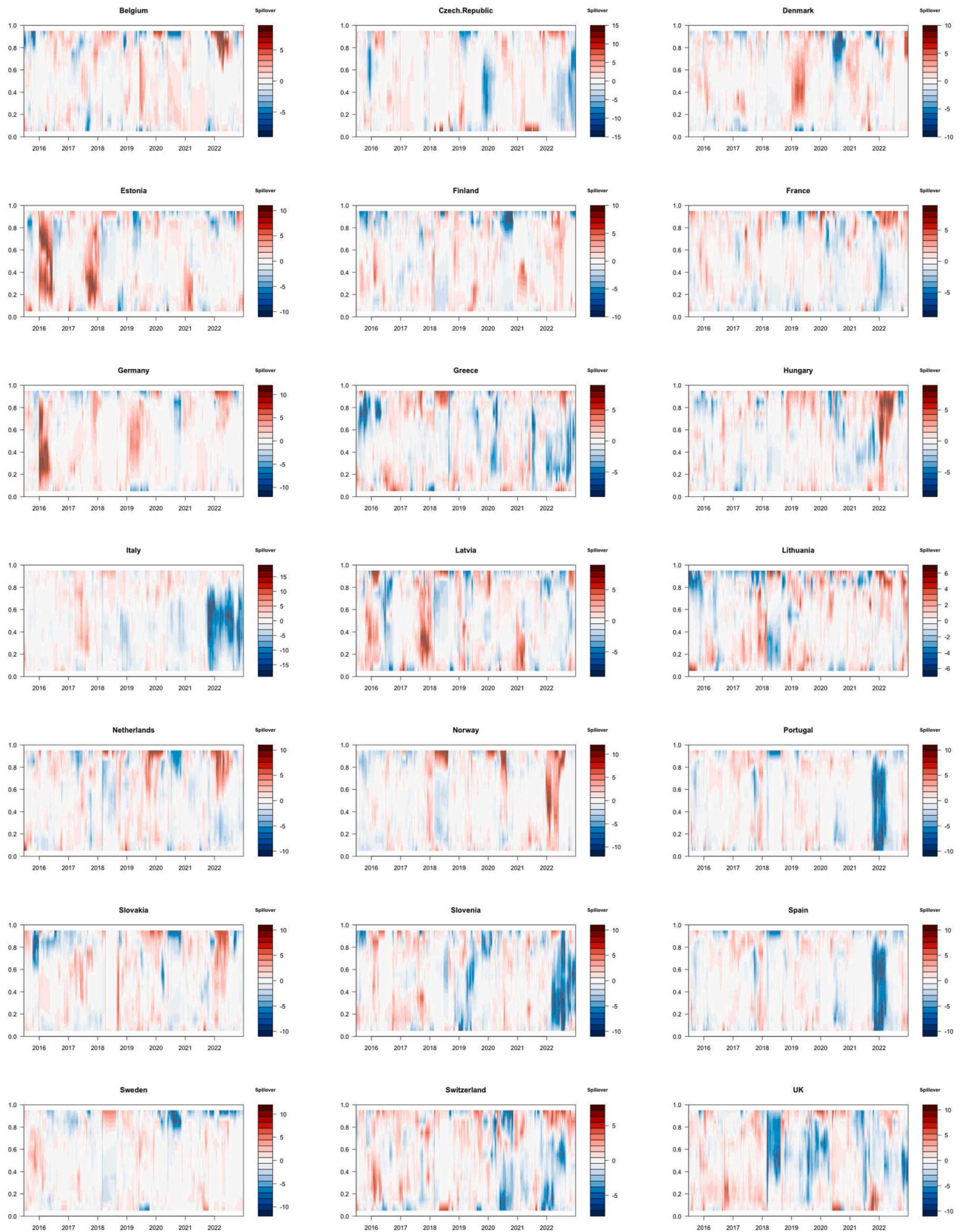


Fig. A4. Net total directional connectedness in electricity markets across time and quantiles.
 Note: The sample period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 125 days (selected based on BIC) and a 20-step-ahead forecast error variance decomposition.

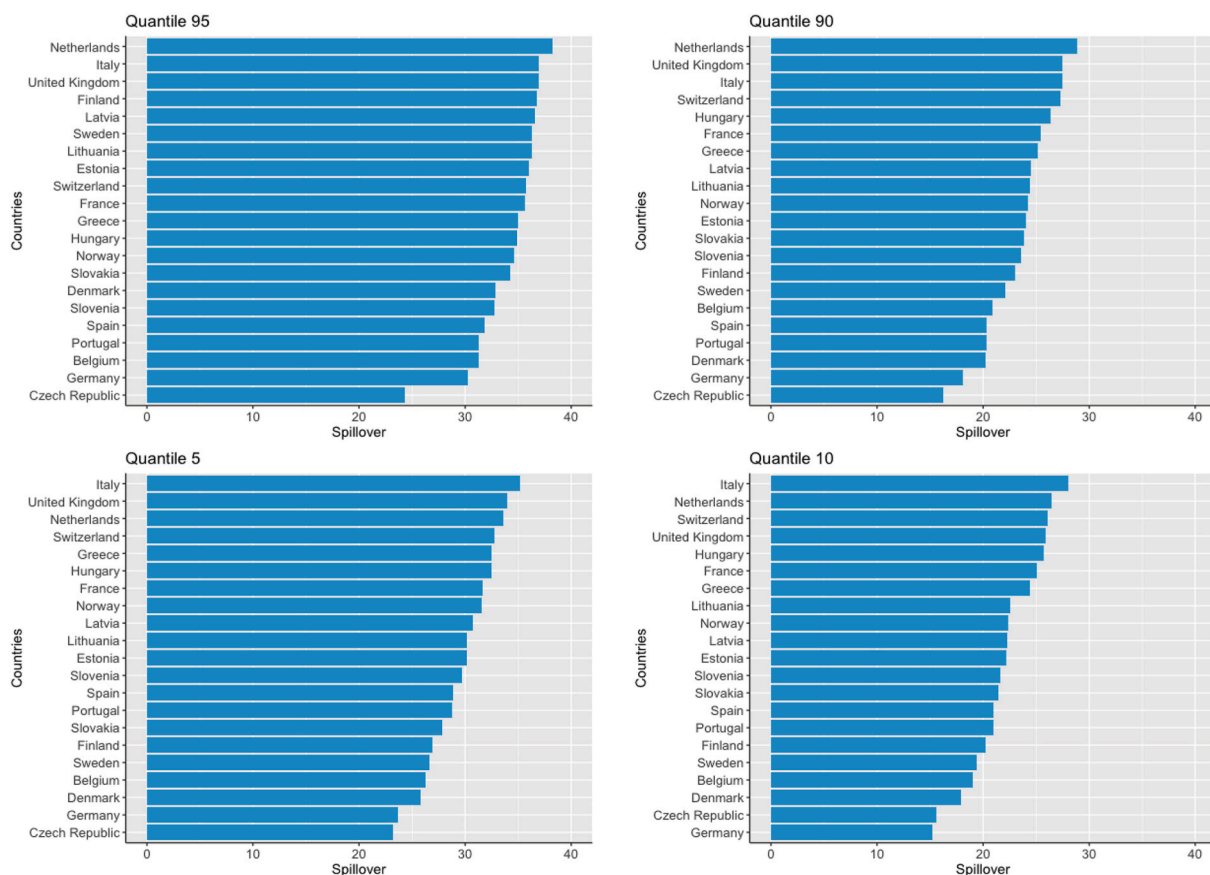


Fig. A5. Average directional connectedness from natural gas to electricity price returns.

Note: Average directional connectedness from natural gas to electricity price returns. The sample period spans from January 01, 2015 to December 30, 2022. Results based on a bivariate QVAR(1) model (selected based on BIC) with a rolling-window of 125 days and a 20-step-ahead forecast error variance decomposition.

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