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PRICE VOLATILITY IN THE EUROPEAN ELECTRICITY MARKET

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PRICE VOLATILITY IN THE EUROPEAN ELECTRICITY MARKET

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ABSTRACT

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The aim of this thesis is to examine the dynamics of volatility spillovers in European electricity markets and to assess how this phenomenon was affected by the recent energy crisis. The sharp increase in electricity prices and their associated volatility in recent years has drawn significant attention, making it important to analyse how volatility propagates across interconnected European markets. The first chapter provides an overview of the European electricity market, including its institutional framework, development, price formation mechanisms, and key determinants of volatility, together with a review of the relevant literature. The second chapter defines the objectives and outlines the applied research methodology. The empirical analysis focuses on selected European markets and examines the evolution of electricity prices and volatility, followed by a spillover analysis. Using the Diebold-Yilmaz framework, the thesis investigated the evolution of market interconnectedness, identifies the main transmitters and receivers of volatility and evaluates changes during the analysed period. The results indicate an increasing trend in total spillovers, suggesting that systemic interconnectedness play now plays a dominant role in price volatility. The crisis period is associated with intensified cross-border transmission and a general amplification of countries' role as net transmitter or receivers of volatility. Additionally, a vulnerability index is constructed to measure exposure to incoming volatility and the level of domestic volatility.

Key words: Volatility spillovers, Electricity markets, Energy crisis, Vulnerability Index

ASTRATTO

PIEŠ, Patrik. *Volatilità dei prezzi nel mercato elettrico europeo*. – Università di Economia di Bratislava. Facoltà di Economia e Finanza; Dipartimento di Banking e Finanza Internazionale. – doc. Ing. Peter Árendáš, PhD. – Bratislava: NHF EU. Università di Pavia; Dipartimento di Economia e Management – Prof. Eduardo Rossi, PhD. – Pavia, 2026, 84 p.

L'obiettivo di questa tesi è esaminare le dinamiche degli spillover di volatilità nei mercati elettrici europei e valutare in che modo questo fenomeno sia stato influenzato dalla recente crisi energetica. Il forte aumento dei prezzi dell'energia elettrica e della relativa volatilità negli ultimi anni ha attirato notevole attenzione, rendendo importante analizzare come la volatilità si propaghi tra i mercati europei interconnessi. Il primo capitolo fornisce una panoramica del mercato elettrico europeo, includendo il suo quadro istituzionale, lo sviluppo, i meccanismi di formazione dei prezzi e i principali determinanti della volatilità, insieme a una rassegna della letteratura rilevante. Il secondo capitolo definisce gli obiettivi e illustra la metodologia di ricerca applicata. L'analisi empirica si concentra su alcuni mercati europei selezionati ed esamina l'evoluzione dei prezzi dell'energia elettrica e della volatilità, seguita da un'analisi degli spillover. Utilizzando il framework di Diebold-Yilmaz, la tesi ha analizzato l'evoluzione dell'interconnessione tra i mercati, identifica i principali trasmettitori e ricevitori di volatilità e valuta i cambiamenti avvenuti nel periodo analizzato. I risultati indicano una tendenza crescente negli spillover totali, suggerendo che l'interconnessione sistemica gioca oggi un ruolo dominante nella volatilità dei prezzi. Il periodo di crisi è associato a una trasmissione transfrontaliera intensificata e a un'amplificazione generale del ruolo dei paesi come trasmettitori o ricevitori netti di volatilità. Inoltre, viene costruito un indice di vulnerabilità per misurare l'esposizione alla volatilità in entrata e il livello di volatilità interna.

Parole chiave: Spillover di volatilità, mercati dell'energia elettrica, crisi energetica, indice di vulnerabilità

Author's Declaration

I hereby declare that I have written this thesis independently and that all resources and literature used have been properly cited. I declare that I have used AI tools in accordance with the principles of academic integrity and the AI tools were used identify relevant research papers for the analysis in the literature review section and to refine the R code for generating graphs.

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Introduction

Electricity markets are a fundamental component of modern economies, providing essential input for industrial production, services and household consumption. Unlike financial or commodity markets, electricity markets exhibit several unique characteristics, including non-storability of electricity, the requirement for real-time balancing of supply and demand and a strong dependence on weather conditions and generation technologies. These features contribute to inherently high and time-varying price volatility, making electricity markets particularly sensitive to shocks of both economic and non-economic nature.

In Europe, the importance of electricity price volatility has increased significantly in recent years. The ongoing transition towards renewable energy sources, while essential for achieving climate objectives, has introduced additional variability into electricity supply due to the intermittent nature of wind and solar generation. At the same time, the progressive integration of national electricity markets into a unified European system has strengthened cross-border flows, allowing shocks to propagate more easily across countries. As a result, electricity price dynamics are increasingly shaped not only by domestic conditions but also by developments in interconnected markets.

These dynamics became especially pronounces during the energy crisis of 2021-2023, driven primarily by the sharp increase in natural gas prices and exacerbated by geopolitical events, most notably Russia's invasion of Ukraine, wholesale electricity prices reached historically unprecedented levels. In addition to the surge in price levels, the crisis was characterized by heightened volatility and stronger cross-border interdependencies, highlighting the systemic nature of electricity market risks in Europe. This environment underscores the need to better understand not only how volatility evolves over time, but also how it is transmitted across markets.

To address this problem, the concept of volatility spillovers provides a useful analytical framework. Volatility spillovers capture the extent to which shocks in one market contribute to uncertainty in another, thereby offering insights into market integration and the transmission of systemic risk. A widely used approach to measuring such spillovers is the framework developed by Francis X. Diebol and Kamil Yilmaz, which is based on forecast error variance decomposition derived from vector autoregressive models. This methodology allows for the quantification of both total interconnectedness across markets and directional relationships between individual countries, proving a comprehensive view on the transmission of volatility.

The objective of this thesis is to analyse price volatility and its cross-border spillovers withing the selected European electricity market, with a particular focus on the impact of the recent energy crisis. Using daily electricity price data for a set of European countries, volatility is measured through the intraday range and spillovers dynamics are examined using the Diebol-Yilmaz framework. The analysis focuses on both the overall level of interconnectedness and its evolution over time as well as on identifying the main transmitting and receiving markets within the system.

This thesis contributes to the existing literature by providing an updated empirical assessment of volatility in European electricity markets during a period of extreme market conditions. By combining time-varying spillover analysis with a country level perspective, it offers additional insights into how structural differences across countries influence their exposure to cross-border shocks.

1 Current state of the issue in Slovakia and abroad

1.1 The process of liberalization of European Energy Market

The European Commission started considering the creation of an internal European energy market, linked to the broader Single Market concept, as early as 1988. Early documents already outlined that deeper integration of national energy markets would bring about various benefits including lower energy costs, improvement of the structure of the energy industry, strengthening of electricity supply security and would support broader economic and social cohesion objectives.[1]

Building upon this, the formal foundation of a common European electricity market, which launched the process of liberalising the European energy markets, was established in 1996 with the passing of the *First Energy Package*, which included Directive 96/92/EC, the first Electricity Directive and following two years later, Directive 98/30/EC, adopted in 1998 and aimed at the gas sector.[2]

This package introduced a distinction between the regulated and competitive parts of the sector, represented respectively by the regulated network on one side and competitive generation and supply on the other. This was connected to the requirement for managerial and accounting unbundling of vertically integrated monopolistic companies and thus the creation of the previously mentioned market participants.[3]

Jamasb and Pollitt highlight that the process of liberalisation of the electricity market advanced on two levels. The first level could be summarised as the process of market opening and enabling electricity companies from across the EU member states to compete with the established national operators, while the second level concerned the introduction of cross-border measures to strengthen interconnections and trading, so that transmission costs could be reduced while competition in the energy market intensified.[4]

The *Second Energy Package*, which further advanced the process that started in 1996, was adopted in 2003 and comprised two Directives: Directive 2003/54/EC and Directive 2003/55/EC, also commonly referred to as the Second Electricity and the Second

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[1] European Commission: The Internal Energy Market (Commission Working Document) [online]. Available at: https://op.europa.eu/en/publication-detail/-/publication/7028d123-2934-4be9-86db-33f61ac2af4d/language-en

[2] Florence School of Regulation: The Clean Energy for all Europeans Package [online]. Available at: https://fsr.eui.eu/the-clean-energy-for-all-europeans-package/

[3] MEUSS,L. *The Evolution of Electricity Markets in Europe*. Edward Elgar Publishing. pg.4-5. ISBN 978-1-78990-546-5

[4] JAMASB, T. – POLLIT, M. *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*. The Energy Journal. 2005, vol. 26

Gas Directive. Alongside these Directives there was also the adoption of Regulation No. 1228/2003 on the conditions for access to the network for cross-border exchanges in electricity.[5]

The Second Energy Package further promoted market competition by deepening market opening, notably by granting all electricity consumers the right to freely choose their electricity supplier, regardless of national boundaries. Another significant reform was the introduction of legal unbundling requirements for Transmission System Operators. In addition, the package mandated the establishment of independent national regulatory authorities, tasked with regulating network activities and supervising the market opening process, including enhanced responsibilities for monitoring market dominance and anti-competitive behaviour. Member States were also required to submit reports to the European Commission on market dominance and anti-competitive behaviour. Moreover, the package introduced changes to the regulatory framework governing the construction of new electricity generation capacity.[6]

The Third Energy Package, adopted in 2009, consisted of two directives and three regulations. The directives, namely Directive 2009/72/EC and Directive 2009/73/EC, concerned respectively the internal markets for electricity and natural gas. In addition the package included three regulations: Regulation (EC) No.713/2009 establishing the Agency for the Cooperation of Energy Regulators (ACER), Regulation (EC) No. 714/2009 on conditions for access to the network for cross-border exchanges in electricity and Regulation (EC) No. 715/2009 on conditions for access to the natural gas transmission network.[7]

The package introduced a further wave of market liberalisation by establishing common rules for the generation, transmission, distribution and supply of electricity. A central element of the reform concerned Transmission System Operators, which were required to undergo certification by the competent National Regulatory Authority under one of three unbundling models:

- Full Ownership Unbundling
- Independent System Operator

[5] Florence School of Regulation: The Clean Energy for all Europeans Package [online]. Available at: https://fsr.eui.eu/the-clean-energy-for-all-europeans-package/
[6] JAKOVAC, P. *Electricity Directives and Evolution of the EU Internal Electricity Market.* Ekonomska misao i praksa. 2012, vol. 21, pg. 315-338
[7] Florence School of Regulation: The Clean Energy for all Europeans Package [online]. Available at: https://fsr.eui.eu/the-clean-energy-for-all-europeans-package/

- Independent Transmission Operator

Moreover, the Third Energy Package led to the establishment of the European Network of Transmission System Operators for Electricity (ENTSO-E). ENTSO-E was tasked with developing network codes, monitoring and analysing their implementation, adopting common network operation tools and producing an annual work plan and report, as well as drafting seasonal adequacy outlooks.[8]

Equally important was the creation of the Agency for the Cooperation of Energy Regulators (ACER), which plays a central role in the EU regulatory framework by issuing opinions on infrastructure planning, developing framework guidelines for network codes, supporting and coordinating national regulatory authorities and monitoring the functioning of electricity and gas markets.[9]

Following these reforms, the *Fourth Energy Package*, known as 'Clean Energy for all Europeans', was adopted in 2019, composed of four directives: Directive 2018/844, 2018/2001, 2018/2002 and 2019/944and four regulations: Regulation (EU) 2018/1999, 2019/943, 2019/941 and 2019/942. The package modernised the EU energy framework with the aim of facilitating a more renewable based and consumer focused energy system, while establishing a coherent policy architecture to deliver the Union's 2030 climate and energy objectives. In the areas of energy efficiency and renewable energy deployment, it introduced provisions to improve the energy performance of buildings and set binding targets for the share of renewable energy sources in the EU energy mix. In addition, the package significantly reshaped the internal electricity market, with a particular focus on wholesale market functioning and network operations. Key reforms included the introduction of a new bidding zone review process and the establishment of regional coordination centres to enhance cross-border system operation and security of supply. The package also laid down updated rules governing the generation, transmission, distribution, supply and storage of electricity, while strengthening consumer rights and participation in energy markets. Furthermore, the package updated the mandate and responsibilities of the Agency for the Cooperation of Energy Regulators (ACER) and required Member States to prepare national plans addressing the prevention and management of future electricity crises.[10]

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[8] MEUSS, L. *The Evolution of Electricity Markets in Europe*. Edward Elgar Publishing. pg. 6. ISBN 978-1-78990-546-5

[9] MEUSS, L. *The Evolution of Electricity Markets in Europe*. Edward Elgar Publishing. pg.7. ISBN 978-1-78990-546-5

[10] Florence School of Regulation: The Clean Energy for all Europeans Package [online]. Available at: https://fsr.eui.eu/the-clean-energy-for-all-europeans-package/

The Fit for 55 package, also referred to as the *Fifth Energy Package*, sets out the core policy framework through which the European Union aims to achieve a net reduction of greenhouse gas emissions of at least 55 % by 2030 compared to the levels in 1990, while progressing towards climate neutrality by 2050. The package covers a wide range of policy areas and within the energy sector it established a revised target for renewable energy sources, initially setting a 40 % share in the EU energy mix, which was later increased to 42,5 %. The package also introduced significant reforms to carbon pricing under the EU Emissions Trading System (ETS), including a tightening of the annual emissions cap and an extension of carbon pricing to additional sectors, such as maritime transport. Furthermore, it established the Carbon Border Adjustment Mechanism (CBAM), designed to impose a carbon cost on selected high emissions imports in order to mitigate the risk of carbon leakage.[11]

Following the Russian invasion of Ukraine in 2022, there was a need for a response in the energy sector as well and thus the REPowerEU plan was adopted with goals ranging from the phase out of Russian energy imports, strengthening energy security by diversifying imports to accelerating the shift to renewable energy and introducing further energy saving measures.[12]

Although the phase out of Russian energy imports was not instantaneous, subsequent policy developments culminated in a provisional agreement between the Council Presidency and the European Parliament to phase out imports of Russian natural gas, with liquefied natural gas imports scheduled to end on 1 January 2027 and pipeline gas on 30 September 2027.[13]

1.2 Institutional architecture of the European Electricity Market

As we have seen, the European electricity market has undergone a series of legislative reforms that shaped its current institutional and operational framework. These regulatory developments have also introduced new market participants, each pursuing distinct objectives, while collectively contributing to the overarching goals of promoting competition, ensuring security of supply, integrating renewable energy sources and

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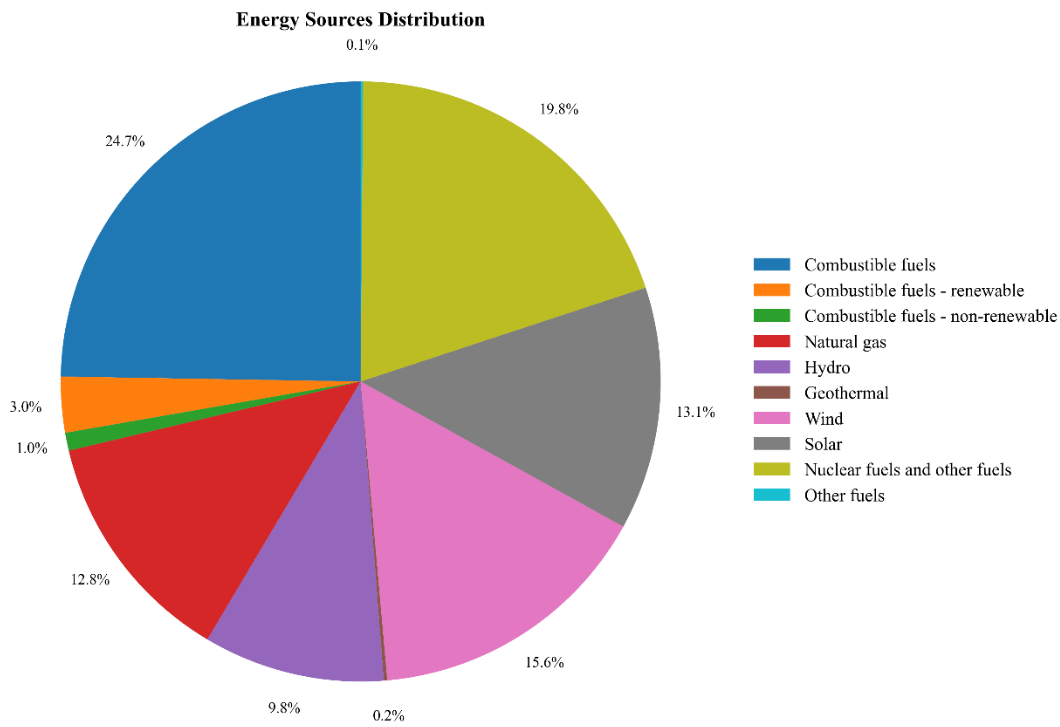
[11] European Commision. *"Fit for 55": Delivering the EU's 2030 Climate Target on the way to climate neutrality.* 2021. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550

[12] European Parliament. *The internal energy market.* 2025. Available at: https://www.europarl.europa.eu/RegData/etudes/fiches_techniques/2017/N54579/doc_en.pdf

[13] Bruegel: European natural gas imports [online]. Available at: https://www.bruegel.org/dataset/european-natural-gas-imports

harmonising national electricity systems into a single internal market. The key market participants include generators, storage operators, utilities, traders, suppliers, consumers, national regulatory authorities (NRAs), transmission system operators (TSOs), distribution system operators (DSOs), market operators, energy exchanges, national governments and the European Commission.

Generators, storage units and utilities constitute the primary economic actors in the European electricity market, each with distinct cost and flexibility profiles that shape their trading behaviour and contracting strategies. Conventional generation units convert energy contained in natural resources such as uranium, coal or natural gas into electricity. Technologies such as solar photovoltaics are characterised by near zero marginal costs but are highly dependent on weather conditions, thereby requiring balancing and flexibility from other generation assets. Baseload technologies, including nuclear and lignite, generally operate continuously with relatively low fuel costs but limited short term flexibility, whereas gas or oil fired plants are used primarily when lower cost generation is insufficient to meet demand.[14]



Graph 1 - Electricity generation by fuel - September 2025
Source: Author's own calculations based on Eurostat

[14] ZACHMANN, G. et al. *The design of the European electricity market: Current proposals and way ahead*. Policy Department for Economic, Scientific and Quality of Life Policies, Directorate-General for Internal Policies. Brussels: European Parliament. 2023.

A certain percentage of generation and storage units are self-standing entities, whose owners sign contracts of differing lengths and types to establish a position in the electricity market. They are able to trade derivates such as forwards and futures to secure their position into the future and trade in spot markets by making offers to sell electricity.

Generators are also able to sign power purchase agreements (PPAs) to deliver a guaranteed volume of electricity to large consumers and, if they operate also renewable unit, participate in government auctions for contracts-for-difference (CfDs)

Traders operate primarily at the wholesale level, buying and selling electricity and related products to capture price differences across time, location and commodities, while providing the necessary liquidity and risk transfer to the market. The core instruments include day-ahead and intraday electricity traded on coupled exchanges and financial derivatives such as forwards and futures.[15]

Suppliers act as intermediaries between wholesale and retail electricity markets. They offer retail contracts to different consumer segments and are obliged to purchase a sufficient amount of electricity from wholesale markets to meet their customers' demand. Through this function, suppliers play a central role in translating wholesale price dynamics into retail electricity prices.[16]

Industrial, business and household consumers differ significantly in terms of consumption patterns and contractual arrangements. Some industrial consumers may directly trade on the wholesale spot market, while others might participate in the long-term PPAs. Businesses and households typically purchase electricity through a retail supplier.[17]

National Regulatory Authorities (NRAs) are public bodies responsible for overseeing compliance with regulatory frameworks at the national level. Their tasks include supervising TSOs and DSOs, ensuring the implementation of network codes, regulating network tariffs and fostering the development of competitive and efficiently functioning regional and cross-border electricity markets.[18]

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[15] ZACHMANN, G. et al. *The design of the European electricity market: Current proposals and way ahead*. Policy Department for Economic, Scientific and Quality of Life Policies, Directorate-General for Internal Policies. Brussels: European Parliament.2023.
[16] ZACHMANN, G. et al. *The design of the European electricity market: Current proposals and way ahead*. Policy Department for Economic, Scientific and Quality of Life Policies, Directorate-General for Internal Policies. Brussels: European Parliament.2023.
[17] ZACHMANN, G. et al. *The design of the European electricity market: Current proposals and way ahead*. Policy Department for Economic, Scientific and Quality of Life Policies, Directorate-General for Internal Policies. Brussels: European Parliament.2023.
[18] SCHOUTTET, N. *The Role of National Regulatory Authorities in Market Coupling*. In: European Electricity Market Coupling. Future of Energy. Springer, Cham., 2025, pg. 326 - 327

At the European Union level, they are complemented by the Agency for the Coordination of Energy Regulators, which is responsible for the integration of the energy markets, helping with the transition to renewable and clean energy and deterring market manipulation and abuse.[19]

Transmission system operators (TSOs) are entities operate independently from the other electricity market players and are responsible for the bulk transmission of electricity at either the regional or national level. TSOs also provide grid access on a non-discriminatory basis and under transparent rules and on the European level, TSOs cooperate through the European Network of Transmission System Operators for Electricity (ENTSO-E).[20]

Distribution system operators (DSOs) usually own and operate the electricity distribution network that connects most consumers and also organise the measurement of electricity consumption. These entities are responsible, within their corresponding local networks, for a high share of the overall energy supply costs that are levied through nationally regulated tariffs.[21]

Nominated Electricity Market Operators (NEMOs) are designated entities responsible for operating the Single Day-Ahead Coupling (SDAC) and Single Intraday Coupling (SIDC). Their core functions include collecting bids and offers from market participants, validating price calculations and order matching results and communicating trading outcomes to the market participants. NEMOs also play a central role in the clearing and settlement of electricity trades and in establishing the operating rules governing their respective trading platforms.[22]

1.3 Price formation and market mechanics

Electricity price formation is shaped by a sophisticated interplay of market design, regulatory framework, technical and network constraints of the transmission and distribution system and the technological characteristics of the generation assets. At all times, electricity supply must equal demand in real time at every node or bidding zone in order to maintain system frequency and prevent instability or potential blackouts. Moreover, due to the physical properties of electricity, large scale storage remains economically limited, further constraining system operation. These characteristics have given rise in the European Union

[19] EU Agency for the Cooperation of Energy Regulators [online]. Available at: https://www.acer.europa.eu/
[20] ENTSO-E [online]. Available at: https://www.entsoe.eu/about/inside-entsoe/members/
[21] ZACHMANN, G. et al. *The design of the European electricity market: Current proposals and way ahead*. Policy Department for Economic, Scientific and Quality of Life Policies, Directorate-General for Internal Policies. Brussels: European Parliament. 2023
[22]NEMO Committee [online]. Available at: https://www.nemo-committee.eu/nemo_committee

to a market architecture in which short-term markets play a central role in price formation, complemented by longer-term hedging instruments that allow market participants to manage price risk. [23]

To better understand price dynamics within this framework, it is useful to distinguish between wholesale electricity prices, which are determined on organised electricity markets and retail electricity prices, which are faced by end consumers and incorporate additional regulated components such as network charges and taxes.

1.3.1 Wholesale Price

Wholesale electricity prices are formed by transactions conducted on organised marketplaces, while in Europe, these primarily include the day-ahead market and the intraday market operated by NEMOs such as EPEX Spot and Nord Pool, complemented by balancing markets operated by TSOs.

The day-ahead market represents the principal venue for wholesale electricity price formation in Europe, in this market, electricity is traded for delivery over the following day, historically in hourly contracts. Market operation is based on a blind auction, in which participants submit their bids and offers before a fixed gate time closure.[24]

These orders are submitted by both suppliers and buyers, who send two types of orders. Orders consists of multiple volume-price pairs which represent the willingness of the supplier or buyer to sell or buy a certain volume of electricity at a price that is equal to or higher or lower than the price they specified.[25]

Most European countries participate in the Single Day-Ahead Coupling (SDAC), which integrates the national day-ahead markets operated by the respective NEMOs into a single pan European auction. Bids and offers from all participating bidding zones are then jointly processed by the EUPHEMIA algorithm, which aggregates supply and demand and calculates the hourly clearing price, while respecting cross zonal network constraints, with the objective of maximising the social welfare.[26]

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[23] GLACHANT, J.-M. – JOSKOW, P. L. – POLLITT, M. G. *Handbook on Electricity Markets*. Edward Elgar Publishing, 2021. ISBN 978-1-78897-994-8. pg. 75

[24] EpexSpot: Basics of the Power Market [online]. Available at: https://www.epexspot.com/en/basicspowermarket#day-ahead-and-intraday-the-backbone-of-the-european-spot-market

[25] SHAH, D. - CHATTERJEE, S. *A comprehensive review on day-ahead electricity market and important features of world's major electric power exchanges.* John Wiley & Sons. 2020. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1002/2050-7038.12360

[26] NEMO Committee: SDAC [online]. Available at: https://www.nemo-committee.eu/sdac

From 30 September 2025, the European day-ahead market transitioned from hourly to 15-minute trading intervals, allowing prices to better reflect short-term variations in demand and renewable generation, with aims of this reform to enhance system flexibility and improve the integration of variable renewable energy sources.[27]

On the intraday market, trading continues live for 24 hours within the delivery day and as soon as a buy and sell order match, the trade is executed, which allows for a high degree of flexibility regarding timing of delivery, where electricity can be traded in the same moment as the delivery or over longer time windows through hourly, half-hourly or quarter-hourly contracts. This also allows for members to make adjustments and to balance their positions.[28]

The main objective of the balancing market is to ensure the real-time stability of the power system; it is overseen by the respective TSOs. Deviations in the balance requiring TSO intervention can occur due to various reasons, such as unexpected outages or forecasting errors.[29]

There are three main products on the balancing market:

- Replacement reserve – manually activated balancing reserve characterized by the slowest activation time
- Manual frequency restoration reserve – equivalent to tertiary reserve
- Automatic frequency restoration reserve – equivalent to secondary reserve

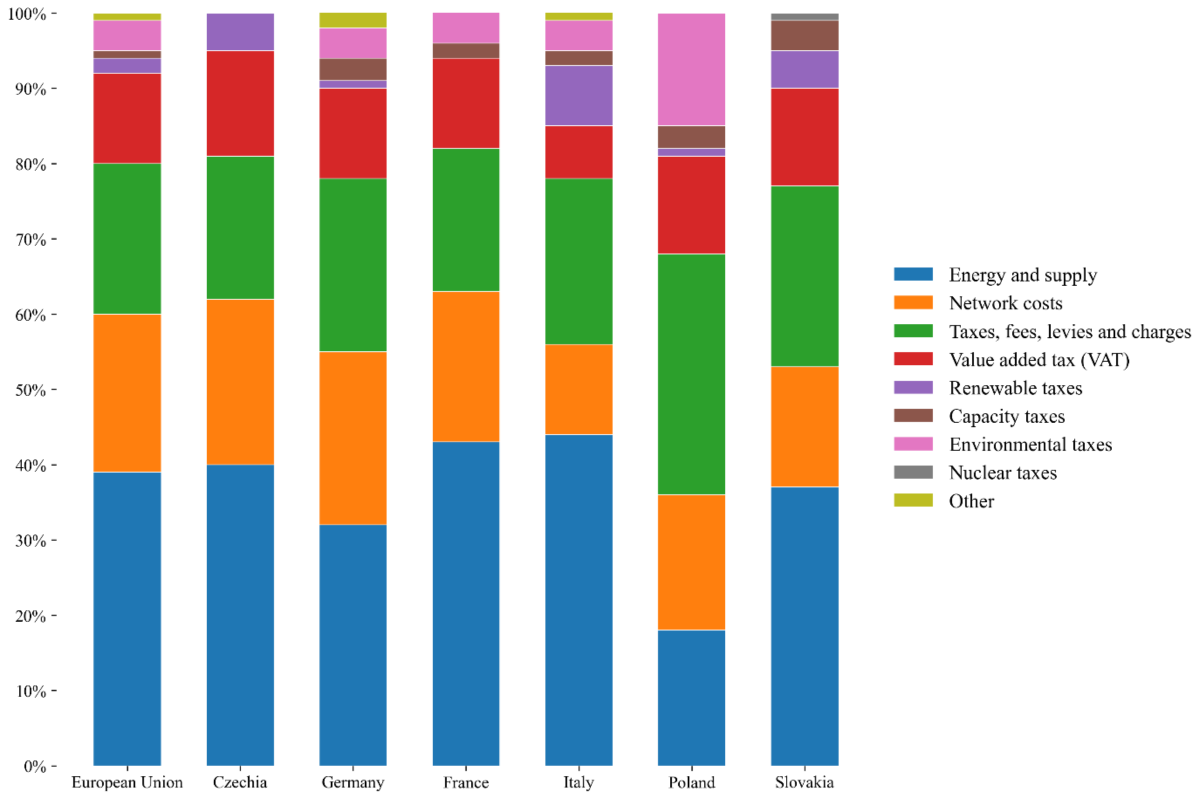
1.3.2 Retail Price

Retail electricity prices refer to the prices paid by end consumers, be they households, businesses or industrial consumers, typically expressed in cents per kWh. In Europe, the final electricity bill in the retail market consists of three main components: the energy cost, transmission and distribution network tariffs, taxes and levies.[30]

The relative weight of these components varies across Member States and, according to Bruegel, the energy supply component accounts for approximately half of final household

[27] European Commission: EU electricity trading in the day-ahead markets becomes more dynamic [online]. Available at: https://energy.ec.europa.eu/news/eu-electricity-trading-day-ahead-markets-becomes-more-dynamic-2025-10-01_en
[28] EpexSpot: Basics of the Power Market [online]. Available at: https://www.epexspot.com/en/basicspowermarket#day-ahead-and-intraday-the-backbone-of-the-european-spot-market
[29] NordPool Group: Balancing Power [online]. Available at: https://www.nordpoolgroup.com/globalassets/download-center/tso/how-does-it-work_balancing-power.pdf
[30] GRAVE K., et al. *Prices and costs of EU Energy*. Final report. Ecofys – European Commission. 2016.

electricity bills on average, while network costs represent around 25 %, VAT about 14 % and various levies and charges around 6 %.[31]



Graph 2 - Electricity price composition
Source: Author's own calculations based on Eurostat

Retail prices are therefore shaped by both wholesale market dynamics and regulatory decisions. Although wholesale price movements influence retail prices, they do not always necessarily translate directly into them and the pass-through depends on a varying number of factors such as contract structures, market regulation and government intervention, which differ between Member States.[32]

As Hernnäs et al. note in their study, retail electricity prices exhibit smoother dynamics than wholesale prices, which on average increased during 2021 by 46 % with a two-month lag. It is also interesting to point out that the pass-through is asymmetric, meaning that the speed of pass-through is faster when prices increase than when they

[31] HEUSSAFF, C. *Decarbonising for competitiveness: four ways to reduce European energy prices.* Policy Brief 32/2024, Bruegel. 2024
[32] HERNNÄS, H. et al.: *Pass-through in EU electricity and gas markets*. Quarterly Report on the Euro Area (QREA). 2023, Vol. 22, No. 2, pg. 23–34

decrease. Member States with heavily regulated retail prices managed to decouple retail and wholesale electricity prices and tend to have lower pass-through.[33]

1.3.3 Merit Order Effect

Efficient wholesale electricity markets in Europe are designed to allocate generation resources at least cost while ensuring system reliability. This is achieved through successive market clearing stages (forward, day-ahead, intraday and balancing), which progressively align supply and demand closer to real time.[34]

Taking into account the limited economic feasibility of a large-scale electricity storage, merit order-based price formation in liquid wholesale markets is essential for both secure grid operation and competitive pricing.[35]

Janda described this mechanism as follows *"the merit order effect is an expression of the correlation between the composition of the energy mix and the spot price of electricity. Based on marginal costs, they are ranked from the cheapest to the most expensive as follows: intermittent renewables (photovoltaics and wind), hydropower, nuclear, coal, gas, oil. In order to provide consumers with the cheapest electricity possible, the sources should be employed according to the price of the last MWh generated."*[36]

The merit order thus defines the ranking according to which electricity is supplied based on the primary source, with the aim of securing an economically optimal supply of electricity. This is done based on the generator's marginal production cost, also known as the variable cost, required to produce an additional unit of electricity. This cost consists of three components: the primary fuel, which is transformed into electricity; carbon emission costs, which in the European Union are determined by EU ETS allowances based on the cap-and-trade mechanism, ultimately depending on the amount of carbon dioxide emitted by the power plant which means that lignite and coal power plants are the most costly in this category and finally the variable operational and management costs, which cover the daily running of the power plant, maintenance and labour expenditures.[37]

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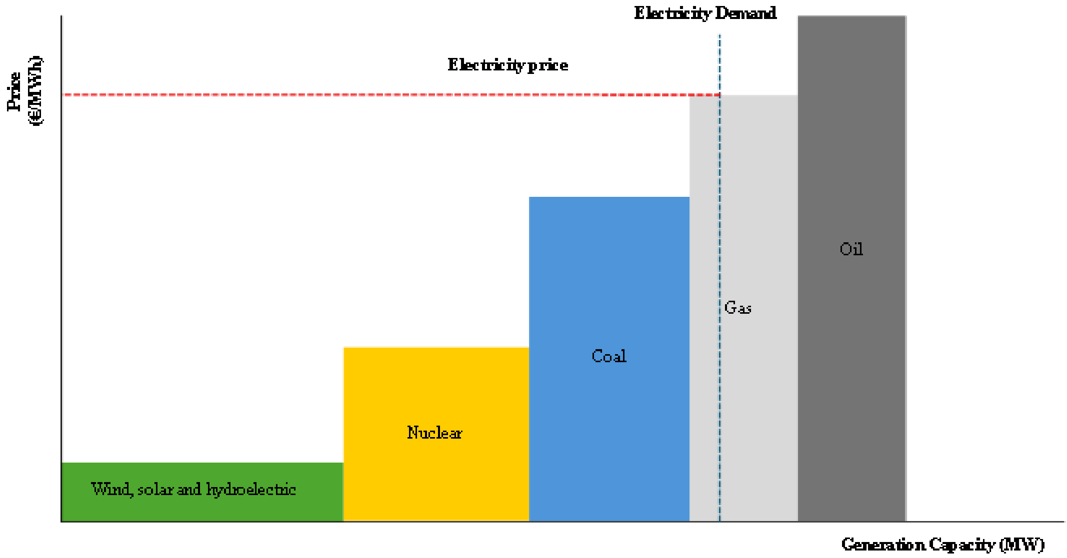
[33] HERNNÄS, H. et al. *Pass-through in EU electricity and gas markets*. Quarterly Report on the Euro Area (QREA). 2023, Vol. 22, No. 2.
[34] GASPARELLA, A. – KOOLEN, D. – ZUCKER, A. *The Merit Order and Price-Setting Dynamics in European Electricity Markets.* European Commission. Petter. 2023
[35] EpexSpot: Merit order and marginal cost – the price formation [online]. Available at: https://www.epexspot.com/en/basicspowermarket#merit-order-and-marginal-cost-the-price-formation-process
[36] JANDA, K. *Slovak Electricity Market and the Merit Order Effect of Photovoltaics*. CAMA Working Papers. 2018, No. 2018-22
[37] GASPARELLA, A. – KOOLEN, D. – ZUCKER, A. *The Merit Order and Price-Setting Dynamics in European Electricity Markets.* European Commission. Petter. 2023

It is important to point out that under the merit order pricing system used in European markets, electricity prices are based on the bids of the most expensive electricity generation technology needed to meet demand in each market session.[38]

The price level at which power plants bid varies greatly depending on the generation technology. For example, conventional fossil fuel-based technologies bid at a price connected to the underlying commodity price. Nuclear power is a partial exception, because uranium fuel itself is a relatively small cost component, instead, marginal costs are more influenced by fuel processing, fabrication of fuel elements and provisions for handling and disposing of spent fuel, which makes nuclear much less sensitive to short-term commodity price swings than fossil plants. By contrast, variable renewable generators such as wind, solar and hydro rely on free natural inputs, so their variable production costs are close to zero aside from modest maintenance costs and some system integration costs and they therefore appear at the leftmost, cheapest end of the merit order supply stack.[39]



Picture 1 - Merit Order Effect
Source: Author's own work

The impact of merit order pricing on wholesale electricity prices in Europe has been researched in various studies and offers different implications for prices, volatility and market structure.

Hirth performed an ex post evaluation of spot prices using a fundamental electricity market model to reproduce hourly day-ahead prices and then changed the key inputs on an

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[38] QUINTANA, J. *The impact of renewables energies on wholesale electricity prices*. Economics Bulletin, Banco de España. 2024

[39] GASPARELLA, A. – KOOLEN, D. – ZUCKER, A. *The Merit Order and Price-Setting Dynamics in European Electricity Markets.* European Commission. Petter. 2023

individual basis to isolate each factor's ceteris paribus impact on prices, focusing on the German and Swedish markets during the years 2008 to 2015. For Germany, the modelled price in 2015 was 59 % lower than in 2008. According to the study, the main contribution to this came from the expansion of renewable energy, which the model estimates decreased spot prices by around 24 %. Other important factors were the decrease in the CO_2 price as well as decreases in natural gas and coal prices. On the other hand, the nuclear energy phase out in Germany as well as higher net exports would have contributed to an increase in spot prices. In the case of Sweden, according to the study, we can observe so called volumetric shocks affecting prices in the Swedish market, those being the increase in renewable electricity generation, additional hydroelectricity supply and a decline in final electricity demand, while increased net exports offset some of these effects. Contrary to the situation in Germany, the decrease in fuel and CO_2 prices has a much lower effect, which can be attributed to the energy mix of this market.[40]

Quintana argues that increasing the share of electricity generated by renewables could have a profound impact on price dynamics, as their lower marginal costs would displace other technologies that are still needed in the energy mix to meet demand during certain time periods. This is important for two reasons. The production of electricity from renewable sources is dependent on meteorological factors, as their output can fluctuate and differ across time periods and they tend to displace a portion of other energy sources, mainly during the day, directly lowering the clearing price. Despite this, combined cycle plants still set wholesale prices for most hours during the day and prices follow the dynamics of gas prices, although the correlation has weakened as the penetration of renewable sources has increased. This, however, led to greater intraday price volatility and an increase in zero or negative wholesale electricity prices, accounting for around 15 % of the time in the first half of 2024, representing periods when renewables alone could meet demand. The paper also argues that the continued renewable build out can lead to greater reductions in wholesale electricity prices, but this will ultimately depend on how demand can adapt to the hourly pattern of renewable generation and the development of technologies to store surplus renewable energy.[41]

[40] HIRTH, L. *What Caused the Drop in European Electricity Prices ? A Factor Decomposition Analysis.* The Energy Journal 39. 2018, pg. 143-158
[41] QUINTANA, J. *The impact of renewable energies on wholesale electricity prices*. Economic Bulletin – Banco de España. 2024

The Science For Policy brief focused on merit order and price setting dynamics in European electricity markets concludes with several interesting findings. Even though gas fired power plants will keep setting the EU wholesale power price through 2030 more often than their share in generation would suggest, in 2022 they generated around 19% of electricity while setting the price around 55% of the time. In 2030, their share in electricity generation is predicted to fall to around 11%, but the proportion of time they set the price is expected to remain at a similar level. The output of renewables and nuclear is expected to grow, but their revenues will come mainly from power purchase agreements and contracts for difference, thus shielding consumers from high market prices and volatility. Interconnection in the EU will further lead to greater price convergence and lower price differentials among Member States, determined by cross-border generation sources. As noted, however, the limited options to store electricity and the need for system flexibility will limit the decrease in wholesale prices and their influence will become more noticeable in later periods when renewable generation meets demand and displaces fossil based power plants from the merit order system.[42]

1.4 Volatility on the electricity market

Volatility is a standard statistical measure of price dispersion observed over a given time horizon, such as minute by minute, hourly, daily, or weekly intervals. In the context of electricity markets, price volatility refers to the magnitude and pattern of short-run fluctuations in wholesale electricity prices around their expected level. Compared with most other traded commodities, electricity prices are characterised by exceptionally high volatility, with pronounced differences across observation frequencies.[43]

Electricity markets exhibit this behaviour due to the specific physical and economic characteristics of electricity. Price volatility is therefore rooted in uncertainty related to the fundamental market drivers operating on hourly, daily, weekly and seasonal horizon, as well as the physical constraints associated with electricity generation, transmission and real time delivery to consumers.[44]

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[42] GASPARELLA, A. – KOOLEN, D. – ZUCKER, A. *The Merit Order and Price-Setting Dynamics in European Electricity Markets*. European Commission. 2023

[43] WERON, R. *Energy price risk management*. Physica A 285. 2000, pg 127 - 134

[44] BENINI, M. et al. *Day-ahead market price volatility analysis in deregulated electricity markets*. Power Engineering Society Summer Meeting IEEE. 2002, vol. 3

As we have noted, electricity price volatility arises as a combination of fundamental drivers, physical properties of electricity and its generation, market structure, as well as cross-market interactions.

The structural features behind electricity price volatility include non-storability and the need for continuous balancing, because unlike oil or gas, electricity cannot be stored economically at scale, which removes the usual buffer that smooths the impact of production shocks in other commodities, leaving room for short-term price volatility to be much more pronounced in electricity markets.[45]

Another important determinant of electricity price volatility is the volatility of fuel prices, such as coal, gas and oil, which are themselves influenced by global commodity markets and exchange rate fluctuations. In addition, weather driven shocks, such as heat waves increasing cooling demand or variability in hydropower generation, can significantly affect both demand and supply and have further implications for the destabilization of prices.[46]

Empirical evidence suggests that the drivers of electricity prices differ across market segments. A study of the German electricity market analysing both spot and futures prices finds that spot prices are primarily driven by renewable generation infeed and electricity demand, whereas futures prices are more strongly influenced by fuel prices (natural gas and coal) and carbon prices. This highlights the role of short-term physical constraints in spot markets and longer-term cost expectations in forward markets.[47]

Another study focused on the Australian electricity market and volatility spillovers found that certain markets are relatively more volatile, leading to divergence in the regional prices, which can be attributed to several factors, such as abuse of the market power, capacity bottlenecks, inappropriate market mechanisms and potential information asymmetries. The study also highlights, that due to the fact that the Australian National Electricity Market is composed of regional spot markets with imperfect integration and limited interconnection, during the peak demand the system can become congested, which leads to price differences across markets.[48]

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[45] BENINI, M. et al. *Day-ahead market price volatility analysis in deregulated electricity markets*. Power Engineering Society Summer Meeting IEEE. 2002, vol. 3

[46] BENINI, M. et al. *Day-ahead market price volatility analysis in deregulated electricity markets*. Power Engineering Society Summer Meeting IEEE. 2002, vol. 3

[47] LÓPEZ-MOSQUERA, S. - NURSIMULU, A. *Drivers of electricity price dynamics: Comparative analysis of spot and futures markets.* Energy Policy 126. 2019, pg. 76-87

[48] APERGIS, N. – BARUNÍK, J. – LAU, M. C. K. *Good volatility, bad volatility: What drives the asymmetric connectedness of Australian electricity markets?* Energy Economics 66. 2017, pg. 108-115

Several studies consistently show that electricity prices display stylised statistical properties that distinguish them from typical financial assets or other commodities traded on financial markets. For example, half-hourly prices are characterized by spikes that are several orders of magnitude above the mean. Certain Australian regions in the years between 1999-2006 exhibited maxima of spot prices above 9,000 AUD/MWh against a mean of around 30-40 AUD/MWh.[49]

Looking at hourly spot prices across three major electricity markets in the European Union, namely Germany, Italy and France, we can observe similar statistical characteristics of spot prices, although with an order of magnitude that is less severe than that observed in the early 2000s in Australian markets, with maximum prices in both Germany and Italy of around 870 EUR/MWh and in France a staggering 2,987 EUR/MWh and mean prices between 71-96 EUR/MWh, reflecting differing energy production in these countries as one of the reasons for this behaviour.

	Germany	Italy	France
Mean	71,32	96,63	78,16
Std. deviation	82,54	92,59	91,44
Min	-316,4	0	-143,94
Max	867,85	870	2987,78
25 % percentile	29,98	45,5	32,44
Median	43,24	61,61	47,76
75 % percentile	82,8	110,07	82,69

Table 1 Descriptive statistics of spot electricity prices (1.1.2015-31.12.2024)
Source: Author's own work based on Ember Data

Another defining feature of electricity price dynamics is volatility clustering, whereby periods of high price variability tend to be followed by further period of heightened volatility, while calm periods are followed by relatively stable prices. Behaviour like this, implies that volatility shocks are persistent, meaning that current volatility influences expectations of future volatility.[50]

Moreover, electricity price volatility exhibits strong intraday, weekly and seasonal patterns, whereby prices and volatility are typically higher on weekdays than on weekends and public holidays, although the magnitude of these effects varies across markets. Seasonal

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[49] CHAN, K . F – GRAY, P. – VAN CAMPEN, B. *A new approach to characterizing and forecasting electricity price volatility.* International Journal of Forecasting 24. 2008, pg. 728-743

[50] HIGGS, H. *Modelling price and volatility inter-relationships in the Australian wholesale spot electricity markets.* Energy Economics 31. 2009, pg. 748-756

patterns are also evident, with volatility peaks occurring during winter or summer months, depending on climate conditions, driven by heating or cooling demand and associated load profiles. These periods are often associated with more frequent and larger price jumps, particularly during peak hours.[51]

1.5 Price volatility in the European electricity market

The previous chapter was devoted to the general characteristics and drivers of electricity price volatility and highlighted several stylised facts about electricity prices. This section aims to review empirical evidence on price volatility and volatility spillovers in European electricity markets, distinguishing between pre-crisis studies and research that already incorporates the 2022–2023 energy crisis, with the aim of summarizing what is known about the level and dynamics of volatility, how it propagates across countries and which factors shape these spillovers.

The first strand of literature documents how volatile European electricity prices are and how volatility differs across selected European regions. Božić et al. examine the price volatility of electricity across 15 markets in Europe, with a focus on Southeastern European markets and compare it to more mature European markets, finding that price volatility is higher in Southeastern European markets than in mature European markets, with Bulgarian and Romanian markets being the most volatile and exhibiting approximately twice the volatility of their mature counterparts, such as the Swiss or Austrian market. The study utilized price volatility measured by price velocity, specifically using velocity based on the overall average price and daily velocity, which is based on the daily average power price, with an extension to monthly, quarterly and yearly average prices during the period from February 2016 until December 2019. Their findings show that average prices are positively correlated, with a high correlation among geographically close and interconnected markets, such as those of Germany, Austria, Slovakia and Czechia. Conversely, turning attention to volatility, the correlation matrix shows some negative correlation between Southeastern European markets and Central European markets.[52]

Stanković et al. extend this perspective to 28 European power exchanges during a four-year period spanning from January 2018 to December 2021, with the aim of comparing pre-pandemic and pandemic price dynamics, relying on the price velocity of hourly spot prices. Their results show that there is a convergent trend in hourly spot prices during the

[51]HIGGS, H. *Modelling price and volatility inter-relationships in the Australian wholesale spot electricity markets.* Energy Economics 31. 200, pg. 748-756
[52] BOŽIĆ, Z. et. al. *Power Exchange Prices: Comparison of Volatility in European Markets.* Energies. 2020

observed period across all 28 power exchanges, with more pronounced growth during the COVID-19 pandemic, with Bulgaria experiencing the largest growth and the Nordic countries, such as Sweden, Norway, Finland and Denmark, marking the lowest growth compared to the average spot electricity price in 2018. The authors also note that volatility dynamics might affect the long-term objectives of a common European energy policy and thus it is vital to employ proper measures in the short and medium term to shield consumers and enhance energy security.[53]

A second strand of research focuses on how volatility spills over across European electricity markets, often using variants of the Diebold–Yilmaz spillover index. Jónsson et al. investigated the level of price volatility effects between four European power exchanges using a volatility spillover index inspired by Diebold and Yilmaz. Using data from January 2007 to December 2015, the authors computed five different measures of directional volatility. Their results show that around 36 percent of volatility during this period was caused by spillovers from other markets, noting that the French EPEX exchange is the largest contributor to volatility, as it is also the largest exporter of electricity in this region, while the smaller exchanges are more prone to receiving volatility from larger neighbours. The findings also suggest that, due to common supply and demand characteristics of electricity, volatility spillovers in the region among power exchanges are present even in the absence of direct physical interconnection.[54]

Uribe et al. examined market integration and volatility spillovers in the Nord Pool electricity market, comprising seven countries in Northern Europe and documented how shocks transmit across various bidding areas. Using hourly spot prices from January 2013 to December 2018, they use a novel approach to estimate the daily realized volatility of intraday electricity prices by decomposing it into positive and negative semi-variances and applying a Heterogeneous Autoregressive Realized Volatility framework combined with directional spillover indices based on VAR to quantify cross-market transmission. Their results reveal an increase in market integration from 2015 onwards, with volatility spillovers occurring unevenly across the distribution tails, with significantly higher upside volatility and thus also consumer risk propagating more than that of producers, showing asymmetric risk sharing. The authors also document that the larger electricity producers in the Nord Pool market, mainly Norway and Sweden, act as net transmitters of volatility shocks, while the smaller

[53] STANKOVIĆ, Z. Z., et al. *The Volatility Dynamics of Prices in the European Power Markets during the COVID-19 Pandemic Period.* 2024
[54] JÓNSSON, E. I. – LORENTZEN, S. – DAHL, R. E. *Volatility spillovers in EU electricity markets*. 2017

and import dependent markets receive disproportionately larger spillovers. They also note that seasonal patterns drive spillover intensity, with stronger transmission during cold months. Their findings underscore how market size, generation mix and physical interconnection infrastructure can shape the propagation of price volatility and risk sharing across highly integrated regional electricity markets.[55]

Ma et al. aimed to understand volatility spillovers across 12 electricity markets and whether economic circumstances and overall uncertainty in European economic policy drive electricity price volatility. As a volatility measure, due to the non-storability of electricity, the authors used the intraday range of prices on data spanning from September 2009 to August 2020 and, applying time frequency volatility spillover methods, they find that close to half of spot price volatility can be attributed to cross-market spillovers, with the majority of spillovers occurring at weekly horizons, while economic policy uncertainty mainly amplifies medium- and long-term spillover effects. Their results show that German, French, Czech, Dutch, Spanish and Portuguese electricity markets are among the most integrated, with more than half of their volatility explained by shocks from other markets. Although short-run spillover dynamics are closely linked to the physical characteristics of electricity and market conditions, the authors also show that major economic and geopolitical events, such as the rise of US shale oil production, Brexit, increases in EU ETS allowance prices and the COVID-19 pandemic, have a significant impact on medium and long-term spillovers, leading to higher overall connectedness of European electricity markets during periods of political and economic instability.[56]

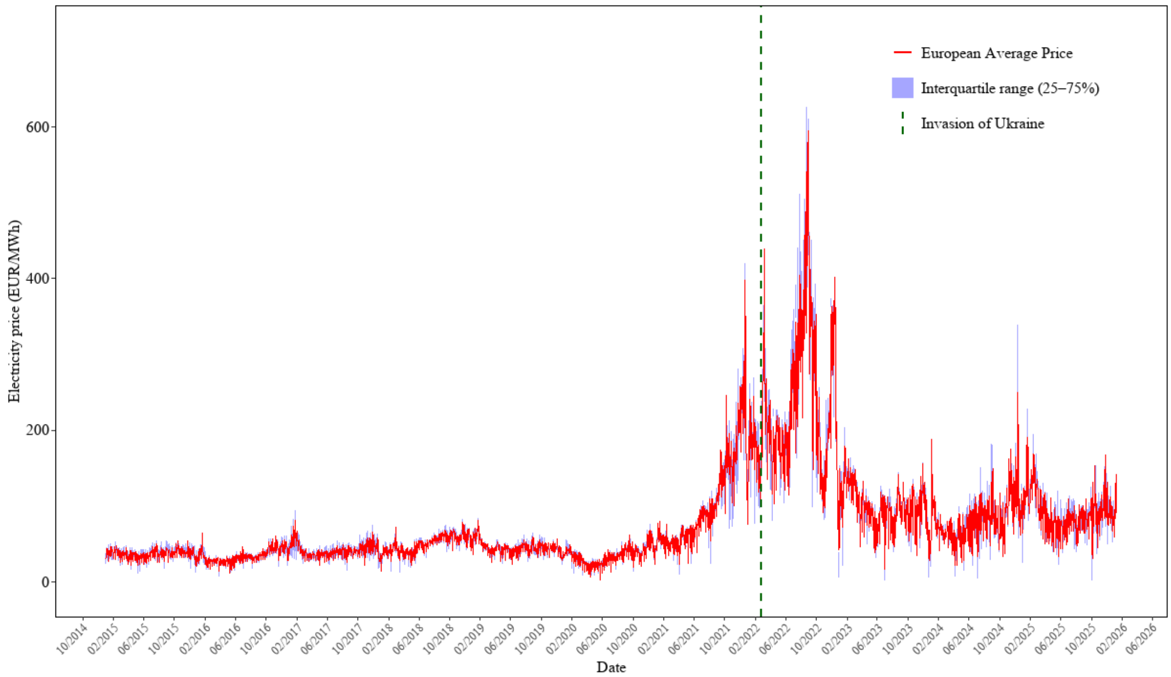
More recent work by Sikorska-Pastuzska and Papież focuses on measuring volatility spillovers in 26 European wholesale electricity markets and documents substantial time-varying connectedness that intensifies during major economic stress episodes, such as the COVID-19 pandemic, with strong volatility spillovers between Northern European and Central and Eastern European markets, also highlighting the role of German, French and Dutch markets as the main net transmitters. Using the intraday range of electricity prices as a volatility proxy over the period from August 2007 to February 2022, ending their observation just the day before the Russian invasion of Ukraine, the study captures volatility connectedness in European electricity markets in light of changes brought over the years by

[55] URIBE, M. J. – LÓPEZ-MOSCQUERA, S. – GUILLEN, M. *Characterizing electricity market integration in Nord Pool*. Energy 208. 2020.
[56] MA, R. – LIU, Z. – ZHAI, P. *Does economic policy uncertainty drive volatility spillovers in electricity markets: Time and frequency evidence.* Energy Economics 107. 2022.

the Third and Fourth Energy Packages, as well as during periods of heightened instability in the broader economy caused by COVID-19 and the buildup to the Russian invasion of Ukraine. Spillover effects are measured using a time-varying parameter VAR model, which mitigates sensitivity to outliers and avoids arbitrary rolling-window choices while accommodating gradual parameter changes. Their results suggest that, while European electricity markets show increasing integration, volatility spillovers remain substantially stronger within regional clusters than across them, with German, French and Dutch markets acting as key transmission hubs.[57]

1.5.1 *2021-2023 Energy Crisis*

The 2021-2023 European energy crisis resulted from the interaction of multiple shocks, primarily the disruption of natural gas supply due to the Russian invasion of Ukraine, as well as a structural shift in generation technology, visible in the rise of renewable energy generation and the design of the European wholesale electricity market under the marginal cost pricing framework, resulting in an all-time high average electricity prices in the European Union.



Graph 3 - Average price of electricity in Europe
Source: Author's own illustration

[57] SIKORSKA-PASTUZSKA, M. – PAPIEŻ, M. *Dynamic Volatility Connectedness in the European Electricity Market*. Energy Economics 127. 2023

Even though there is a substantial body of literature devoted to measuring volatility and investigating volatility spillovers in the European energy markets preceding the energy crisis, there is so far a limited amount of research focusing on the crisis period.

In their research paper, Cevik and Zhao examine volatility spillovers, similarly to previously conducted research, across 24 European Union member states during the period from 2014 to 2024, encompassing changes in the electricity generation landscape as well as economic and geopolitical shocks that have rattled the markets since the COVID-19 period and continued due to the Russian invasion of Ukraine. Using wholesale electricity prices at a 15-minute frequency, they compute volatility as the standard deviation of log returns. Their results show that, with the spillover index having a value of 73%, cross-border volatility spillovers dominate the behaviour of prices in national electricity markets, with variation among member states, Ireland having the lowest spillover from others while Hungary having the highest. There is also evidence that physically connected markets, such as Spain and Portugal, have the strongest bilateral interaction. Interestingly, the Baltic countries in this study exert the largest net spillover.[58]

Building on this analysis, Cevik and Zhao further investigate the determinants of bilateral volatility spillovers using a novel augmented gravity framework. In this setting, spillover intensity between country pairs is related to standard gravity variables, such as income, population, geographic distance and contiguity, as well as the share of renewable energy in electricity generation. Their estimates show that a higher share of renewables in the generation mix is positively and significantly associated with stronger bilateral volatility spillovers. At the same time, higher GDP in the origin country dampens outgoing spillovers, while population, as a proxy for electricity demand, amplifies spillover intensity in both origin and destination markets. Together, these findings suggest that volatility transmission in European electricity markets is shaped not only by physical interconnection and market integration, but also by structural characteristics of national energy systems.[59]

The importance of renewable energy generation and its impact on electricity price volatility in European power markets was studied by Shischke and Rathgeber in their paper, where they utilized regression models to understand the determinants of volatility across 13 European electricity markets in the period from 2015 to 2023. They show that electricity

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[58] CEVIK, S. – ZHAO, Y. *Shocked: Electricity Price Volatility Spillovers in Europe*. IMF Working Papers 2025

[59] CEVIK, S. – ZHAO, Y. *Shocked: Electricity Price Volatility Spillovers in Europe*. IMF Working Papers 2025

price volatility is primarily driven by electricity load, with higher electricity demand usually leading to an increase in market risk and by extraordinary geopolitical events such as the Russian invasion of Ukraine. Renewable energy sources have heterogeneous effects, while solar power amplifies volatility, wind power in most cases provides a stabilizing effect, apart from Spain. The authors also highlight that conventional power sources, such as nuclear and coal power, have a stabilizing effect and can thus reduce risks in electricity markets. Interestingly, fundamental fuel prices and broader macroeconomic conditions prove to be statistically insignificant determinants of volatility in country-level regressions.[60]

Recent work has also moved beyond documenting heightened volatility to asking how the energy crisis should reshape the design of European electricity markets. Fabra examines how the energy crisis revealed structural weaknesses in the current system, which is based on the merit order system and uses these lessons to propose a hybrid architecture that combines liquid short-run markets with extensively regulatory backed long-term contracting. With gas prices spiking after the fall of Russian gas supply and given that, due to the nature of the merit order, gas plants often set the market price, wholesale electricity prices soared to multiples of historical levels, producing extreme profits for nuclear and hydro plants and helping to push up inflation in the Eurozone. Volatile spot prices alone often cannot provide adequate guidance for investment in expensive low carbon generation, storage and demand response, especially as higher renewable penetration lowers prices exactly when renewables produce. Fabra proposes to keep a transparent day-ahead market, with an additional layer of competitive auctions for technology specific contracts-for-differences, flexibility contracts, reliability options and capacity payments, thereby derisking investments in renewable generation, allowing the passage of lower costs to consumers and achieving carbon free and diversified power markets.[61]

his emerging crisis era literature shows that European electricity price volatility is not only high but also increasingly shaped by cross-border spillovers, changes in the generation mix and large geopolitical shocks. It also highlights the importance of renewables and conventional capacity for the propagation and mitigation of volatility, which is directly relevant for assessing the impact of price volatility on individual countries in an integrated European market.

[60] SCHISCHKE, A. – RATHGEBER, A. *Unrevealing European Electricity Price Volatility: The Impact of Renewables*. 2025. Available at: https://ssrn.com/abstract=5549982
[61] FABRA, N. *Reforming European electricity markets: Lessons from the energy crisis*. Energy Economics, 126. 2023

2 Objective of the Thesis and the Methodology

In the first chapter of our thesis, we explored the institutional framework of the European electricity network, introduced the mechanism of price formation and presented the existing academic literature and research findings on the topic of volatility in electricity markets to provide theoretical background for our research on price volatility in the European electricity markets. This chapter defines the main objective and the corresponding partial objectives, outlines the data selection and collection process and presents the applied econometric methodology.

The primary objective of our master thesis is to measure and assess the volatility spillovers in the electricity markets among our selected European countries and the impact of the energy crisis on these spillovers at both the system-wide and country-specific level.

To reach the main objective, we set up the following partial subobjectives:

- To provide a structured overview of the European electricity market and define the key concepts relevant to the analysis
- To select and describe the sample of countries, taking into account their economic position within the European electricity market
- To collect and preprocess wholesale electricity price data over the defined time horizon
- To analyse price dynamics and volatility dynamics across countries
- To apply the Diebold–Yilmaz framework to measure volatility spillovers in both static and rolling settings, followed by their interpretation
- To construct and evaluate a vulnerability index capturing the joint effect of volatility and spillover transmission

The empirical analysis is based on wholesale hourly electricity prices obtained from the Ember database, covering the period from 1 January 2015 to 31 December 2025. For analytical purposes, the sample is divided into three subperiods: a pre-crisis period 2015–June 2021, a crisis period July 2021– December 2023 and a post-crisis period 2024–2025.[62]

This classification is designed to capture structural changes in market dynamics and to assess the impact of the energy crisis on both volatility and its cross-border transmission.

[62] EMBER: Data [online]. Available at: https://ember-energy.org/data/

The pre-crisis period covers from 2015 to June 2021 and represents a relatively stable phase of market development, characterised by gradual integration and moderate volatility levels. The crisis period is defined as beginning on 1 July 2021, with the aim of capturing the approximate onset of the European energy crisis, driven by factors such as increasing energy demand during the post-pandemic economic recovery and, subsequently, the Russian invasion of Ukraine. The crisis period ends in December 2023, when electricity prices began to decline from their peak levels and market conditions started to stabilise, despite the continued presence of elevated uncertainty. The post-crisis period, covering 2024 onwards, allows for the assessment of whether the effects of the crisis led to a persistent structural change in volatility dynamics and spillover transmission across European electricity markets.[63]

The sample consists of 14 European countries, including both major European Union economies and their closely interconnected neighbouring markets, ensuring sufficient variation in market size, energy mix and degree of integration.

Our analysis as well as the following methodology was computed and performed using the programming language R with the use of specific libraries, mainly vars and ConnectednessApproach.[64]

In order to fulfil our goals and measure how volatility transmitted in our selected network, we have followed a well-established methodology proposed by Diebold and Yilmaz, which as we have noted in the theoretical part is frequently used for similar studies. The methodology builds on the principle of forecast error variance decomposition, which quantifies how much of the future uncertainty in one market can be attributed to shocks originating in another. These bilateral contributions are then aggregated across all markets in the system to construct a total spillover index, which captures the overall degree of interdependence and shock transmission within the network at any given point in time.[65]

If we assume that X_t is a vector of volatility series for an electricity market and can be modelled by a covariance stationary VAR(p):

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[63] European Council: How did the EU respond to the 2022 energy crisis ? [online]. Available at: https://www.consilium.europa.eu/en/policies/how-did-the-eu-respond-to-the-2022-energy-crisis/timeline-how-did-the-eu-respond-to-the-2022-energy-crisis/

[64] CRAN-R:
vars: VAR Modelling [online]. Available at:
https://cran.r-project.org/web/packages/vars/index.html
ConnectednessApproach: Connectedness Approach [online]. Available at:
https://cran.r-project.org/web/packages/ConnectednessApproach/index.html

[65] DIEBOL, F.X. – YILMAZ, K. *Better to give than to receive: Predictive directional measurement of volatility spillovers*. International Journal of Forecasting 28. 2012, pg. 57-66

$$X_t = \sum_{i=1}^{p} \Phi_i X_{t-i} + \varepsilon_t \qquad \text{in which } \varepsilon_t \sim N(0, \Sigma)$$

The VAR model can be written also in a moving average form:

$$X_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$$

,where the $N \times N$ coefficient matrices A_i obey the recursion $A_i = \phi_1 A_{i-1} + \phi_2 A_{i-2} + \cdots + \phi_p A_{i-p}$ with A_0 being an $N \times N$ identity matrix with $A_i = 0$, for $i < 0$.

The p denotes the lag order of the VAR model. To select the optimal lag for our model, we used the Schwarz/Bayesian Information Criterion as it is the most conservative one, imposing the heaviest penalty for model complexity. In our output the criterion pointed to select p = 2.[66]

Once the moving average representation is obtained, variance decomposition is applied to separate two distinct sources of forecast uncertainty for each variable in the system. The first is the share of a variable's forecast error variance that stems from its own past shocks, referred to as the own variance share. The second is the share attributable to shock originating in all other variables, referred to as cross variance shares or spillovers.

Following Diebold and Yilmaz we have used the generalized forecast error variance decomposition (GFEVD), to achieve that results are invariant to the variable ordering.[67]

For a selected forecast horizon H, the contribution of variable k's shocks to j's generalized forecast error variance, $\Theta_{j,k}^{H}$, can be computed as follows:

$$\Theta_{j,k}^{H} = \frac{\sigma_{kk}^{-1} \sum_{h=0}^{H-1} (e_j' \psi_h \Sigma_\varepsilon e_k)^2}{\sum_{h=0}^{H-1} (e_j' \psi_h \Sigma_\varepsilon \psi_h' e_j)}$$

where:

ψ_h is the moving average coefficient matrix corresponding to lag h

Σ_ε is the variance-covariance matrix for the vector of disturbances ε_t

σ_{kk} is the k-th diagonal element in Σ_ε

e_j is the j-th entry for a selection vector

e_k is the k-th entry for a selection vector

The sum of the contributions to the GFEVD does not necessarily equal 1:

$$\sum_{k=1}^{n} \Theta_{j,k}^{H} \neq 1$$

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66 WALTER, E. *Applied econometric time series.* Fourth Edition. John Wiley & Sons. 2015. ISBN 978-1-118-80856-6

67 DIEBOL, F.X. – YILMAZ, K. *Better to give than to receive: Predictive directional measurement of volatility spillovers*. International Journal of Forecasting 28. 2012, pg. 57-66

In order to calculate the spillover index, we normalise $\Theta_{j,k}^{H}$, the elements of the H-step ahead GFEVD matrix, by the row sums as follows:

$$\widetilde{\Theta}_{j,k}^{H} = \frac{\Theta_{j,k}^{H}}{\sum_{k=1}^{n} \Theta_{j,k}^{H}}$$

By construction, we have $\sum_{k=1}^{n} \widetilde{\Theta}_{j,k}^{H} = 1$ and thus $\sum_{j,k}^{n} \widetilde{\Theta}_{j,k}^{H} = n$.

The total volatility spillover index is defined as the sum of the off-diagonal elements divided but the sum of all the elements in the GFEVD matrix:

$$S^{H} = \frac{\sum_{\substack{j,k \\ j \neq k}}^{n} \widetilde{\Theta}_{j,k}^{H}}{\sum_{j,k=1}^{n} \widetilde{\Theta}_{j,k}^{H}} \times 100 = \frac{\sum_{\substack{j,k \\ j \neq k}}^{n} \widetilde{\Theta}_{j,k}^{H}}{N} \times 100$$

The generalized VAR approach allows us to also study also the direction of volatility spillovers. We calculate the directional spillovers using the normalised elements of the generalized variance decomposition matrix. We can measure the directional volatility spillovers received by market *j* from all other markets *k* as follows:

$$S_{j\leftarrow\cdot}^{H} = \frac{\sum_{\substack{k=1 \\ j \neq k}}^{n} \widetilde{\Theta}_{j,k}^{H}}{N} \times 100$$

Similarly, we can measure the directional volatility spillovers transmitted by market *j* to all other markets as follows:

$$S_{\cdot\leftarrow j}^{H} = \frac{\sum_{\substack{k=1 \\ j \neq k}}^{n} \widetilde{\Theta}_{k,j}^{H}}{N} \times 100$$

This can help us to calculate the net transmitters or net receivers in the system as:

$$S_{j}^{H} = S_{\cdot\leftarrow j}^{H} - S_{j\leftarrow\cdot}^{H}$$

If we are interested in the net pairwise volatility spillovers between two countries, we can use the following calculation:

$$S_{j,k}^{H} = \widetilde{\Theta}_{j,k}^{H} - \widetilde{\Theta}_{k,j}^{H}$$

To capture both the intensity of volatility and its cross-border transmission, we have constructed a composite vulnerability index. The index combines directional volatility spillovers received from other markets and the domestic level of volatility, represented by our volatility proxy.

Let $S_{j\leftarrow\cdot,t}^{H}$ denote the directional spillover received by country *j* from all other countries and $VOL_{j,t}$ the volatility measure. To ensure comparability across different units, both variables are standardised using z-scores computed over the full sample:

$$z_{FROM} = \frac{S^{H}_{j\leftarrow\cdot,t} - \mu_{S^{H}_{j\leftarrow\cdot}}}{\sigma_{S^{H}_{j\leftarrow\cdot}}}$$

$$z_{VOL} = \frac{VOL_{j,t} - \mu_{VOL}}{\sigma_{VOL}}$$

The vulnerability index is then defined as:

$$VI = 0{,}5 * z_{FROM} + 0{,}5 * z_{VOL}$$

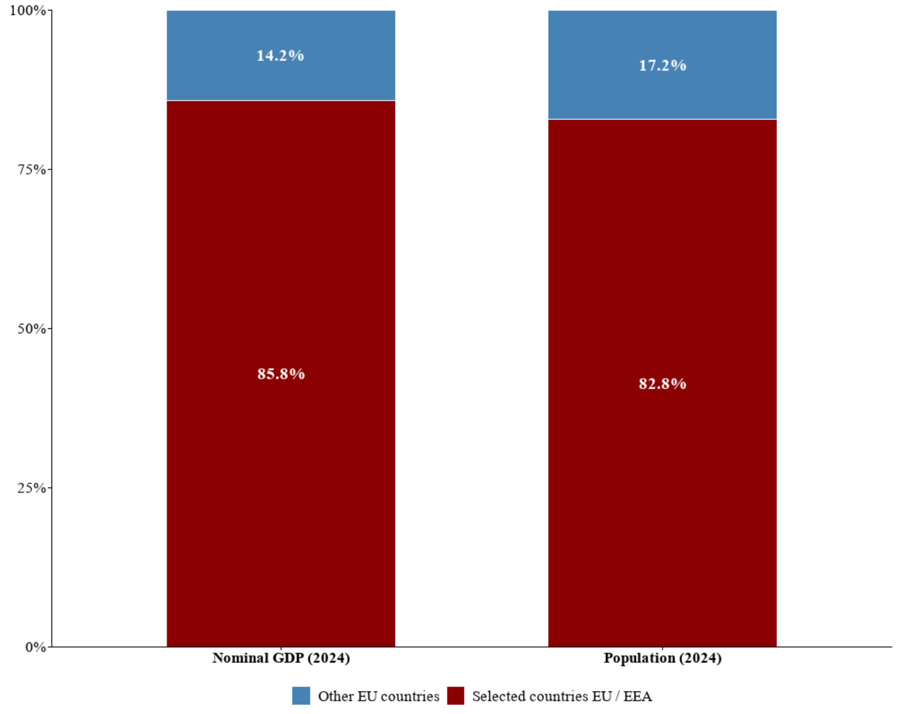
This index measures the relative exposure of each country to systemic stress, capturing periods when volatility is elevated and strongly driven by cross-border shocks. Higher values of the index indicate greater vulnerability to cross-market volatility transmission.

3 Results of the Thesis

3.1 Overview of the selected markets

Price volatility in the wider European electricity market has attracted greater public attention in recent years, particularly due to its heightened levels and its impact on the everyday lives of millions of European citizens. This analysis focuses on a heterogeneous group of countries that differ in terms of economic size, population, electricity consumption and production and geographical location. The analysed countries can be divided into three major geographical groups. The first group consists of advanced Western European countries, including four of the largest European economies: Germany, France, Italy and Spain, together with the Netherlands. The second group comprises Central European countries, namely Poland, Czechia, Slovakia, Austria and Hungary. Lastly, the analysis includes Nordic countries, specifically Sweden, Finland, Norway and Denmark. All of the analysed countries except Norway are members of the European Union.

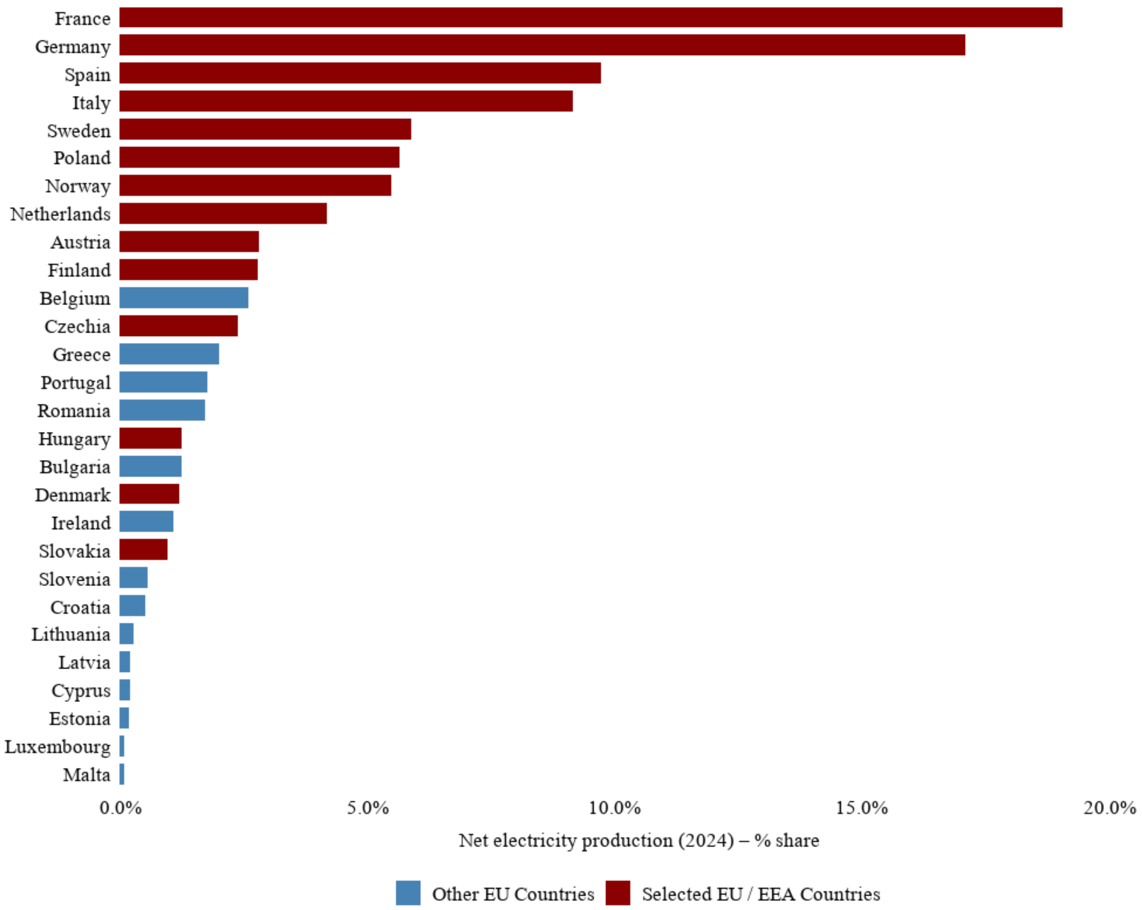
Although the sample consists of only 13 EU Member States and Norway, these countries together accounted for a nominal GDP of €15 391 957 million in 2024 and represented markets with more than 371 million inhabitants. This corresponds to nearly 86% of the nominal GDP produced in the EU-27 plus Norway, highlighting that the sample covers the vast majority of the broader European electricity market in economic terms.



Graph 4 - Nominal GDP and Population of EU27 + Norway
Source: Eurostat, Author's own illustration

The countries we have analysed similarly represent the majority of net production and consumption of electricity in the European market, with their share of net production standing at around 87% of the combined EU-27 plus Norway market as of 2024 and consuming around 86% of the total electricity consumption in the same market.

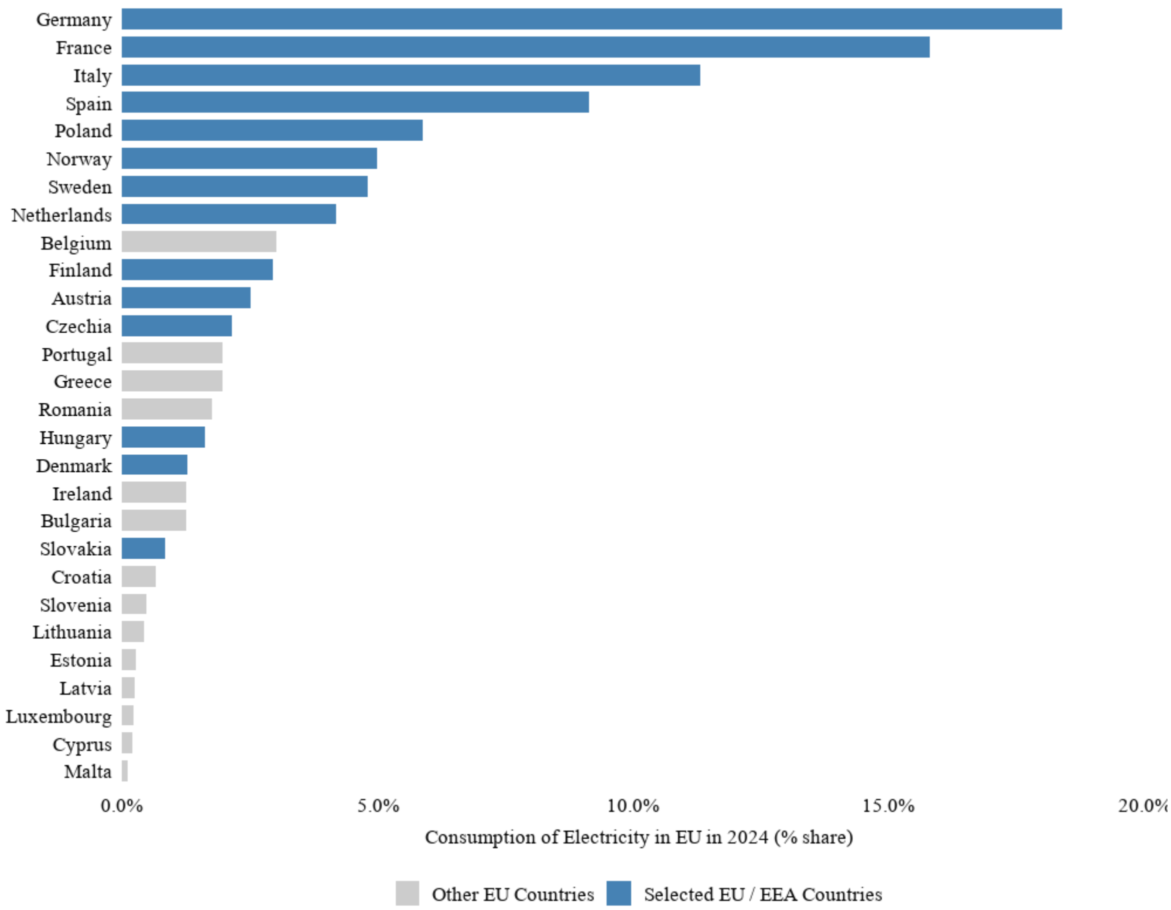
Regarding net production of electricity, France leads with the highest share in the overall net production of electricity, at 19%, followed by Germany, Italy and Spain. Interestingly, even though Norway's share of GDP only stands at 2,4% of total EU-27 plus Norway GDP as of 2024, its net production is about 5,5% of the same market, being higher than that of the Netherlands, which in terms of GDP makes up 6,1% of the total GDP share.



Graph 5 - Net electricity production
Source: Eurostat, Author's own illustration

Shifting our attention to the consumption of electricity, we can observe a change in ranking, with Germany, as the major economic player in Europe, constituting 18,4% of total electricity consumption in the EU-27 plus Norway market, followed by France, Italy and Spain, as expected due to their role as the workhorses of the European economy. As with electricity production, we can similarly observe interesting numbers in connection to Norway, with its share of final consumption being 5%, surpassing countries with higher total

GDP and population, such as the Netherlands and Sweden, which could be attributable, for example, to Norway's energy intensive industries such as aluminium production.



Graph 6 - Final electricity consumption
Source: Eurostat, Author's own illustration

3.1.1 Electricity generation mixes in the selected countries

The analysed European electricity markets as of 2024 exhibit substantial heterogeneity in their electricity generation structures, which represents an important structural determinant of price volatility, since technology specific marginal costs, fuel dependencies and intermittency characteristics directly shape price formation under the current merit order mechanism and can potentially influence cross-border spillover dynamics.[68]

Nuclear energy plays a dominant role in France, where it accounts for approximately 68 % of total electricity production and in Slovakia, where its share reaches 62 %. Nuclear generation also represents a significant component of the energy mix in Czechia, Finland

[68] MACEDO, D. P. – MARQUES, A. C. – DAMETTE, O. *The role of electricity flows and renewable electricity production in the behaviour of electricity prices in Spain*. Economic Analysis and Policy, vol. 76. 2022

and Hungary. Due to its low marginal cost and high baseload characteristics, nuclear capacity typically contributes to lower wholesale price volatility under normal operating conditions. However, outages or maintenance disruptions, as was the case in France during 2022, when over half of the French nuclear reactor fleet was offline, can generate substantial price shocks due to limited short-run flexibility.[69]

Hydropower represents the second most important generation source across the sample. Norway stands out as the most hydro dependent country, with nearly 89 % of its electricity generated from hydropower, followed by Austria and Sweden, with 58 % and 38 % of their generation originating from hydropower, respectively. Italy, Finland and Slovakia also maintain meaningful hydro shares.

Wind generation dominates the Danish electricity mix, accounting for approximately 58 % of total production. In Finland, Germany, the Netherlands, Spain and Sweden, wind contributes between 22 % and 28 % of generation.

Natural gas, as of 2024, does not exceed 50 % of generation in any analysed country, however, it remains structurally important in Italy, with a 44 % share of generation and in the Netherlands, with a 36 % share of generation. Gas fired generation is a highly flexible source of electricity and typically sets the marginal price in periods of elevated demand, therefore gas dependent markets can be particularly exposed to fuel price shocks.

Coal based generation of electricity remains significant in Poland, where, as of 2024, it generated the majority of Polish electricity, with a 55 % share. Another country where coal is an important source of energy is Czechia, with a 31 % share of generation, followed by Germany, where coal accounted for 21 % of total electricity generation.

As can be observed, solar energy contributes meaningfully to the energy mix in Hungary and Spain, where it accounts for 24 % and 21 % of electricity production, respectively, and accounts for between 10 % and 17 % in Austria, Denmark, Poland, Germany and the Netherlands. Similar to wind, solar generation has been found to lower average electricity prices due to the merit order effect, but also to affect intraday volatility, with a study focused on the Spanish market finding that solar tends to decrease volatility in off-peak hours while increasing it during midday peak hours.[70]

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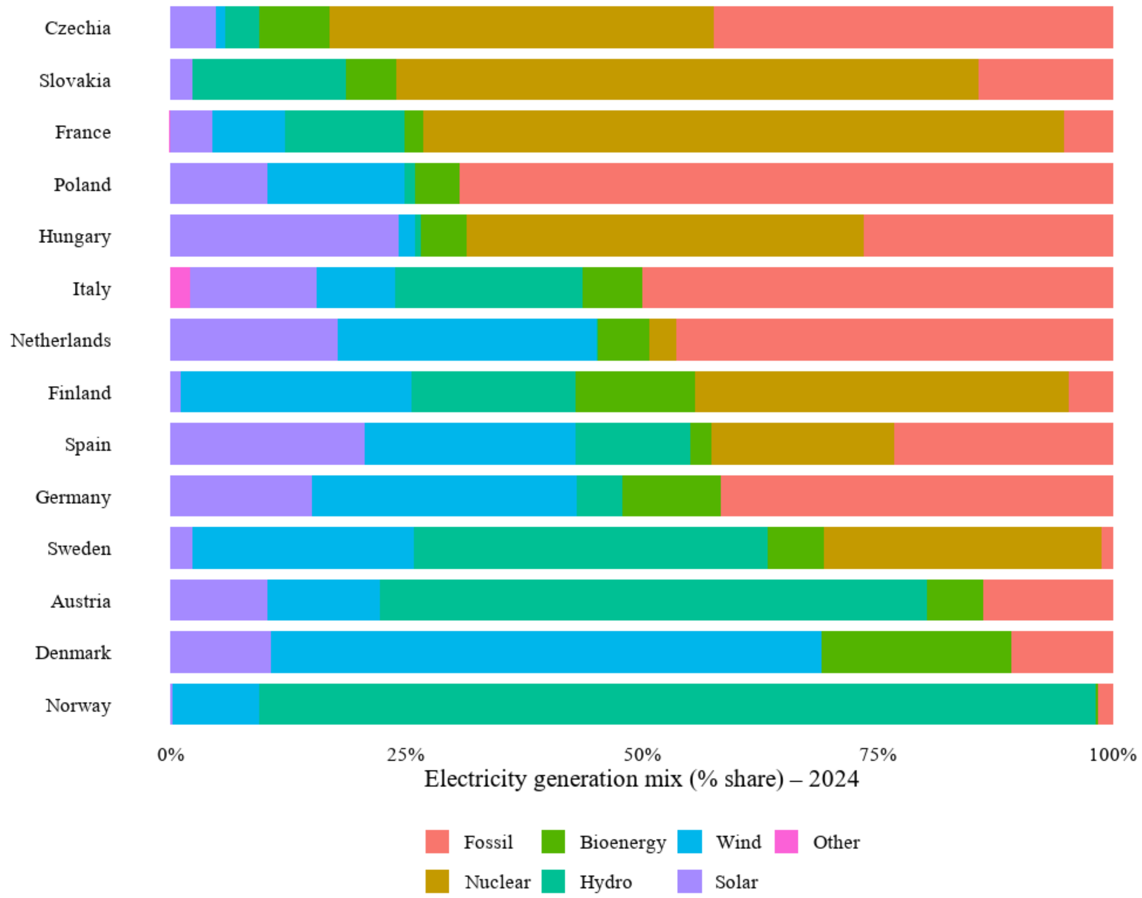
[69] World Nuclear Report: EDF reactor outages rise 47 % in “disastrous” 2022 – study [online]. Available at: https://www.worldnuclearreport.org/EDF-reactor-outages-rise-47-in-disastrous-2022-study

[70] MACEDO, D. P. – MARQUES, A. C. – DAMETTE, O. *The role of electricity flows and renewable electricity production in the behaviour of electricity prices in Spain*. Economic Analysis and Policy, vol. 76. 2022

The last major source of electricity is bioenergy, which is generated from organic materials or biomass. It plays an important role in the generation mix of Denmark, where it accounts for approximately 25 % of the generation mix, as well as in Finland and Germany.

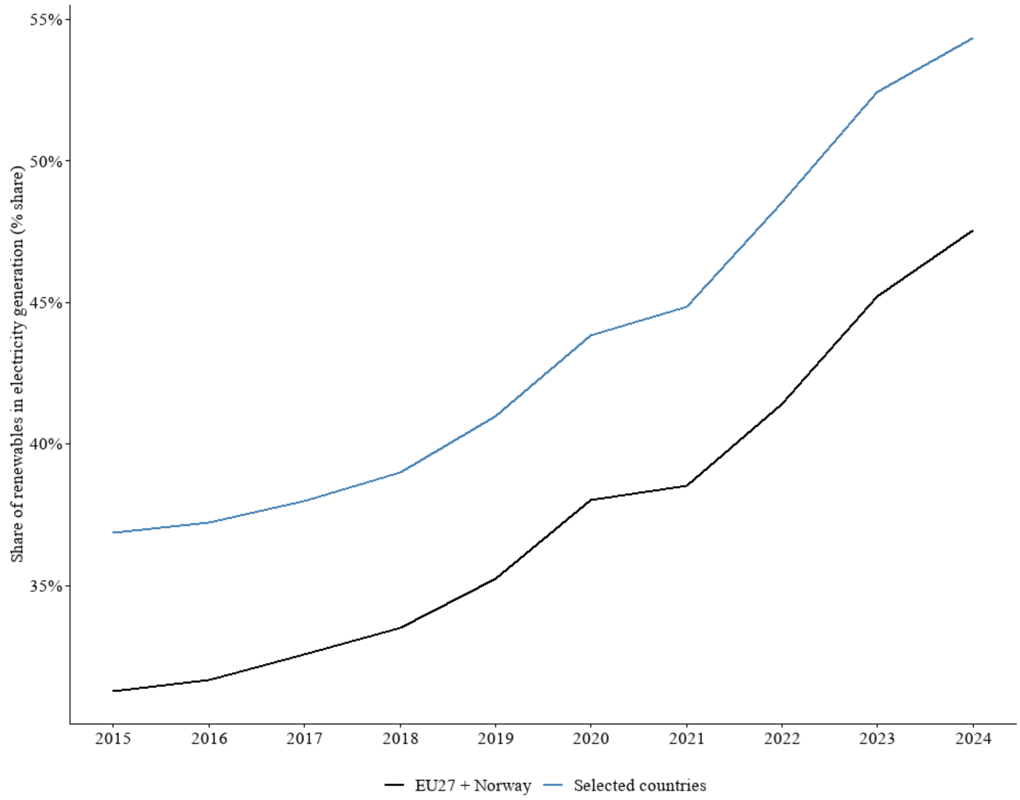


Graph 7 - Electricity generation mix in the selected countries
Source: Ember Data

The evolution of renewable electricity generation between 2015 and 2024 is illustrated in Graph 8. Across the selected countries, the share of renewable generation increased from 36,8 % in 2015 to 54,3 % in 2024. This corresponds to a cumulative increase of approximately 47 % over the period and an annual growth rate, represented by a CAGR, of 4,4 %.

A decomposition of the sample period reveals an acceleration in renewable penetration. Between 2015 and 2020, the renewable share grew at a CAGR of 3,5 %. In contrast, during the 2020–2024 period, growth intensified to 5,5 % annually, which suggests that the expansion of renewable capacity gained momentum in the latter part of the investigated period. The observed dynamics likely reflect a combination of strengthened EU climate policy, notably the European Green Deal in 2019 and the Fit for 55 legislative package, as well as the policy response to the Russian invasion of Ukraine, particularly the REPowerEU plan adopted in 2022.

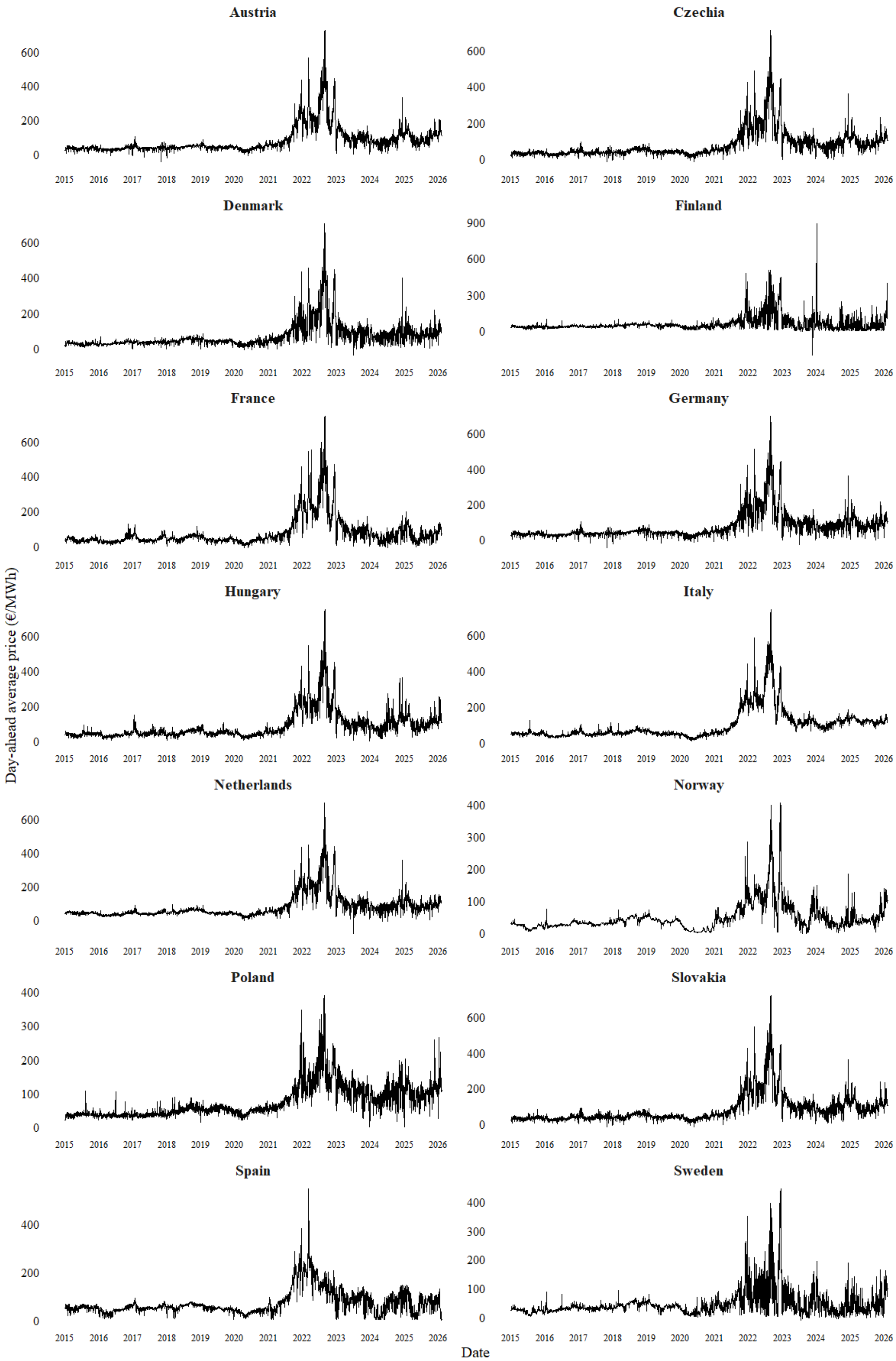
For comparison, the broader market comprising the EU-27 countries and Norway experienced even faster growth in renewable penetration, with a CAGR of 4,7 % and a total increase of approximately 52 % over the same period.



Graph 8 - Share of renewables in electricity generation
Source: Eurostat; Author's own illustration

3.1.2 Price dynamics of wholesale electricity prices

Looking at Graph 9, we can observe the price evolution of wholesale day-ahead prices in the analysed European countries over the period 2015–2025. The time series show pronounced regime dependence, as prices were comparatively stable during the pre-crisis period before the July 2021–2023 energy crisis, followed by a noticeable upward shift and a sharp increase in price variability during the crisis period. After this crisis period, prices declined from their peak in most of the observed countries but remained more volatile than in the previous years.



Graph 9 - Day-ahead average prices
Source: Author's own illustration

	Mean	SD	Min	Max	Median	Skewness	Kurtosis
Austria	79,0	84,7	-270,0	839,0	47,0	3,00	15,4
Czechia	77,8	81,2	-224,0	871,0	50,0	3,11	16,7
Denmark	67,1	76,5	-299,0	936,0	42,1	3,49	20,1
Finland	53,7	66,4	-500,0	1 896,0	36,4	4,78	51
France	77,0	88,0	-135,0	2 988,0	48,7	3,80	36,7
Germany	73,3	80,1	-316,0	868,0	45,8	3,16	17,0
Hungary	88,5	89,2	-500,0	1 047,0	58,4	3,01	15,8
Italy	99,2	88,4	0,0	870,0	67,2	2,94	14,6
Netherlands	76,9	78,4	-500,0	873,0	49,9	3,03	16,4
Norway	47,0	45,2	-32,2	587,0	34,9	3,50	21,4
Poland	75,8	55,4	-133,0	771,0	56,8	2,49	14,9
Slovakia	82,1	86,6	-203,0	900,0	52,3	3,02	15,7
Spain	70,6	54,3	-15,0	700,0	54,7	2,07	10,0
Sweden	46,1	50,8	-60,0	648,0	33,4	4,47	28,3

Table 2 - Descriptive statistics of the hourly day-ahead prices of electricity (2015-2025)
Source: Author's own analysis

Table 2 illustrates descriptive statistics for hourly day-ahead electricity prices across the selected European markets over the full period. The results show substantial differences in average prices, ranging from roughly 46–47 €/MWh in Sweden and Norway to about 99 €/MWh in Italy. Price variability, measured by the standard deviation, is pronounced in all countries and is often comparable to the mean level. The distribution is also characterized by extreme positive spikes, with maximum prices above 1 000 €/MWh in Finland, France and Hungary. Skewness is strongly positive and kurtosis is far above the usual benchmark of normal distribution, implying heavy tails in the distribution and deviation from normality. We can also observe negative minimum prices, which are not a usual characteristic of other markets, such as equity markets, but are characteristic of the European electricity market, with the lowest price observed in the dataset being -500 €/MWh, which corresponds to the harmonised minimum clearing price set by ACER.[71]

For the subsequent empirical analysis, the sample is divided into three subperiods. The pre-crisis period spans from January 2015 to June 2021 and represents a phase of

[71] ACER: Harmonised maximum and minimum clearing prices for single day-ahead coupling [online]. Available at: https://www.acer.europa.eu/sites/default/files/documents/Individual%20Decisions_annex/ACER-Decision-02-2026-AnnexI.pdf

relatively stable market conditions. The crisis period covers July 2021–December 2023 and coincides with the European energy crisis and the Russian invasion of Ukraine. Finally, the post-crisis period captures the normalization phase following the peak market stress, which is characterized by declining wholesale prices but heightened levels of volatility in comparison to the pre-crisis period.

	Mean	SD	Min	Max	Median	Skewness	Kurtosis
Austria	36,7	16,1	-130,1	163,5	35,8	0,2	4,7
Czechia	38,4	17,2	-65,0	141,0	36,5	0,5	1,8
Denmark	33,7	16,9	-53,6	200,0	31,7	0,7	2,4
Finland	36,6	17,8	-1,7	255,0	34,5	1,7	10,8
France	41,7	19,8	-75,8	874,0	39,6	4,6	154,1
Germany	36,0	17,3	-130,1	254,8	35,2	0,1	4,8
Hungary	45,7	19,8	-35,0	300,1	43,2	1,1	4,0
Italy	51,5	16,7	0,0	170,0	50,0	0,7	1,7
Netherlands	40,9	15,8	-79,2	200,0	38,9	0,9	3,1
Norway	28,9	14,2	-0,3	171,4	28,3	0,4	1,9
Poland	45,1	15,7	1,2	331,3	42,6	2,2	17,6
Slovakia	39,9	18,8	-65,0	141,0	37,5	0,7	1,7
Spain	47,7	16,2	0,0	121,2	48,3	-0,1	0,5
Sweden	32,0	15,3	-1,7	255,0	30,7	1,3	9,2

Table 3 - Descriptive statistics of the hourly day-ahead prices of electricity (2015-06/2021)
Source: Author's own analysis

Table 3 presents the descriptive statistics for the hourly wholesale day-ahead prices of electricity across 14 European markets over the pre-crisis period 2015–06/2021. Prices are markedly lower and more stable than in the full sample, the cross-sectional variance of country average prices falls from 224,75 to 89,87, and in no country does the standard deviation exceed the mean, which is a notable contrast to the full sample results. Skewness remains positive across the majority of markets, except Spain, while kurtosis values are elevated in several countries, reflecting the presence of fat tails and occasional extreme observations. Negative prices are present but remain above the regulatory floor, reflecting periodic renewable surplus under normal market conditions. Heterogeneity across countries is evident, as Norway exhibits the lowest mean price, 28,9 €/MWh, while Italy, Spain and Hungary record the highest average prices.

	Mean	SD	Min	Max	Median	Skewness	Kurtosis
Austria	177,4	121,3	-270,4	838,7	141,7	1,6	3,2
Czechia	167,5	118,7	-68,5	871,0	130,0	1,7	3,6
Denmark	144,5	119,0	-299,0	871,0	108,7	1,8	4,2
Finland	103,6	107,6	-500,0	1000,1	76,3	2,0	6,4
France	180,9	132,6	-134,9	2987,8	143,3	2,2	17,5
Germany	160,4	119,5	-316,4	867,9	123,1	1,7	3,4
Hungary	184,6	124,9	-500,0	1047,1	148,2	1,6	3,4
Italy	209,0	123,4	2,4	870,0	174,5	1,6	2,8
Netherlands	164,8	116,1	-500,0	871,0	132,0	1,5	3,4
Norway	95,7	68,4	-32,2	587,0	82,4	2,0	5,7
Poland	133,6	66,6	-13,8	771,0	118,8	2,4	10,8
Slovakia	176,9	125,2	-24,4	900,2	137,8	1,7	3,3
Spain	134,8	71,4	0,0	700,0	124,2	0,9	2,7
Sweden	85,7	86,4	-60,0	648,4	62,2	2,2	6,2

Table 4 - Descriptive statistics of the hourly day-ahead prices of electricity (07/2021-2023)
Source: Author's own analysis

In Table 4, we present the statistics of hourly day-ahead electricity prices during the crisis period covering 07/2021–2023. Compared with the pre-crisis period, electricity prices surge substantially across all countries in the sample. Average prices rise sharply, ranging from 85,7 €/MWh in Sweden and 95,7 €/MWh in Norway to 209,0 €/MWh in Italy. As can be seen, several Central European markets also record very high average prices, including Slovakia, Hungary and Austria. Median prices show a similar pattern, confirming that the increase in prices is widespread across the distribution rather than driven only by a few extreme observations. Price variability also rises significantly during this period, with the standard deviation of prices increasing markedly in most countries, indicating much higher volatility in electricity markets during the crisis. The highest observed price in the sample occurs in France, reaching almost 3 000 €/MWh, followed by Finland, with an observed price of approximately 1 000 €/MWh and several other markets recording maximum prices close to or above 900 €/MWh. The distribution of prices remains positively skewed in all markets, meaning that very high prices occur more frequently than very low ones. However, skewness and kurtosis are generally lower than in the pre-crisis period, suggesting that the crisis period is characterized not only by occasional spikes but also by generally elevated price levels across many hours. Negative prices continue to occur in several markets, in some cases reaching the aforementioned regulatory price limit.

	Mean	SD	Min	Max	Median	Skewness	Kurtosis
Austria	90,1	47,4	-199,5	711,7	91,2	0,97	12,8
Czechia	90,9	50,2	-224,5	844,6	91,1	1,57	20,3
Denmark	76,5	49,8	-60,0	936,3	78,5	2,02	21,6
Finland	42,9	63,9	-21,4	1896,0	24,0	8,86	186,3
France	60,4	42,9	-118,0	473,3	59,8	0,44	3,8
Germany	83,6	50,6	-205,1	808,9	86,3	1,37	16,1
Hungary	104,6	72,3	-210,1	999,0	97,6	3,44	29,1
Italy	115,1	25,8	0,1	275,1	116,2	-0,07	5,5
Netherlands	82,3	49,0	-350,0	873,0	85,9	1,04	18,4
Norway	41,7	23,9	-30,9	405,0	38,3	2,87	23,8
Poland	100,0	49,4	-132,9	630,2	98,4	1,12	10,5
Slovakia	97,6	57,3	-202,7	850,0	94,7	1,71	15,5
Spain	64,9	46,4	-15,0	240,0	68,7	0,11	2,0
Sweden	39,3	36,7	-55,4	560,1	31,9	2,28	16,2

Table 5 - Descriptive statistics of the hourly day-ahead prices of electricity (2024-2025)
Source: Author's own analysis

Post-crisis statistics of the hourly day-ahead electricity prices can be found in Table 5. Compared with the crisis period, average electricity prices decline across most countries, with lower cross-country variance, indicating a partial stabilization of electricity markets following the extreme market conditions observed during 2021–2023. Nevertheless, price levels generally remain higher than those observed during the pre-crisis period, with average prices varying noticeably across countries, with the highest mean price being observed in Italy at 115,1 €/MWh, followed by Hungary and Poland, while the lowest average prices are recorded in the Nordic markets as before, in countries such as Sweden and Norway. Median prices follow a similar pattern and, in most cases, are very close to the mean. Price variability decreases compared with the crisis period but remains higher than in the pre-crisis years. Standard deviations range from 23,9 €/MWh in Norway to 72,3 €/MWh in Hungary, indicating that while volatility has subsided, electricity prices still fluctuate considerably across markets. Extreme values continue to occur in some countries, with Finland again, as in the pre-crisis period, recording the highest maximum price of 1 896 €/MWh. The degree of skewness and kurtosis varies across markets, suggesting that post-crisis price distributions remain affected by occasional extreme observations, with Finland being the clearest exception due to very high skewness and kurtosis.

Overall, the descriptive statistics highlight clear differences in electricity price dynamics across the three analysed periods. The pre-crisis period is characterized by relatively low and stable price levels, with moderate volatility and price spikes occurring only occasionally. In contrast, the crisis period shows a dramatic increase in both average prices and price variability across all countries, reflecting the exceptional conditions in European electricity markets during the energy crisis. The post-crisis period indicates a partial normalization of market conditions, as average prices decline and volatility decreases compared with the crisis years. However, price levels and variability generally remain higher than in the pre-crisis period, suggesting that electricity markets have not fully returned to their earlier stability. We note that, similarly to Luy et al. (2024), we have not modified in any way the electricity prices obtained and used the raw data.

3.2 Volatility dynamics

To characterize the dynamics of electricity price volatility across the analysed markets, we employed the daily intraday range as a proxy for realized price volatility, following Ma et al. (2022) and Sikorska-Pastuszka and Papież (2023). The intraday range for market i on day t is defined as the squared difference between the maximum and minimum hourly price within the day, as follows:

$$IR_{i,t} = (max_j\{p_{i,t,j}\} - min_j\{p_{i,t,j}\})^2, j = 1, \dots, 24$$

where $p_{i,t,j}$ denotes the hourly price in market i on day t at hour j. This measure captures the full extent of price fluctuations within a given day and its use is suitable for electricity markets. In the literature, there is also use of other measures, such as realized variance.

To achieve approximate normality of the series, as required by the generalized forecast error variance decomposition underlying the Diebold–Yilmaz framework, the natural logarithm of the intraday range was taken. On a small number of days, the intraday range equals zero, indicating that all 24 hourly prices cleared at an identical level. Such observations represent at most 0,57 % of the sample in any given country, with the largest concentration in Poland. Since the logarithmic transformation is undefined for zero values, these observations were replaced by a small positive constant of 0,01125.[72]

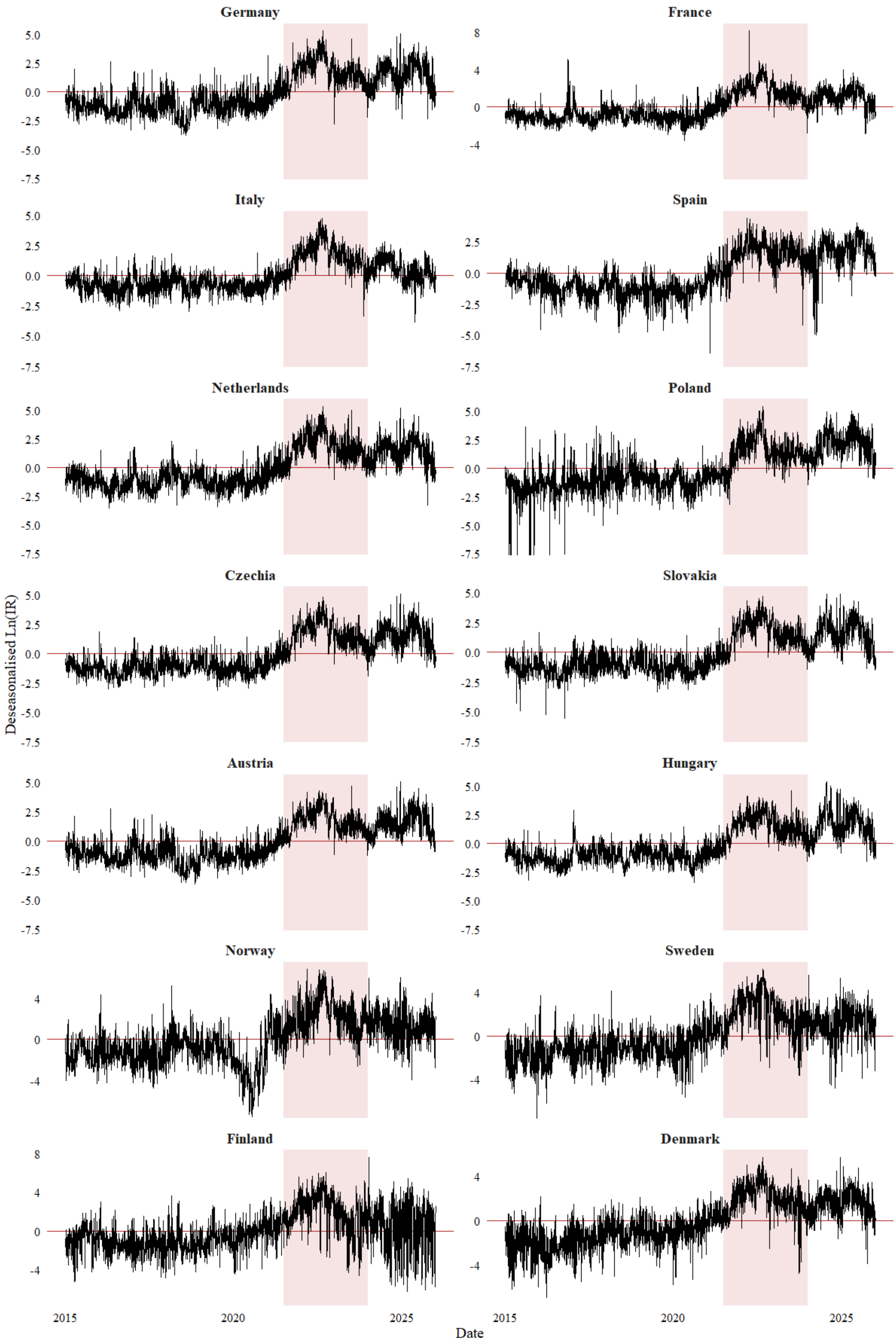
[72] SIKORSKA-PASTUZSKA, M. – PAPIEŻ, M. Dynamic Volatility Connectedness in the European Electricity Market. Energy Economics 127. 2023

Finally, to account for the seasonality of electricity markets, the log transformed series were adjusted by regressing each country's series on day-of-week, monthly and public-holiday dummy variables and retaining the residuals. Formal F-tests confirmed that both day-of-week and monthly seasonal components are statistically significant at the 1 % level across all 14 markets, with F-statistics ranging from 6,19 to 86,64 for day-of-week effects and from 5,33 to 18,46 for monthly effects. The resulting deseasonalised series, with means of zero by construction, serves as the input to all subsequent empirical analysis.

	F-Stat (DOW)	p-value (DOW)	F-Stat (Monthly)	p-value (Monthly)
Austria	10,49	0,00	9,26	0,00
Czechia	10,75	0,00	11,59	0,00
Denmark	14,23	0,00	9,32	0,00
Finland	86,64	0,00	5,33	0,00
France	15,61	0,00	15,43	0,00
Germany	8,34	0,00	8,97	0,00
Hungary	7,50	0,00	14,15	0,00
Italy	6,93	0,00	17,87	0,00
Netherlands	6,19	0,00	6,08	0,00
Norway	10,19	0,00	18,46	0,00
Poland	14,34	0,00	6,89	0,00
Slovakia	11,45	0,00	12.80	0,00
Spain	6,50	0,00	15,09	0,00
Sweden	45,01	0,00	8,57	0,00

Table 6 - F-test results for seasonality
Source: Author's own analysis

As a robustness check, we applied the non-parametric Kruskal-Wallis test to verify that the seasonality findings are not dependent on the distributional assumptions underlying the F-test. The Kruskal-Wallis test, which requires no assumption of normality and is therefore robust to the excess kurtosis and heavy tails that can be present in the series, confirmed the presence of statistically significant day-of-week and monthly seasonal components at the 1 % significance level across all 14 markets, yielding conclusions identical to those of the parametric F-test.



Graph 10 – Deseasonalised Ln(IR)
Source: Author's own illustration; Red indicates 07/2021-2023

	Mean	SD	Min	Max	Median	5^{th} Percentile	95^{th} Percentile
Austria	0,00	1,66	-11,83	5,07	-0,31	-2,26	2,85
Czechia	0,00	1,60	-3,14	5,10	-0,46	-2,03	2,88
Denmark	0,00	1,98	-6,88	5,69	-0,14	-3,14	3,18
Finland	0,00	2,01	-6,25	7,61	-0,25	-3,03	3,60
France	0,00	1,52	-11,97	8,15	-0,37	-1,90	2,63
Germany	0,00	1,74	-12,01	5,30	-0,35	-2,32	2,92
Hungary	0,00	1,59	-3,41	5,38	-0,38	-2,12	2,87
Italy	0,00	1,36	-11,76	4,73	-0,29	-1,17	2,49
Netherlands	0,00	1,70	-12,09	5,34	-0,40	-2,21	2,90
Norway	0,00	2,27	-7,54	6,84	-0,12	-3,36	3,77
Poland	0,00	2,02	-12,18	5,42	-0,35	-2,48	3,29
Slovakia	0,00	1,65	-5,53	4,87	-0,39	-2,17	2,97
Spain	0,00	1,66	-6,39	4,36	-0,34	-2,28	2,81
Sweden	0,00	2,07	-10,4	6,18	-0,21	-3,18	3,59

Table 7 - Descriptive statistics for the deseasonalised log intraday range
Source: Author's own calculations

Table 7 presents descriptive statistics for the deseasonalised log transformed intraday range, which is used as the volatility proxy in the subsequent spillover analysis. Since the series represents residuals from a regression that removes deterministic calendar effects, mainly day-of-week and monthly effects, the mean values are close to zero across all countries. Therefore, the analysis of descriptive statistics focuses primarily on the dispersion and distributional characteristics of the series.

The variability of volatility differs noticeably across markets. The largest standard deviations are observed in Norway and Sweden, which interestingly had among the lowest variability in prices, while in contrast, Italy and France exhibit the lowest standard deviations, suggesting comparatively more stable volatility dynamics once deterministic seasonal effects are removed.

The percentile statistics further highlight the dispersion of volatility shocks. For most countries, the 5th percentile lies between approximately -3,4 and -1,7, while the 95th percentile ranges roughly between 2,5 and 3,8. This implies that, under typical conditions, deviations from the seasonal volatility pattern remain within a relatively stable band, however the minimum and maximum values reveal that extreme volatility shocks occasionally occur across all markets. It should be noted that the minimum values observed for Austria, France, Germany, Italy, the Netherlands, Poland and Sweden partly reflect the treatment of zero intraday range observations. On a small number of days, representing at most around 0,5 % of the sample in each country, the intraday range equals zero. As mentioned before, since the logarithmic transformation is undefined for zero values, these observations were replaced by a small positive constant prior to transformation and, as a result, the reported minimum values partly reflect this adjustment rather than purely market driven volatility dynamics.

Before moving on to the construction of the VAR model, the stationarity of the deseasonalised log intraday range series was tested using the Augmented Dickey-Fuller test, resulting in rejection of the unit root null hypothesis at the 1 % significance level across all countries. These results confirm that the VAR requirement of covariance stationarity is satisfied for all series entering the spillover analysis.

	ADF Statistic	p-value
Austria	-5,05	0,01
Czechia	-5,22	0,01
Denmark	-7,44	0,01
Finland	-8,28	0,01
France	-5,61	0,01
Germany	-5,34	0,01
Hungary	-5,91	0,01
Italy	-5,24	0,01
Netherlands	-5,27	0,01
Norway	-6,49	0,01
Poland	-8,78	0,01
Slovakia	-5,35	0,01
Spain	-6,17	0,01
Sweden	-7,92	0,01

Table 8 - ADF test results
Source: Author's own calculations

After estimating the VAR model, we tested the roots of the model to confirm the stability of the system. The diagnostic tests suggest the presence of multicollinearity and heteroskedasticity, which is not surprising given the strong interconnectedness of European electricity markets and the volatile nature of electricity prices. To account for heteroskedasticity and time-varying volatility, the static spillover analysis is supplemented with rolling window estimation, which allows us to better capture the evolution of volatility transmission over time.

3.3 Volatility spillover analysis

3.3.1 Static volatility spillover

The static analysis of volatility spillovers in electricity markets among the selected countries was performed over the whole period, from 1.1.2015 to 31.12.2025, encompassing numerous changes in European electricity markets, including the expansion of renewable generation and several major shocks, such as COVID-19, the Russian invasion of Ukraine and the related energy crisis. The total spillover index among the countries during this period stood at 81,17 %, meaning that 81,17 % of the forecast error variance can be attributed to cross-border variance shares among the 14 countries. Thus, over the whole period, only 18,83 % of forecast error variance can be attributed to shocks in individual countries. These numbers imply that, during the observed time frame, cross-border volatility spillovers dominate the behaviour of electricity prices in the 14 analysed European markets.

	DE	FR	IT	ES	NL	SK	CZ	AT	PL	HU	SE	NO	FI	DK	From	Net
DE	**14,2**	8,1	4,6	5,9	9,8	9,7	11,2	12,3	3,1	8,7	2,4	2,9	1,2	5,8	85,8	19,2
FR	9,1	**16,2**	5,9	6,6	11	8,7	9,9	9,1	3,0	7,7	2,6	4,1	1,3	4,8	83,8	12,1
IT	7,8	9,3	**21,0**	5,2	9,1	7,6	8,8	7,9	2,8	7,3	2,6	4,6	1,8	4,1	79	-19,9
ES	7,7	7,1	3,5	**21,9**	7,7	9,0	9,7	8,3	3,5	8,8	2,6	4,2	1,2	4,9	78,1	-6,1
NL	9,7	9,7	5,3	6,1	**14,9**	9,4	10,7	9,2	3,4	8,6	2,6	3,8	1,2	5,4	85,1	22
SK	8,8	7,1	4,5	5,9	8,5	**15,3**	13,3	8,6	3,6	12,3	2,3	3,3	1,0	5,5	84,7	30,6
CZ	9,4	7,5	4,5	6,1	8,9	12,3	**14,9**	9,4	3,4	10,3	2,6	3,6	1,2	5,8	85,1	42,9
AT	12,3	8,3	4,8	6,2	9,2	9,4	11,1	**14,9**	3,0	8,6	2,4	3,2	1,3	5,3	85,1	20,5
PL	7	6,4	3,5	5,8	7,9	9,6	9,9	6,9	**19,9**	9,4	3,2	3,6	1,0	5,9	80,1	-38,9
HU	8,3	6,7	4,6	6,2	8,3	13,2	11,7	8,2	3,7	**17,7**	2,1	3,3	0,9	5,1	82,3	22,7
SE	6,0	6,4	3,9	4,4	6,5	6,3	7,7	6,3	3,4	5,3	**20,5**	6,5	6,9	9,9	79,5	-27,8
NO	5,2	7,1	5,5	5,6	6,8	6,6	7,8	5,8	3	6,3	6,0	**26,4**	2,8	5,1	73,6	-21,2
FI	4,8	5,4	4,6	3,1	5,1	4,5	5,9	5,4	1,7	3,8	13,7	5,4	**30,3**	6,4	69,7	-45,7
DK	9,0	6,8	3,7	5,1	8,3	9,0	10,4	8,2	3,5	7,8	6,5	4,0	2,1	**15,6**	84,4	-10,4
Contribution to Others	105	96	59	72	107	115	128	106	41	105	52	52	24	74		
Contribution including Own	119	112	80	94	122	131	143	120	61	123	72	79	54	90		

Table 9 - Static spillover table (full period)
Source: Author's own calculations

The estimated total static connectedness level in our sample substantially exceeds the 36 % reported by Jónsson et al. (2017) for four Western European markets over 2007–2015 and is broadly consistent with the 73 % documented by Cevik and Zhao (2025) for 24 European countries over 2014–2024 and the 70 % reported by Sikorska-Pastuszka and Papież (2023) for 26 European markets over 2007–2022, with the somewhat higher figure in our sample likely reflecting a narrower sample of countries with relatively strong physical and market interconnections.

The From column in Table 9 presents the extent of spillovers from other countries to a given market. We can observe the highest value in the case of Germany, with 85,8 %, while the lowest figure in the full sample belongs to Finland, with 69,7 %. The row Contribution to Others, on the other hand, shows how much of a shock a given market emits to the system, with Czechia and Slovakia being the most prominent exporters, while Finland is at the lower end of the distribution.

The net spillover indices show a clear and geographically structured divide between net transmitters and net receivers of volatility in European electricity markets. From the point of view of net transmitters, Central European markets emerge as the dominant exporters of volatility in our sample, with Czechia recording the highest net transmission of volatility at 42,9 percentage points, followed by Slovakia (30,6 p.p.), Hungary (22,7 p.p.) and Austria (20,5 p.p.). Interestingly, Poland is an exception in this case, as it is the most prominent receiver of volatility among the Central European markets. Germany, at 19,2 percentage points and the Netherlands, with 22,0 percentage points represent the main Western European net transmitters, while France also contributes positively, but to a lesser extent. One possible explanation for the prominence of the Central European region is its central geographic position within the European transmission network and its role in facilitating electricity flows between Nordic, Western and Southeastern Europe. The elevated spillover values observed for this cluster of countries may also be linked to the historically close integration of Germany, Austria and Czechia, including the legacy of the former German-Austrian bidding zone prior to its split in 2018.

On the receiver side, the results reveal an interesting pattern mainly among the Nordic countries. Finland emerges as the largest net receiver of volatility shocks during 2015–2025 among our selected countries, with an index of -45,7 percentage points, followed by Poland (-38,9 p.p.), Sweden (-27,8 p.p.), Norway (-21,2 p.p.) and Italy (-19,9 p.p.). The classification of the Nordic markets as net receivers may appear counterintuitive, given their relatively high volatility dispersion identified in the descriptive analysis, as can be seen in

Table 7. However, this result highlights an important distinction between the magnitude of domestic volatility fluctuations and the direction of volatility transmission. Although Nordic markets can experience large changes in volatility, which could be attributed to their generation mix, these shocks do not appear to spread to the rest of Europe as strongly or as regularly as shocks coming from the continental core. Instead, the results suggest that Nordic markets are more often influenced by volatility from the more strongly interconnected continental markets, while their own shocks appear to remain more concentrated within the Nordic region. A similar interpretation may apply to Poland, which appears to be strongly influenced by volatility originating in the wider cluster of Central European markets, especially Czechia, Slovakia, Hungary, Austria and Germany, while playing a more limited role in transmitting domestic shocks to other markets.

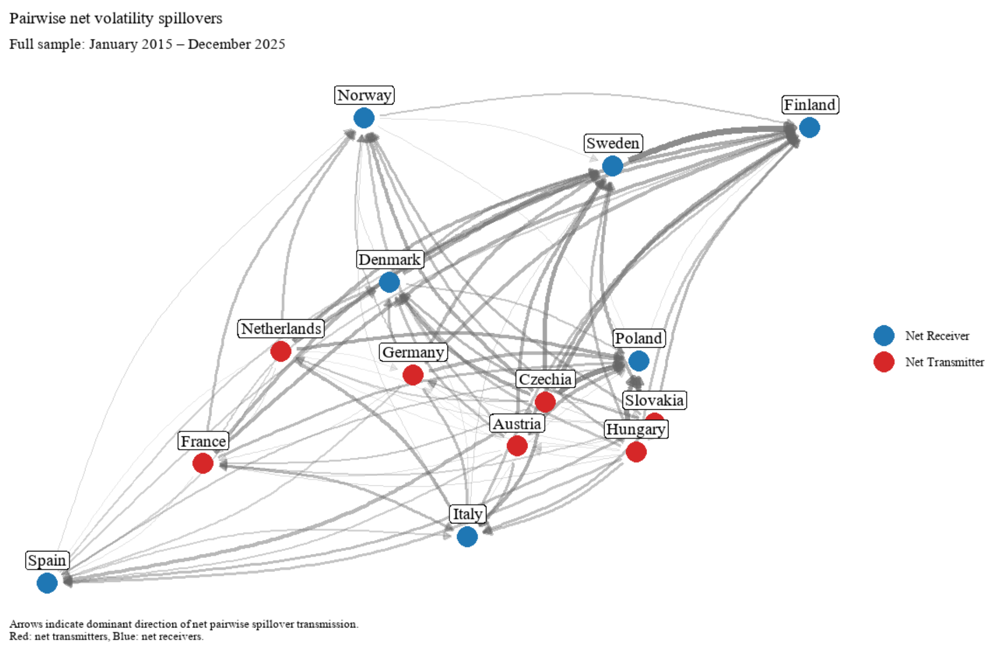
The diagonal elements of the spillover matrix may provide additional insight into the degree of market isolation. The highest own variance shares are recorded in the Nordic markets, especially Finland (30,3 %) and Norway (26,4 %), followed by Sweden at 20,5 %. A similar, though less pronounced, pattern can be observed in Spain (21,9 %) and Italy (21,0 %), where own-market factors also retain a relatively important role. In contrast, Central European markets, such as Austria (14,9 %), Czechia (14,9 %) and Slovakia (15,3 %), show lower own variance shares, indicating that their volatility dynamics are shaped more strongly by cross-border spillovers. Overall, these results indicate that the Nordic markets are relatively more isolated from the rest of the sample, while the Central European region forms a more tightly interconnected spillover cluster.

Strongest bilateral pairs			Weakest bilateral pairs		
To	From	%	To	From	%
Finland	Sweden	13,70	Finland	Poland	1,71
Slovakia	Czechia	13,30	France	Finland	1,32
Hungary	Slovakia	13,16	Austria	Finland	1,26
Germany	Austria	12,34	Netherlands	Finland	1,24
Slovakia	Hungary	12,34	Czechia	Finland	1,20
Czechia	Slovakia	12,31	Germany	Finland	1,17
Austria	Germany	12,28	Spain	Finland	1,16
Hungary	Czechia	11,71	Slovakia	Finland	1,03
Germany	Czechia	11,21	Poland	Finland	0,98
Austria	Czechia	11,09	Hungary	Finland	0,92

Table 10 - Top 10 strongest and weakest bilateral spillover pairs
Source: Author's own calculations

Table 10 presents the ten strongest and ten weakest bilateral spillover pairs in the sample. The strongest pair is Sweden–Finland (13,70 %), while the remaining top spillovers are dominated by Central European markets. In particular, the pairs Czechia–Slovakia, Slovakia–Hungary, Germany–Austria, Czechia–Hungary, Czechia–Germany and Czechia–Austria appear repeatedly among the strongest bilateral links. This pattern further confirms the existence of a tightly interconnected Central European spillover cluster in our analysed sample and is consistent with the earlier result that Czechia is the largest net transmitter in the system.

The weakest bilateral spillovers show a very different structure. In most of these cases, Finland appears as the transmitting market, for example in spillovers from Finland to France, Austria, the Netherlands, Czechia, Germany, Spain, Slovakia and Hungary. This indicates that Finland transmits only a very limited amount of volatility to the rest of the system, which is consistent with its role as the largest net receiver in the sample. In other words, although Finland is affected by cross-border volatility shocks and at the same time records the highest own variance share, its own volatility shocks tend to remain relatively contained and do not spread strongly to other European markets. A similar pattern may also be present for other Nordic markets, especially Sweden, which appears more frequently among weak outward spillovers once Finland-dominated pairs are set aside.



Graph 11 - Pairwise net volatility spillovers
Source: Author's own illustration

Net pairwise volatility spillovers are illustrated in Graph 10, where a thicker line indicates a stronger net transmission of volatility between two countries. The strongest net pairwise spillover is observed from Sweden to Finland, amounting to 6,76 percentage points. It is followed by spillovers from Czechia to Poland (6,50 p.p.), Slovakia to Poland (6,05 p.p.), Hungary to Poland (5,72 p.p.) and Czechia to Sweden (5,05 p.p.).

At the other end of the distribution, the weakest net pairwise spillovers are observed from the Netherlands to Austria (0,05 p.p.), Austria to Germany (0,06 p.p.), the Netherlands to Germany (0,07 p.p.), Poland to Sweden (0,15 p.p.) and Spain to Denmark (0,22 p.p.). The very low net spillover between Spain and Denmark may partly reflect the large geographic distance and limited direct market interaction between the two countries. By contrast, the low net values for pairs such as Austria and Germany or Germany and the Netherlands do not imply weak overall bilateral linkages. Rather, they suggest that volatility is transmitted in both directions at relatively similar magnitudes, so the resulting net difference remains small.

3.4 Sub-period analysis

To further analyse the spillover dynamics among the selected European electricity markets during the period, we have divided the time frame into three subperiods, similarly as we have done during the analysis of prices and volatility dynamics at the country level.

3.4.1 Pre-crisis period

The static spillover analysis for the pre-crisis period, covering the time from 2015 to June 2021, reveals a total spillover index of 55,87 %, indicating that even before the formal onset of the energy crisis and the full-scale invasion of Ukraine, cross-border volatility transmission already dominated the behaviour of electricity prices across the 14 analysed markets, with more than half of the forecast error variance attributable to shocks originating in other markets rather than purely domestic dynamics.

The structure of net transmitters and receivers, as can be observed in Table 11, broadly resembles the full sample results during the pre-crisis period, though with some notable differences in magnitudes. Germany emerges as the largest net transmitter, with a net spillover index of 21,3 percentage points. Austria (15,6 p.p.), France (13,2 p.p.), Czechia (8,5 p.p.) and the Netherlands (4,5 p.p.) similarly maintain their transmitter status, consistent with the full period findings. Slovakia also remains a net transmitter, though with lower values than in the full period, suggesting that its transmission role intensified over the full period partly as a result of crisis dynamics.

	DE	FR	IT	ES	NL	SK	CZ	AT	PL	HU	SE	NO	FI	DK	From	Net
DE	**26,8**	9,7	4.0	1,8	8,5	6,5	9,2	21,3	0,5	4,4	0,9	0,9	0,9	4,6	73,2	21,3
FR	11,4	**32,8**	7,8	2,9	14,8	4,4	6,1	10,8	0,9	2,7	0,7	2,4	0,3	2,1	67,2	13,2
IT	6,7	12,7	**45,9**	1,7	10,0	3,4	3,7	7,6	1,6	4,4	0,1	1,4	0,3	0,6	54,1	-12,0
ES	3,8	4.0	1,7	**70,2**	3,4	2,5	3,3	4,7	0,1	1,8	0,5	2,9	0,2	1,1	29,8	-11,4
NL	11,0	15,8	6,4	2,9	**33,4**	4,4	5,9	9,4	1,0	2,8	1,0	2,0	0,8	3,2	66,6	4,5
SK	8,1	5,3	3,9	1,3	4,5	**29,8**	19,3	6,8	0,8	14,3	0,7	1,1	0,7	3,5	70,2	0,6
CZ	10,6	6,4	3,1	2,0	5,5	17,3	**27,2**	9,1	0,7	9,5	1,2	1,8	0,9	4,6	72,8	8,5
AT	22,6	10,2	4,7	2,3	7,7	5,6	8,2	**28.0**	0,3	3,6	1,1	0,9	1,0	3,9	72.0	15,6
PL	0,9	1,9	1,1	0,1	2,3	2,3	2,2	0,6	**75,3**	1,8	4,0	2,3	1,1	4,0	24,7	-12,1
HU	5,9	4.0	5,6	1,0	3,5	16,7	11,2	5.0	0,5	**42,6**	0,2	1,1	0,3	2,4	57,4	-7,2
SE	2,0	1,7	0,3	0,2	2,2	1,0	2,1	2,1	2,5	0,2	**46,4**	8,1	13,4	17,7	53,6	-1,7
NO	1,5	4,1	1,9	1,7	2,8	1,2	2,1	1,4	1,5	1,5	7,6	**65,9**	3,6	3,3	34,1	-1,2
FI	2,4	1,3	0,9	0,2	1,8	1,1	1,7	2,5	0,7	0,6	18,2	4,9	**54,9**	8,8	45,1	-16,3
DK	7,6	3,2	0,6	0,4	4,1	4,5	6,3	6,1	1,6	2,5	15,8	3,3	5,5	**38,6**	61,4	-1,7
Contribution to Others	94	81	42	18	71	71	81	88	13	50	52	33	29	60		
Contribution including Own	121	113	88	89	105	101	109	116	88	93	98	99	84	98		

Table 11 - Static spillover table (2015-06/2021)
Source: Author's own calculations

On the receiver side, Finland records the largest negative net index of -16,3 percentage points, by far the lowest in the sample. This position could be explained by the low value of Contribution to Others, indicating how much volatility Finland exported to the system. Poland and Italy, with net indices of -12,1 and -12,0 percentage points, respectively, follow as the next largest receivers, which is again consistent with the full-sample picture. Norway and Spain record the second and third highest own variance shares, reflecting their relative geographical isolation from the rest of the analysed countries.

Table 12 below shows the bilateral spillovers, where the Austria–Germany pair stands out as the strongest bilateral connection in the pre-crisis period, with Germany transmitting 22,55 % to Austria and Austria transmitting 21,28 % to Germany. Within the Nordic cluster, the Sweden–Finland bilateral link remains prominent at 18,19 % and Sweden–Denmark at 17,71 %. Among other pairs, Czechia–Slovakia and Slovakia–Hungary are again present.

Strongest bilateral pairs			Weakest bilateral pairs		
To	From	%	To	From	%
Austria	Germany	22,55	France	Finland	0,30
Germany	Austria	21,28	Sweden	Italy	0,26
Slovakia	Czechia	19,29	Sweden	Spain	0,24
Finland	Sweden	18,19	Finland	Spain	0,24
Sweden	Denmark	17,71	Sweden	Hungary	0,21
Czechia	Slovakia	17,31	Spain	Finland	0,17
Hungary	Slovakia	16,67	Hungary	Sweden	0,17
Denmark	Sweden	15,80	Italy	Sweden	0,14
Netherlands	France	15,76	Spain	Poland	0,05
France	Netherlands	14,79	Poland	Spain	0,05

Table 12 - Top 10 strongest and weakest bilateral spillover pairs (2015-06/2021)
Source: Author's own calculations

3.4.2 Crisis period

The dynamics of volatility transmission in the selected countries during the turbulent period spanning 07/2021–2023 can be observed in Table 13. The total spillover index rises to 78,72 %, representing a substantial increase compared to the pre-crisis level, which confirms that the 2021–2023 energy crisis not only elevate volatility levels within individual markets but also intensified the cross-border transmission of volatility shocks across the sampled European electricity system.

Moving onto the structure of net transmitters, we can observe it is mostly preserved from the pre-crisis period, though with some notable shifts in magnitudes and rankings. Czechia emerges as one of the dominant net transmitters with a net index of 42,7 percentage points, an increase from 8,5 percentage points in the pre-crisis period, suggesting that its role as a transmission hub intensified during the crisis. Austria (33,9 p.p.) and Slovakia (31,6 p.p.) similarly record higher net values compared to the pre-crisis period, with a particularly pronounced shift in Slovakia's role from a value close to 0 in the pre-crisis period to becoming the 4th largest transmitter of volatility. The major economies of Germany and France, with values of 32,9 and 24,6, respectively, show record noteworthy increases relative to their pre-crisis net values of 21,3 and 13,2. This shift in case of Germany may have been connected to unusually high natural gas prices and natural gas playing a relatively important role in the electricity mix of Germany. The shift in France's role to one of the largest exporters of volatility during the crisis could be connected to the extraordinary circumstances around the French nuclear fleet that was unavailable during this time due to maintenance and repairs. The Netherlands (13,8 p.p.) maintains its transmitter status but with a lower net index than in the pre-crisis period, suggesting its relative transmission role diminished somewhat as other markets became more dominant during the crisis.[73]

On the receiver side, Poland deepens its receiver status to -33,9 percentage points from -12,1 percentage points in the pre-crisis period, becoming the largest net receiver in the system, followed by Finland (-32,2 p.p.), Norway (-28,9 p.p.) and Sweden (-28,7 p.p.). Italy, with a value of -8,1 percentage points, moves closer to neutral compared to its pre-crisis value, suggesting a partial convergence toward the continental transmission structure during the crisis period. It is interesting to note that no country changes its role from net transmitter to net receiver, or vice versa, rather the existing roles become more pronounced. Moreover, the lower own variance shares across markets are noteworthy, as they are consistent with the higher total spillover index and indicate that the markets in the sample became more interconnected during the crisis period. This is especially visible in the case of Poland and Norway, whose own variance shares declined by approximately 54 and 35 percent, respectively.

	DE	FR	IT	ES	NL	SK	CZ	AT	PL	HU	SE	NO	FI	DK	From	Net
DE	**15,3**	9,5	5,6	2,9	10,5	10,3	12,7	11,7	3,8	5,8	1,5	2,6	1,2	6,6	84,7	32,9
FR	10,6	**18,2**	6,9	3,3	9,7	9,4	11,1	10,7	3,0	5,9	1,5	3,1	1,6	5,0	81,8	24,6
IT	8,7	9,7	**19,6**	3,1	7,6	9,0	9,7	9,0	4,2	5,7	2,3	3,5	2,4	5,5	80,4	-8,1
ES	7,7	7,1	2,9	**38,2**	6,0	7,0	7,1	6,1	3,4	3,1	2,1	3,1	0,9	5,2	61,8	-24,6
NL	11,7	9,9	5,7	2,9	**16,4**	10,4	11,8	10	3,5	6,9	1,4	2,6	1,3	5,5	83,6	13,8
SK	10,5	8,5	6,2	2,9	8,9	**15,9**	13,3	10,5	3,7	9,2	1,5	2,2	1,5	5,2	84,1	31,6
CZ	11,7	9,2	5,8	2,6	9,4	12,4	**15,4**	11,8	3,7	6,6	1,5	2,4	1,5	5,9	84,6	42,7
AT	11,6	10	6	2,8	9,2	10,5	12,6	**15,1**	3,6	6,5	1,6	3,0	1,6	5,9	84,9	33,9
PL	8,8	7,3	5,8	2,9	7,6	9,2	9,4	9,0	**21,1**	4,8	3,1	2,4	2,5	6,0	78,9	-33,9
HU	9,2	8,8	6,5	2,9	8,9	14,4	11,1	9,8	2,8	**16,2**	1,3	2,3	1,3	4,5	83,8	-16,8
SE	5,1	6,1	4,6	2,7	3,5	5,0	6,0	6,6	3,6	2,5	**26,8**	5,0	14,1	8,4	73,2	-28,7
NO	6,5	7,6	6,0	2,8	4,9	5,5	6,7	7,6	2,3	3,5	5,2	**30,9**	3,9	6,6	69,1	-28,9
FI	4,2	5,1	4,6	2,0	3,0	4,5	5,3	5,9	3,3	2,3	17,1	4,4	**31,6**	6,6	68,4	-32,2
DK	11,2	7,5	5,8	3,1	8,1	8,1	10,3	10	4,2	4,2	4,3	3,8	2,4	**17**	83	-6,1
Contribution to Others	117	106	72	37	97	115	127	118	45	67	44	40	36	76		
Contribution including Own	132	124	91	75	113	131	142	133	66	83	71	71	67	93		

Table 13 - Static spillover table (07/2021-2023)
Source: Author's own calculations

[73] IEA: Germany – Natural Gas [online]. Available at: https://www.iea.org/countries/germany/natural-gas

The bilateral spillover analysis for the crisis period reveals some continuity with the pre-crisis structure but also some meaningful changes. Even though both Finland and Sweden are overall net receivers of volatility in the system, it is interesting to note their strong bilateral exchange of volatility. Sweden exports the strongest bilateral spillover in the sample to Finland, while Finland represents the third strongest source of volatility directed to Sweden, reinforcing the tight intra-Nordic integration documented in the full sample analysis. The Hungary–Slovakia pair strengthens to 14,36 % and the Czechia–Slovakia and Czechia–Germany connections remain prominent, confirming the resilience of the Central European spillover cluster under crisis conditions. At the lower end of the distribution, Finland and Sweden dominate the weakest outward spillovers, with Finland transmitting less than 1 % to Spain and 1,24 % to Germany, confirming that Nordic markets' own volatility shocks remain largely contained within the regional system even during the most intense phase of the energy crisis.

Strongest bilateral pairs			Weakest bilateral pairs		
To	From	%	To	From	%
Finland	Sweden	17,13	Slovakia	Sweden	1,51
Hungary	Slovakia	14,36	Germany	Sweden	1,48
Sweden	Finland	14,05	Czechia	Finland	1,46
Slovakia	Czechia	13,29	Slovakia	Finland	1,46
Germany	Czechia	12,68	Netherlands	Sweden	1,40
Austria	Czechia	12,60	Hungary	Sweden	1,33
Czechia	Slovakia	12,44	Netherlands	Finland	1,32
Czechia	Austria	11,75	Hungary	Finland	1,30
Netherlands	Czechia	11,75	Germany	Finland	1,24
Czechia	Germany	11,74	Spain	Finland	0,90

Table 14 - Top 10 strongest and weakest bilateral spillover pairs (07/2021-2023)
Source: Author's own calculations

3.4.3 Post-crisis period

The post-crisis total volatility spillover index stands at 65,21 %, indicating a decline from the crisis peak while attaining a higher value than the pre-crisis level of 55,87 %. This indicates that even though the interconnectedness of the sampled markets has fallen in the post-crisis period, the markets became more connected than in the years leading up to the crisis.

The net transmitter structure in the post-crisis period shows both continuity and notable changes relative to the crisis period. Slovakia emerges as the dominant net transmitter, with a net index of 43,3 percentage points, surpassing Czechia (29,9 p.p.), which had led the ranking in the crisis period. Germany and Austria maintain their transmitter status with values broadly comparable to the pre-crisis period, suggesting that these countries reverted closer to their pre-crisis volatility transmission roles following the normalization of gas prices.

	DE	FR	IT	ES	NL	SK	CZ	AT	PL	HU	SE	NO	FI	DK	From	Net
DE	**17,9**	4,7	1,6	1,1	13,3	12,3	12,4	13,1	4,9	9,2	0,7	1,0	0,1	7,8	82,1	19,5
FR	7,2	**30,5**	0,5	4,9	11,6	11,1	9,1	6,6	3,6	8,6	0,5	0,7	0,6	4,5	69,5	-18,4
IT	5,7	1,1	**61,2**	0,3	4,1	5,8	5,3	4,2	0,5	5,9	1,8	1,6	0,2	2,4	38,8	-23,2
ES	2,9	6,5	1,1	**62,1**	2,5	5,4	4,1	2,9	4,8	6,0	0,2	0,2	0,4	0,9	37,9	-23,5
NL	12,8	6,8	1,3	0,7	**18,9**	12,8	13,4	10,3	4,6	9,8	0,6	0,9	0,1	7,1	81,1	21,4
SK	10,0	4,4	1,6	1,0	10,5	**20,0**	13,6	9,2	7,7	1,0	0,2	0,7	0,0	5,1	80,0	43,3
CZ	11,3	4,5	1,7	0,9	12,1	15,1	**18,0**	12,2	6,1	10,8	0,5	0,8	0,1	5,9	82,0	29,9
AT	14,0	4,7	1,3	1,1	11,4	12,1	14,0	**20,3**	4,5	8,4	0,7	1,1	0,1	6,3	79,7	13,8
PL	8,5	3,6	0,5	1,9	8,5	15,2	11,7	8,0	**23,6**	13,9	0,3	0,2	0,1	4,1	76,4	-25,3
HU	9,0	3,0	1,8	1,1	9,3	17,9	11,2	7,3	8,4	**26,0**	0,1	0,5	0,0	4,2	74,0	25,0
SE	3,5	2,3	0,3	0,1	3,2	2,0	2,7	4,3	0,6	0,8	**48,2**	11,5	12,9	7,7	51,8	-10,2
NO	3,6	1,4	2,4	0,2	2,9	3,1	3,1	4,2	1,0	1,7	13,1	**54,4**	4,8	4,1	45,6	-19,5
FI	0,4	1,7	0,3	0,6	1,0	0,2	0,6	0,8	0,1	0,1	20,3	5,4	**67,0**	1,5	33,0	-13,2
DK	12,7	6,4	1,2	0,7	12,0	10,3	10,6	10,6	4,1	7,9	2,6	1,6	0,4	**18,9**	81,1	-19,7
Contribution to Others	102	51	16	14	103	123	112	94	51	99	42	26	20	62	102	51
Contribution including Own	120	82	77	77	121	143	130	114	75	125	90	81	87	80	120	82

Table 15 - Static spillover table (2024-2025)
Source: Author's own calculations

On the receiver side, Finland remains a net receiver in the post-crisis period, with a value of -13,2 percentage points. Although this is still a clearly negative position, it is less extreme than during the crisis period, when the value reached -32,2 percentage points, which may point to a partial normalization of Finnish market dynamics after the peak of the energy crisis. Italy (-23,2 p.p.) and Spain (-23,5 p.p.) both strengthen their positions as net receivers compared with the earlier periods, while also having the second and third highest own variance shares in this period.

Sweden and Norway also remain net receivers, which is consistent with the full sample and pre-crisis results. Poland (-25,3 p.p.) continues to be a major net receiver as well, but its own variance share of 23,6 % is much lower than in the pre-crisis period and slightly above the crisis period value, which may suggest that the Polish market became more integrated with the rest of the sampled countries.

Interestingly, we can observe a role reversal in two cases, namely Hungary and France. Hungary becomes a net transmitter of volatility in the post-crisis period, with a net index of 25,0 percentage points, suggesting a structural change in Hungary's position in the network. Another reversal can be seen in the case of France, which was one of the dominant transmitters during the crisis at 24,6 percentage points and then shifted dramatically to a net receiver, with a value of -18,4 percentage points in the post-crisis period. This could likely be attributed to a normalization of French nuclear power availability following the resolution of maintenance issues, but nevertheless represents a change even compared to the pre-crisis period.

Strongest bilateral pairs			Weakest bilateral pairs		
To	From	%	To	From	%
Finland	Sweden	20,3	Hungary	Sweden	0,14
Hungary	Slovakia	17,9	Netherlands	Finland	0,13
Slovakia	Hungary	15,9	Finland	Poland	0,12
Poland	Slovakia	15,1	Poland	Finland	0,09
Czechia	Slovakia	15,1	Czechia	Finland	0,07
Austria	Germany	14,0	Finland	Hungary	0,07
Austria	Czechia	14,0	Germany	Finland	0,07
Poland	Hungary	13,9	Sweden	Spain	0,05
Slovakia	Czechia	13,6	Slovakia	Finland	0,01
Netherlands	Czechia	13,3	Hungary	Finland	0,01

Table 16 - Top 10 strongest and weakest bilateral spillover pairs (2024-2025)
Source: Author's own calculations

The analysis of bilateral spillover pairs reveals important structural changes in the post-crisis network. The Sweden–Finland bilateral spillover strengthens further to 20,3 % from Sweden to Finland, being the highest bilateral value in the entire sample across all three periods, implying a deepening of integration in the Nordic markets in the post-crisis years. Slovakia–Hungary and Hungary–Slovakia emerge as the strongest Central European bilateral pairs in this period, reflecting the intensification of the Central European cluster's internal transmission dynamics. A new entrant among the strongest pairs is Poland and its connections with Slovakia and Hungary, suggesting a deeper integration of Poland's electricity market with the Central European core. Finland again dominates the lower end of the distribution, with the weakest outward spillovers approaching zero for pairs such as Finland–Hungary, Finland–Slovakia or Finland–Germany, indicating that Finland's internal volatility dynamics do not spill over to the continental core.

3.4.4 *Sub-period comparison of net spillovers*

Summarising the three sub-periods, Table 17 shows the net spillover indices across the three sub-periods, and from the previous results, several conclusions emerge. First, the total connectedness of the selected European electricity markets increased from the pre-crisis level of 55,87 % to 78,72 % during the crisis period, before falling to 65,21 %. This indicates that volatility spillovers rose sharply during the energy crisis and then moderated afterwards, although they remained above the pre-crisis level. The results therefore suggest that the crisis represented a period of exceptionally strong cross market transmission, followed by a partial normalisation rather than a permanent shift to crisis-level connectedness.

Country	Pre-Crisis Net Spillover	Crisis Net Spillover	Post-Crisis Net Spillover
DE	21,3	32,9	19,5
FR	13,2	24,6	-18,4
IT	-12,0	-8,1	-23,2
ES	-11,4	-24,6	-23,5
NL	4,5	13,8	21,4
SK	0,6	31,6	43,3
CZ	8,5	42,7	29,9
AT	15,6	33,9	13,8
PL	-12,1	-33,9	-25,3
HU	-7,2	-16,8	25,0
SE	-1,7	-28,7	-10,2
NO	-1,2	-28,9	-19,5
FI	-16,3	-32,2	-13,2
DK	-1,7	-6,1	-19,7

Table 17 – Static net spillover index by time period
Source: Author's own calculations

Second, the ranking of dominant net transmitters proves relatively stable across the three periods, with Czechia, Slovakia, Germany and Austria consistently emerging as net transmitters in all three subperiods. This suggests that the Central European cluster's role in the selected network is a structural feature rather than a phenomenon driven by the energy crisis alone. At the same time, the magnitude of these net positions varies substantially over time, with Germany's net spillover value rising from 21,3 p.p. in the pre-crisis period to 32,9 p.p. during the crisis before easing to 19,5 p.p. in the post-crisis period. Slovakia records an even stronger increase, from 0,6 p.p. before the crisis to 31,6 p.p. during the crisis and further to 43,3 p.p. in the post-crisis period, making it the strongest net transmitter in the final subperiod. Austria, by contrast, reaches its strongest transmitter position during the crisis and, similarly to Germany, weakens afterwards. The Netherlands also remains a net transmitter throughout all three periods, with values of 4,5 p.p., 13,8 p.p. and 21,4 p.p., pointing to a gradually strengthening role over time.

Third, some of the most interesting results can be seen in countries whose directional role changes across periods. Hungary shows one of the clearest reversals in the sample, as it is a net receiver in the pre-crisis period (-7,2 p.p.) and then becomes an even stronger net receiver during the crisis (-16,8 p.p.), before shifting to a net transmitter in the post-crisis period (25,0 p.p.). This indicates that Hungary acted mainly as a receiver of cross-border volatility shocks during the pre-crisis and crisis periods, whereas it shifted its role to a net transmitter in the post-crisis period. France follows a different trajectory: it moves from a moderate net transmitter before the crisis (13,2 p.p.) to a stronger transmitter during the crisis (24,6 p.p.), before turning into a net receiver in the post-crisis period (-18,4 p.p.). Italy remains a net receiver throughout all three subperiods, although its receiver position becomes somewhat less negative during the crisis, moving from -12,0 p.p. to -8,1 p.p., before weakening again to -23,2 p.p. in the post-crisis period. Denmark also remains a net receiver in all three periods, with its net spillover becoming more negative over time, which indicates a gradual strengthening of its receiver role.

Fourth, Poland's development across the three periods is also worth highlighting, as it points to a gradual increase in market integration. Its own variance share, which shows how much of its volatility is explained by domestic rather than foreign shocks, falls sharply from 75,3 % in the pre-crisis period to around 21,1 % and 23,6 % in the crisis and post-crisis periods, respectively. Although Poland remains a net receiver throughout all three subperiods, this decline in its own variance share suggests that cross-border influences became much more important over time. Together with the stronger bilateral links with Slovakia and Hungary observed in the post-crisis period, this may indicate that Poland has become more closely connected to the wider Central European electricity market over the sample period.

Finally, the Nordic markets, namely Finland, Sweden and Norway, remain net receivers in all three sub periods, which suggests that this is a stable feature of their position within the sampled European volatility network rather than a temporary effect of the crisis. At the same time, the bilateral spillover from Sweden to Finland strengthens steadily across the investigated period, rising from 18,19 % in the pre-crisis period to 20,3 % in the post-crisis period. This points to a strengthening of linkages within the Nordic cluster, even though the relationship between the Nordic region and the continental core remains uneven.

As can be observed, the total spillover index for the full 2015–2025 sample is 81,17 %, which is higher than the values estimated separately for the pre-crisis, crisis and post-crisis periods. One reason is that the full sample captures both the relationships within each period and the broader shifts between them, especially the move from lower volatility before the crisis to much higher volatility during the energy crisis and the later adjustment afterwards. These changes across regimes are not reflected in the same way when the periods are analysed separately. In addition, the full sample estimation uses a larger number of observations, which generally leads to more stable estimates and can contribute to a higher spillover value. The subperiod indices should therefore be interpreted as measures of connectedness specific to each regime, rather than as values that should add up to the full sample result.

3.5 Rolling spillover analysis

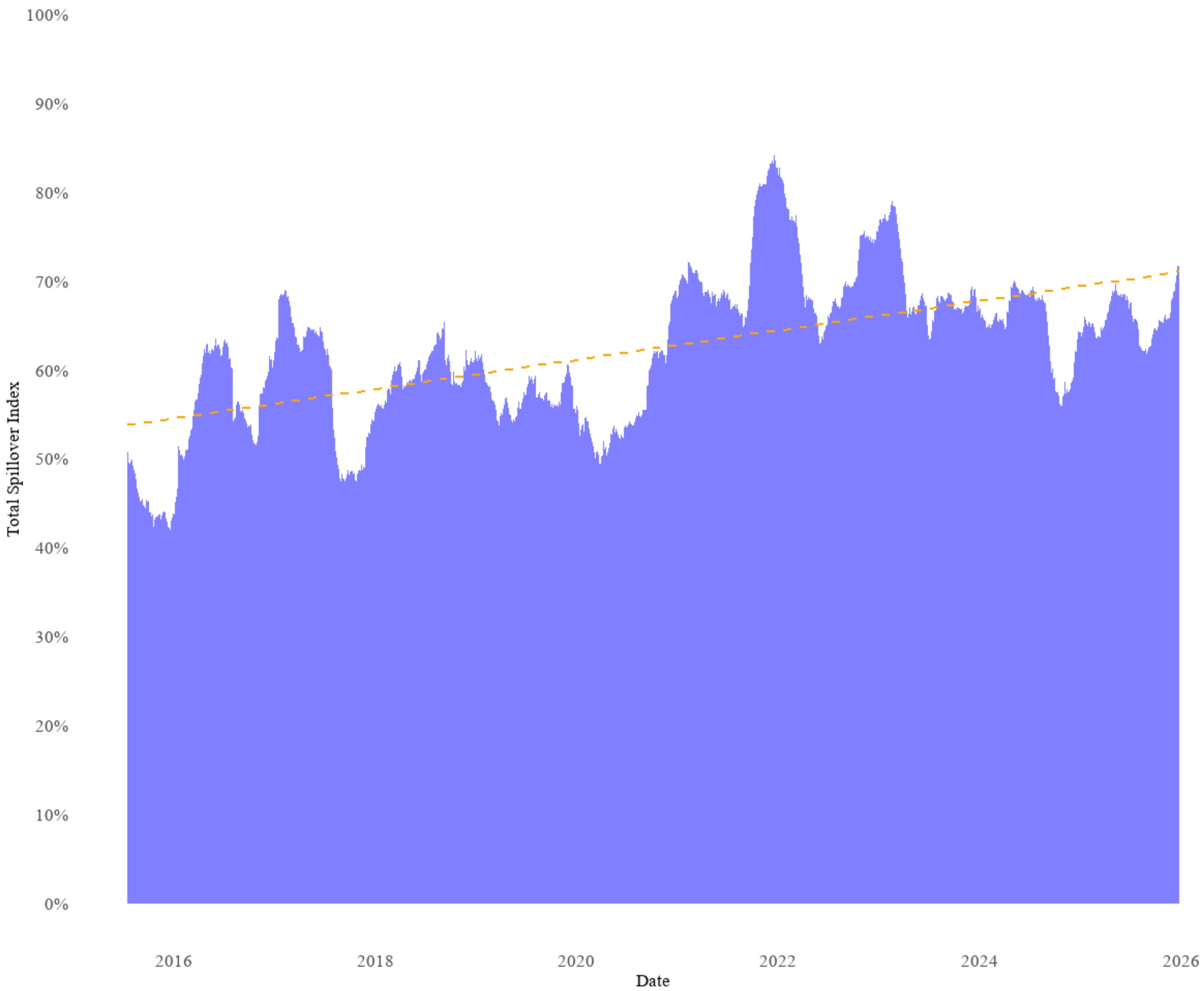
While the static full sample and subperiod analyses provide an overview of the average structure of volatility spillovers, they do not capture how connectedness evolves over time within each regime. Moreover, sub period definitions based primarily on major geopolitical events may not precisely reflect the true onset of rising volatility transmission across markets. To address this limitation, this section briefly examines the rolling spillover results, with a particular focus on the evolution of rolling net spillover indices. The aim is not to replicate the static findings for each country, but rather to identify the timing, intensity and persistence of changes in volatility transmission across European electricity markets.

For the computation of the rolling total spillover index, we used a 200-day window, following previous research devoted to spillovers in electricity markets.[74]

The average value of the rolling total spillover index for the full period stands at 62,43 %, which is noticeably lower than the 81,17 % obtained from the static full sample estimation. This difference is not surprising, given that the two approaches measure volatility spillovers in fundamentally different ways. While the static estimate uses all available

[74] LUY, C. et al. Volatility spillovers and carbon price in the Nordic wholesale electricity markets. Energy Economics, vol. 134. 2024

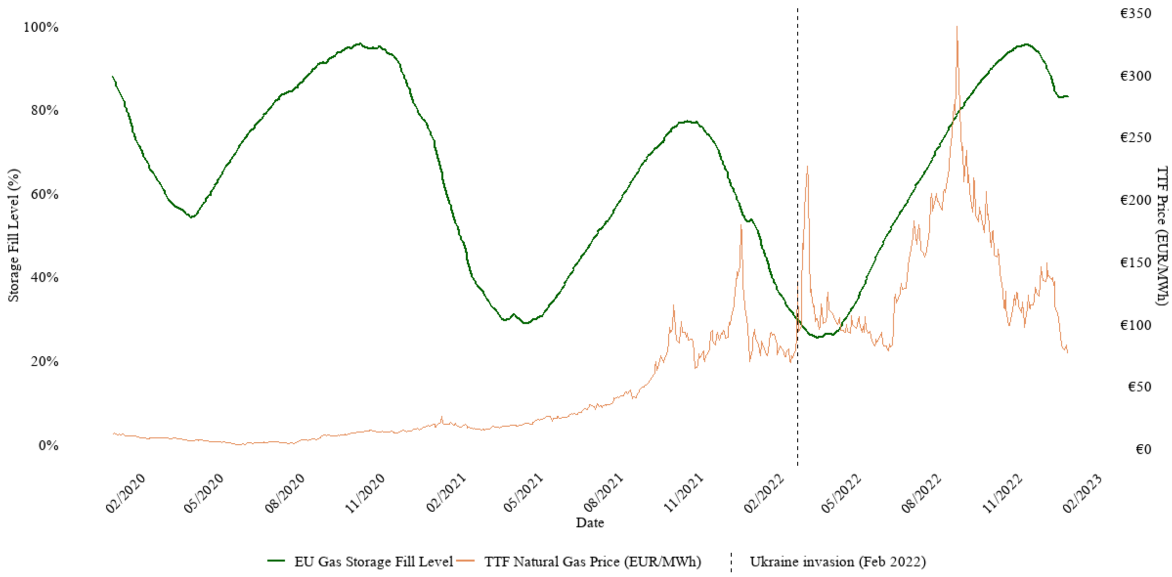
observations at once, the rolling average continually updates its window and slowly disregards old observations.



Graph 12 - Rolling Total Spillover Index
Source: Author's own analysis

As shown in Graph 12, the total spillover index during the pre-crisis period starts at 54,84 % at the beginning of 2015 and initially declines to its lowest point of 41,93 % on 24 December 2015. The index then rebounds strongly, reaching 69,24 % by 8 February 2017. This increase may be partly associated with the severe cold wave affecting continental Europe in early 2017. For the remainder of the pre-crisis period, the index fluctuates within a relatively stable range of approximately 55 % to 60 %. The average connectedness over the full pre-crisis period from January 2015 to June 2021 is 57,71 %.

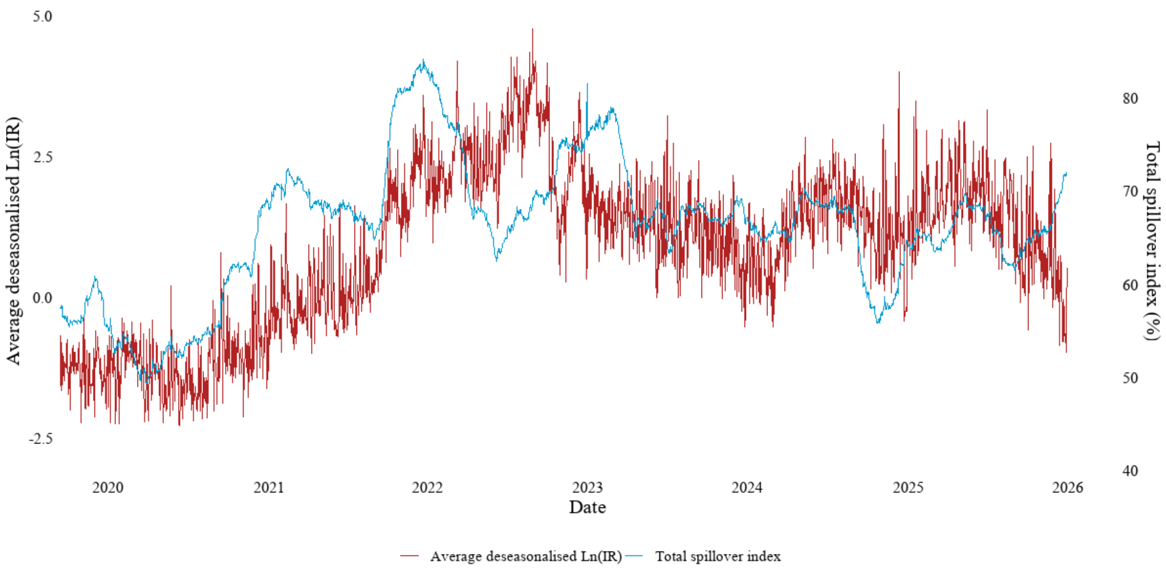
Notably, the index begins to rise already from mid-2021, well before the Russian invasion of Ukraine in February 2022. On 21 December 2021, the rolling spillover index reaches 84,22 %, representing its highest value prior to the crisis period. This development coincides with significant stress in European gas markets during the second half of 2021, when storage levels declined and TTF gas prices increased sharply. This suggests that the transmission of the energy crisis may have already been underway before the outbreak of the military conflict.



Graph 13- Gas Storage Fill Level in EU vs TTF Natural Gas Price
Source: Author's own illustration based on data from Yahoo Finance and GIE

Entering the period of July 2021–2023, the average total spillover index increases to 71,64 %, representing an increase of nearly 14 percentage points compared to the pre-crisis average. Throughout 2022 and 2023, the index remains persistently elevated, indicating that the crisis not only increased volatility within individual markets but also strengthened cross-market transmission.

In the post-crisis period from January 2024, the index gradually eases back, averaging 65,33 % and ending the sample at 71,82 % on 31 December 2025. While this represents a meaningful decline from the crisis peak, it remains well above the pre-crisis average of 57,71 %, suggesting that European electricity markets have not fully returned to their pre-crisis connectedness levels.

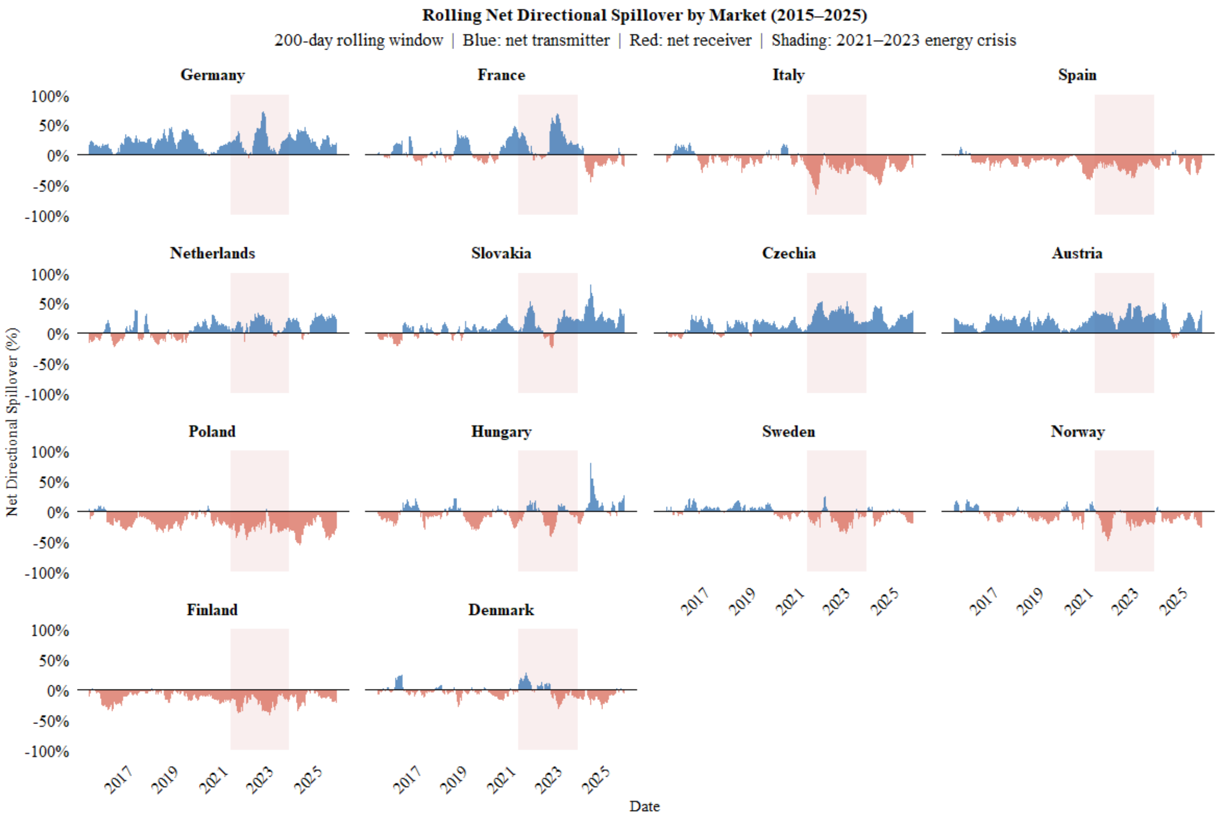


Graph 14 - Total Spillover Index vs Average deseasonalised ln(IR)
Source: Author's own illustration

Graph 14 presents the evolution of the cross-country average volatility proxy, measured as the deseasonalised logarithm of the intraday range, together with the rolling spillover index, capturing the two-year period before the most volatile market conditions as well as the post-energy crisis period. The pre-crisis period in this sample captures the dynamics during the COVID-19 period, where we can observe a gradual increase in volatility as well as an intensification in the connectedness of the selected countries, with the spillover measure reaching all-time high values leading up to the crisis period. The computed correlation coefficient between the total spillover index and the volatility proxy between 2020 and the end of 2021 stands at 0,85, indicating a strong correlation and suggesting that volatility increases were closely aligned with intensified cross-market spillovers during this period.

However, this pattern does not persist into the period underlined by the energy crisis. Despite the sharp rise in volatility, we can notice a decline in the spillover index in the first part of the observed period, followed by a rebound towards the end of 2023, possibly capturing some of the volatility from the most turbulent period due to the construction of the rolling spillover index. The corresponding correlation between the volatility proxy and the total spillover index falls to only 0,038, implying that the most turbulent phase of the crisis was not accompanied by similarly strong spillover intensity. This suggests that, during the most turbulent phase of the crisis, the relationship between volatility levels and cross-border transmission intensity was weaker than during the period prior to the peak of the energy crisis, possibly reflecting that some portion of the extreme volatility was driven by country-specific shocks.

In the post-crisis period, the correlation remains positive but modest at 0,114, indicating that although both volatility and connectedness partially normalise, their relationship is considerably weaker than during the COVID phase. This phase captures both the market dynamics related to the pandemic and the stress that markets were under, including the rapid economic recovery after the pandemic, weather conditions and Russia's decision to withhold gas supplies to Europe prior to its full scale invasion.[75]



Graph 15 - Rolling Net Directional Spillover by Market
Source: Author's own illustration

Taken together, these results suggest that connectedness does not simply rise one-for-one with volatility, but that its association with volatility depends on the nature of the underlying shock and on whether market stress manifests itself as a common regional event or as a disturbance at the national level.

To complement the analysis of the net spillover indices obtained from the static spillover framework, Graph 15 presents the evolution of the 200-day rolling net directional spillover index for each market over the 2015–2025 period. This dynamic perspective

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[75] IEA: 2022 Energy Crisis [online]. Available at: https://www.iea.org/topics/2022-energy-crisis

reveals patterns that cannot be captured by the static approach alone. In particular, it shows that even if a market appears, on average, to be a net transmitter or net receiver of volatility over a longer horizon, its role may change substantially over time.

Germany appears to be the most consistent net transmitter over the sample period. Czechia, Austria, Slovakia and, to a lesser extent, the Netherlands also display predominantly positive net positions, particularly in the later part of the sample. This suggests that these markets played a comparatively stronger role in transmitting volatility across the regional system. By contrast, in line with the static analysis, Italy, Spain, Poland and Finland remain predominantly in negative territory for most of the period, indicating that their volatility dynamics were more strongly shaped by shocks originating in foreign markets. Denmark and Norway also exhibit mainly receiver behaviour, although with smaller and less persistent deviations.

The crisis period, highlighted by the shaded area, shows that the energy crisis did not affect all markets symmetrically. Rather than producing a uniform increase in net transmission across the system, it appears to have intensified the differentiation between transmitting and receiving markets. In particular, most Central European countries, with the exception of Poland, strengthened their transmitter roles, although Slovakia briefly switched position. By contrast, several Northern and Southern European markets moved further into net receiver territory. At the same time, Denmark experienced a temporary reversal around the end of 2021 and the beginning of 2022. France is especially notable in this regard, as it moved from a relatively balanced position in the earlier years of the sample to a pronounced net transmitter immediately before and during the energy crisis. On the other hand, Sweden assumes the role of a net receiver, similarly to the results of the static analysis.

The post-crisis period is, in most cases, a continuation of the patterns established during the crisis, with a few important exceptions. France subsequently shifts into a net receiver position, Hungary switches its role to a net transmitter and Slovakia further intensifies its transmitting role. These developments indicate that the crisis not only increased market stress, but in some cases also altered the structural position of individual markets within the spillover network.

Overall, the figure suggests that European electricity market connectedness is not only time-varying but also structurally uneven and these results confirm the findings from the static analysis. The transmission of volatility appears to be concentrated in a subset of markets that repeatedly act as net exporters of shocks, while others remain persistently exposed to externally generated disturbances.

3.6 Vulnerability index

As a supplementary analysis, we have utilised a vulnerability index, which combines the average rolling spillover from other markets (FROM), reflecting the extent to which a country's volatility is driven by shocks originating in other markets, and the average values of the volatility proxy. It thus provides a composite indicator of market vulnerability, which is subsequently used to rank countries across the full sample and within each of the defined subperiods.

For the full period ranking, the most vulnerable countries in our sample were the Central European countries, with Germany, Austria and Czechia occupying the first three spots. This could be attributed to their relatively above-average volatility compared to the rest of the sample, as well as higher FROM values, which is to be expected in our sample due to their proximity and existing interconnections. At the opposite end of the ranking, Spain, Poland and Finland emerge among the least vulnerable markets. This is particularly interesting in the case of Poland, which had previously been identified as a pronounced net receiver of volatility. This highlights the importance of distinguishing between net positions and gross directional exposures, as a country may be a net receiver while still exhibiting lower overall vulnerability if its absolute volatility or gross received spillovers remain comparatively limited.

Table 18 below reports the country ranking based on the vulnerability index across the pre-crisis, crisis and post-crisis periods. We can observe a relatively stable pattern in the top four places, occupied by Germany, Austria, Czechia and Slovakia. This points to persistent vulnerability of the Central European core, suggesting that these markets were structurally more exposed to externally transmitted volatility over the sample period. By contrast, Spain is consistently positioned near the bottom of the ranking, which is likely related to both its lower average volatility and its lower received spillovers from the rest of the system, while its location on the geographical periphery of the sampled market network may have contributed to this outcome.

	Pre-Crisis		Crisis		Post-Crisis	
Rank	Country	VI	Country	VI	Country	VI
1	Germany	0,004	Germany	1,032	Germany	0,949
2	Austria	-0,002	Czechia	1,019	Czechia	0,938
3	Czechia	-0,023	Austria	1,014	Slovakia	0,919
4	Slovakia	-0,079	Slovakia	0,982	Austria	0,883
5	France	-0,206	Denmark	0,975	Poland	0,862
6	Netherlands	-0,323	Netherlands	0,959	Netherlands	0,857
7	Denmark	-0,333	Hungary	0,873	Denmark	0,830
8	Hungary	-0,412	France	0,867	Hungary	0,731
9	Sweden	-0,492	Norway	0,621	France	0,365
10	Finland	-0,630	Italy	0,540	Sweden	0,082
11	Italy	-0,678	Sweden	0,567	Norway	-0,044
12	Norway	-0,878	Poland	0,375	Italy	-0,208
13	Poland	-1,060	Finland	0,351	Spain	-0,444
14	Spain	-1,280	Spain	0,097	Finland	-0,522

Table 18 - Vulnerability Index
Source: Author's own analysis; VI denotes vulnerability index

It is also noteworthy to look at the values of the vulnerability index, as in the pre-crisis period, we can observe lower values and even negative ones across all sampled countries. This indicates that most markets experienced limited cross-border exposure and lower volatility prior to July 2021. In the crisis period covering July 2021 to 2023, the vulnerability index rises noticeably across the full sample. All countries record positive values, pointing to a broad intensification of exposure to energy market shocks. This confirms that the crisis represented a generalized period of elevated stress, not only in terms of volatility itself, but also in the extent to which shocks were transmitted across borders.

The post-crisis period, covering 2024 and 2025, reveals a more differentiated pattern in the value of the vulnerability index. Germany together with the Central European core remains at the top of the ranking, joined by Poland, whose position improves markedly relative to the pre-crisis period. This appears to reflect a persistent strengthening of incoming spillovers relative to earlier years. At the same time, several countries move back toward lower or even negative index values, indicating a partial return to pre-crisis conditions. Norway, Italy, Spain and Finland record negative post-crisis values, suggesting that their relative vulnerability has subsided as market conditions normalised.

Overall, the vulnerability index reinforces the broader findings of the empirical analysis, as it shows that exposure to volatility shocks in European electricity markets is not distributed evenly across countries. At the same time, the variation across subperiods confirms that vulnerability is not static but intensifies significantly during episodes of stress and then only partially reverts afterwards.

3.7 Discussion

The empirical results of the thesis suggest that price volatility in the European electricity market is strongly interconnected. The full sample spillover index indicates that a substantial part of forecast error variance is explained by cross-market shocks rather than by purely domestic volatility, which supports the view that electricity price volatility should be understood not purely as a country-level phenomenon, but also as a system-wide process.

The analysis of the time period using both the static and dynamic approach shows that volatility spillovers rose noticeably during the crisis period. This fact suggests that the period from July 2021 to December 2023 represented a systemic stress episode for the analysed European electricity markets. In the pre-crisis period, the total spillover index stood at 55,71 % for the static approach and 57,71 %, pointing to a situation where even in the pre-crisis period, more than half of the forecast error variance could be attributed to cross-border spillovers. This figure markedly rose during the crisis period to over 70 %, indicating that cross-border shocks became more important in explaining country level volatility. The post-crisis results indicate a partial normalisation, although total spillover index remained above the pre-crisis levels. This suggests that there was more of a structural change in the market, where cross-border volatility transmission remained relevant even after the most extreme phase of the crisis.

Shifting our attention to country-level results, these show that the role of individual markets is heterogeneous, as Germany, Austria, Czechia and later Slovakia appear as the most prominent net transmitters of volatility, which could be linked to their central position in the continental European electricity system. By contrast, Spain, Poland and Finland more often behave as net receivers of volatility, indicating that their volatility is more strongly influenced on a net basis by cross-border shocks than their own shocks influence the rest of the system.

The vulnerability index provides an additional perspective on these results by combining spillover reception with the level of domestic volatility. This distinction is important because high exposure to incoming spillovers does not automatically translate to high vulnerability if the level of domestic volatility remains controlled. The index therefore tries to capture a broader form of market exposure, where countries are considered more vulnerable when they simultaneously receive high volatility spillovers and experience elevated volatility levels domestically.

Overall, our findings confirm that the recent energy crisis strengthened the system-wide transmission of volatility in the European electricity market, which is consistent with the results in literature focused on electricity market connectedness authored by Cevik and Zhao (2025) or Sikorska-Pastuszka and Papież (2023). The results point to the fact that the spillovers are time-varying and tend to intensify during periods of geopolitical stress, while the analysis at the same time shows that these effects are not uniform across countries, as some markets act mainly as transmitters while others are more exposed to volatility originating elsewhere and the role of countries can also evolve over time as we have observed.

Conclusion

Electricity prices and their associated volatility in the interconnected European market have become a central topic of academic and policy debate in recent years, given their significant implications for both households and industrial consumers. The primary objective of this thesis was to quantify volatility spillovers across European electricity markets and to assess the relative position of individual countries within this system, distinguishing between net transmitters and net receivers of volatility.

To achieve the goal, we utilise the Diebold-Yilmaz framework to measure volatility spillovers among selected European markets and investigate their evolution in the last decade, which has been marked by rather turbulent times. Additionally, we have constructed a vulnerability index, with the aim of identifying the most vulnerable countries in the sense of incoming volatility and domestic volatility.

Throughout our analysis, we have arrived at interesting findings mainly regarding the already high interconnectedness of European markets in the pre-crisis period, which further intensified during the crisis years, indicating that the volatility in European electricity markets was more influenced by cross-border propagation rather than isolated domestic factors. In the post-crisis years, the spillover figure has subsided compared to the crisis period, but remained higher than in the pre-crisis period, which could point to a structural change in the overall European electricity market framework. The net transmitter countries in our sample were mainly represented by Germany, Austria, Czechia and Slovakia, while the countries that received the highest net volatility were Finland and Poland. Furthermore, our analysis revealed that in the pre-crisis and crisis periods, none of the countries changed their role, instead, in most cases their positions were amplified. Interestingly, in the post-crisis years we have observed a role reversal in the case of Hungary and France. The framework also allows us to study the bilateral relations between individual countries, where we have observed strong flows between Sweden-Finland, Germany-Austria, Czechia-Slovakia and Slovakia-Hungary among others.

The analysis conducted using the rolling window approach provides additional insights by capturing the time-varying nature of spillover dynamics. Notably, the results indicate that the peak spillover intensity occurred even prior to the Russian invasion of Ukraine, suggesting that the market was already under stress. This finding underscores the importance of a dynamic approach, as static or even a regime-based periodization may not fully capture the timing of systemic risk buildup.

Despite the contributions of the thesis, we should also acknowledge the limitations. The analysis focuses on 14 European markets, which, as presented, represent the majority of electricity consumption and production, but excludes potentially relevant regions such as the Baltic and Balkan countries. Including these markets could provide additional insights into the peripheral dynamics and possibly alter the observed network structure. Furthermore, while the study identifies the existence and direction of spillovers, it does not model their underlying drivers. Future research could extend the analysis by incorporating variables such as energy mix composition, interconnection capacity, carbon prices or macroeconomic indicators to model spillovers.

Overall, the findings of this thesis highlight that volatility in European electricity markets is increasingly driven by cross-border interactions rather than purely domestic factors. This has important implications for policymakers, as in a highly integrated system, interventions at the national level may be insufficient to address volatility and coordinated policies at European level become essential. This is consistent with the market reforms recommended by Pollitt et al. (2024), who argue that the experience of the energy crisis points to the need for a reform of the electricity market. In their paper, they divide the recommendations into four major baskets and include proposals such as an increased role of long-term contracts, better coordination of capacity markets, adding granularity to the wholesale market pricing, appropriate energy taxation and others. In the context of the thesis, these recommendations are particularly relevant because the empirical results show that volatility shocks are transmitted across borders, therefore, resilience cannot be achieved solely through country-level measure and policies should take into account the interconnected nature of European electricity markets and the possibility that shocks originating in one market could affect the wider system. As the share of renewable energy continues to grow and geopolitical uncertainty remains elevated, ensuring resilience against cross-border volatility transmission will be a key challenge for the European energy market.

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