THE IMPACT OF ELECTRICITY EXPORTS, IMPORTS AND PRICES IN THE EASTERN EUROPEAN COUNTRIES ON PRICES IN THE UKRAINIAN DAY-AHEAD ELECTRICITY MARKET AFTER INTEGRATION INTO ENTSO-E NETWORK

by

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Date ______________________________________

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LIST OF ABBREVIATIONS

ENTSO-E European Network of Transmission System Operators for Electricity

DAM Day-Ahead Market

IDM Intraday Market

BM Balancing Market

BCM Bilateral Contracts Market

VECM Vector Error Correction Model

1. INTRODUCTION

In March 2022, the Ukrainian power system was synchronized with the Continental European grid under the European Network of Transmission System Operators for Electricity (ENTSO-E). This was planned to be done earlier, but the process kept getting delayed. Then, one of the requirements for joining the system was to prove that the Ukrainian energy system is autonomous and can sustain itself without assistance from others. This integration happened quickly because of the geopolitical situation. It aimed to improve the stability, security, and flexibility of Ukraine's electricity system. The European Union has provided the opportunity for energy businesses to exchange power with each other across borders (Poland, Romania, Slovakia and Hungary) with Ukraine by establishing physical transmission links.

The increased interdependence of the EU electricity sector has some advantages, such as the possibility for Ukraine to export surplus energy to neighboring countries, but at the same time volatility of electricity prices has increased. Price changes in one country can cause instant price changes in neighboring countries through cross-border flows.

Ukraine's electricity price may be influenced by many factors that are beyond their control, which include the price structure and trading terms of the EU energy markets that Ukraine sells to. While international trade provides income and support stability in the system, it can also create certain price fluctuations for the Ukrainian market. This topic hasn't been studied in detail since Ukraine became part of ENTSO-E. The role of this study is to identify the effects of Ukraine's imports/exports and the electricity prices of EU neighboring countries on Ukraine's electricity prices after integration into ENTSO-E.

This study contributes to research on electricity market integration by applying VECM econometric model to measure the impact of neighboring EU market prices on Ukraine, including volume data (imports/exports) to assess the aggregate impact of cross-border trade and external price signals.

The purpose of this work is to study the impact of electricity prices in the European Union, as well as cross-border trade on the Ukrainian electricity market. The study uses a vector error correction model (VECM) applied to data collected from ENTSO-E, the Ukrainian market operator, and Ukrenergo. A descriptive analysis of electricity price trends and trade volumes in Ukraine will be provided. This will be followed by an econometric evaluation of the model. The main conclusions of the study describe the short-term and long-term impact of EU prices and trade volumes on electricity prices in Ukraine.

2. INDUSTRY OVERVIEW AND RELATED STUDIES

Electricity market reforms

Until mid-2019 the Ukrainian electricity market used an "all buyers" or single buyer model – a centralised system in which all generated electricity was purchased by the state-owned company Energorynok. It was the only wholesale buyer of electricity purchasing electricity from producers at regulated prices and then selling it to distribution companies (oblenergo) and some large industrial consumers. Prices were regulated by the National Energy and Utilities Regulatory Commission (NEURC).

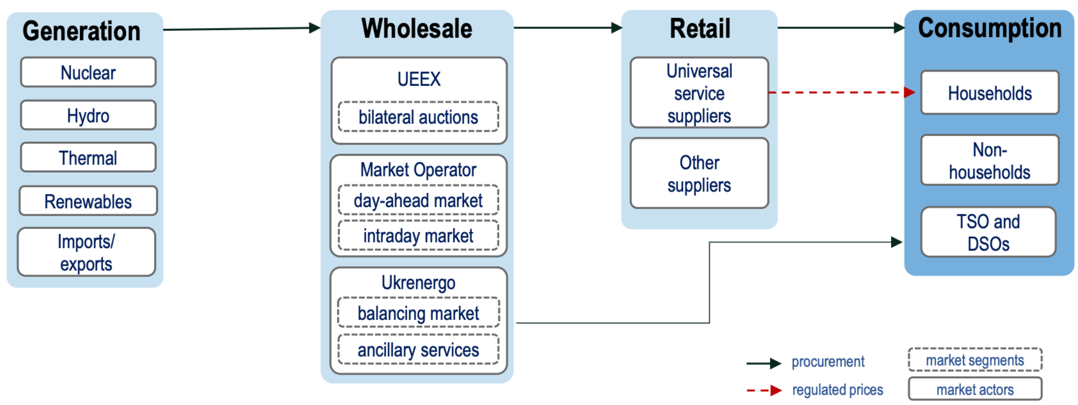
The Law of Ukraine "On the Electricity Market" was adopted in 2017 and in accordance with Ukraine's commitment under the Association Agreement between the EU and Ukraine. It created the basis for a competitive electricity market. In July 2019, new law replaced the electricity market structure of a single buyer with four different market segments:

1. Bilateral contracts for long-term agreements between producers and consumers
2. Day-ahead and intraday markets for the purchase and sale of electricity on a daily basis according to supply and demand.
3. A balancing market to maintain the balance between supply and demand.

In addition to the above reforms, this process also included the creation of corporate structures through the corporatisation of Ukrenergo. Other market participants were created by government decision, such as a Market Operator responsible for managing the day-ahead market (DAM) and intraday market (IDM), as well as a Guaranteed Buyer responsible for promoting transparent trading between market participants and supporting the development of renewable energy sources, and the Ukrainian Energy Exchange for monitoring bilateral contracts.

These changes allow Ukraine to implement and operate according to market principles and structures that follow EU requirements and also provide technical synchronisation of the Ukrainian transmission system with ENTSO-E. The new market structure provides the necessary legal and institutional framework for cross-border electricity trading between Ukraine and neighbouring countries, which is an important step on the way to further developing deeper economic interdependence with other European countries.

Figure 1: Electricity market design in Ukraine



Source: Competition Market Study of Ukraine's Electricity Sector © OECD. 2023

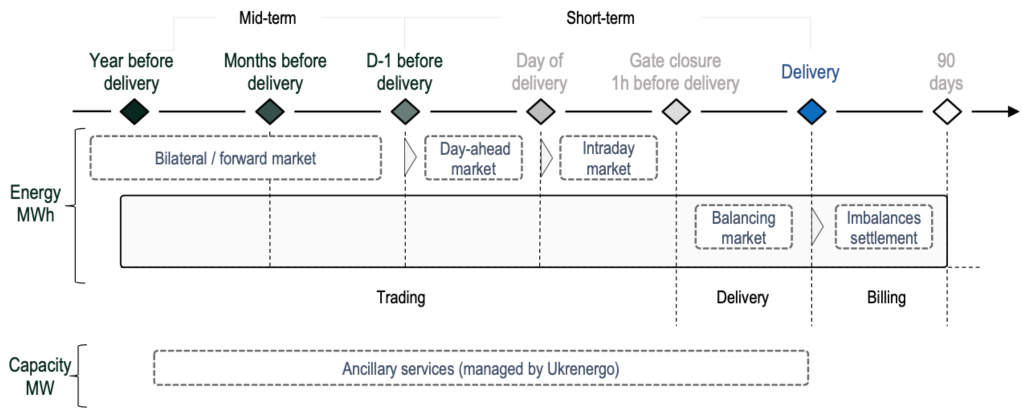
Wholesale market

Wholesale electricity markets allow for the sale and purchase of large volumes of electricity, which is then supplied to domestic and commercial consumers.

The components of wholesale electricity markets differ depending on the time when electricity is bought or sold compared to the time of its consumption by customers. The main wholesale electricity markets, specifically designed for short-term trading, include: the day-ahead market (DAM), the intraday market (IDM) and the balancing market (BM). All three markets are designed for transactions 24 hours before the physical delivery of electricity or almost in real time. Participants in the wholesale electricity market have the opportunity to adjust their positions based on updated forecasts, which increases their ability to adapt.

In addition to these short-term markets, forward markets make it possible to plan electricity deliveries for the future. In Ukraine, these transactions take place in the Bilateral Contracts Market (BCM). This allows participants to make sure they have enough electricity and manage price risks over longer periods.

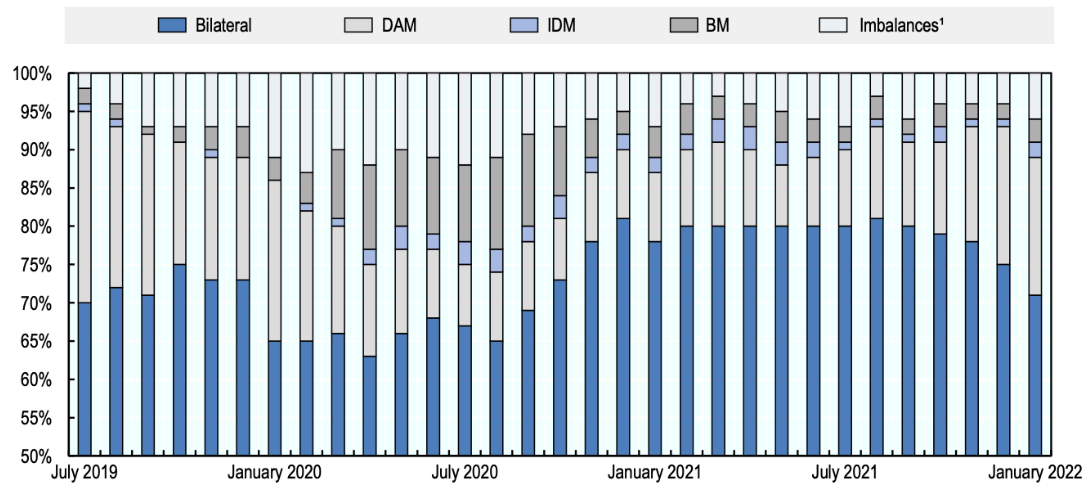
Figure 2. The sequence of Ukraine's wholesale electricity market



Source: Competition Market Study of Ukraine's Electricity Sector © OECD. 2023

The graph below provides a comprehensive visualization of the market share distribution across Ukraine's wholesale electricity market segments.

Figure 3. Distribution of trading across segments in Ukraine's electricity market, July 2019-January 2022



Source: Share of trade in different market segments, NEURC (2022)

Table 1. Market Structure of electricity.

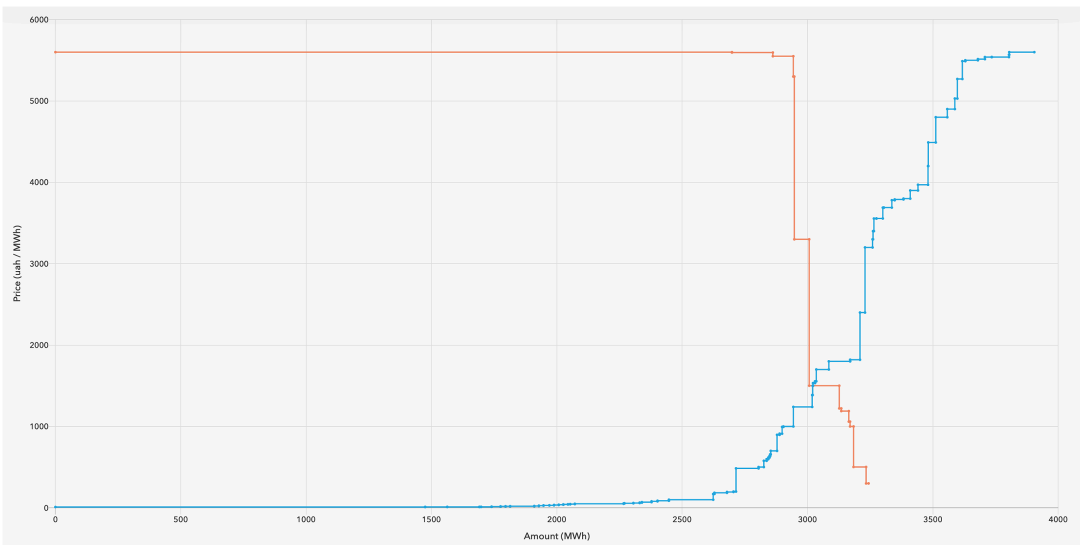
Market	Description	Trade period	Volume
BC	Long-term sales	1 year, 1 month, 1 decade	80%
DAM	Spot sales for next day	1 day	18%
IDM	Spot sales for today	1 hour	Up to 2%
BM	Emergency sales to balance electricity generation or consumption within an hour or right now	1 hour	+/-4%

Day-Ahead Market

The day-ahead market (DAM) is a major component of modern wholesale electricity markets created to allow for the planning and pricing of electricity the day before it is physically delivered. It allows market participants including producers, suppliers, traders, and large consumers, to submit bids and offers indicating the amount of electricity they wish to buy or sell for each hour of the following day.

DAM operates using a centralised auction system, which is managed by market operator. Participants submit a 'price-quantity' pair every hour, reflecting their bid price as a buyer or seller. The demand curve is then matched with the supply curve to determine the hourly market price, at which the last unit of energy accepted has a marginal cost of that price.

Figure 4. Example of day-ahead trading on 22.08.2025 15:00

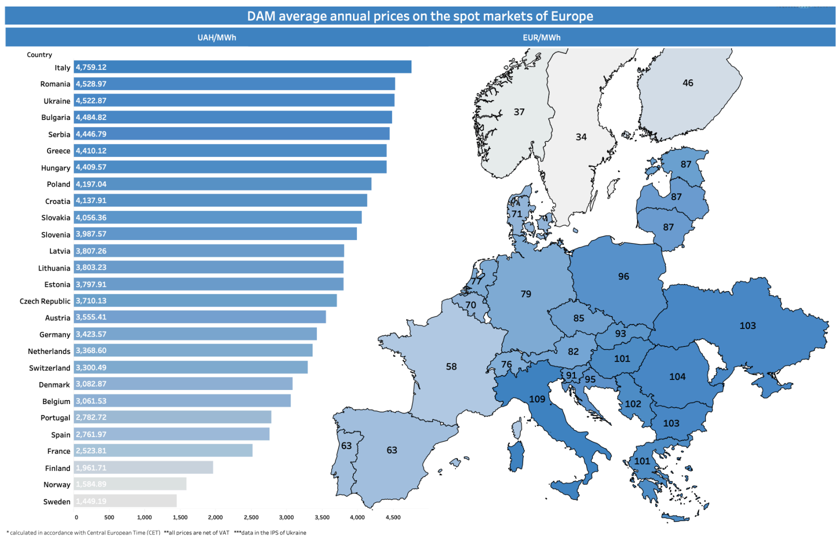


Source: Market Operator

This process will result in a daily (next day) obligation to buy and sell the required amount of electricity based on the trading schedule, ensuring full transparency for all market participants. Marginal pricing will lead to effective generation resource planning, as the cheapest available producers will be selected first, minimising overall system operating costs.

The DAM's prices also serve as a crucial benchmark for other market segments, significantly increasing transparency and competition compared to the previous state-regulated system.

Figure 5. DAM average annual prices in Europe (2024)



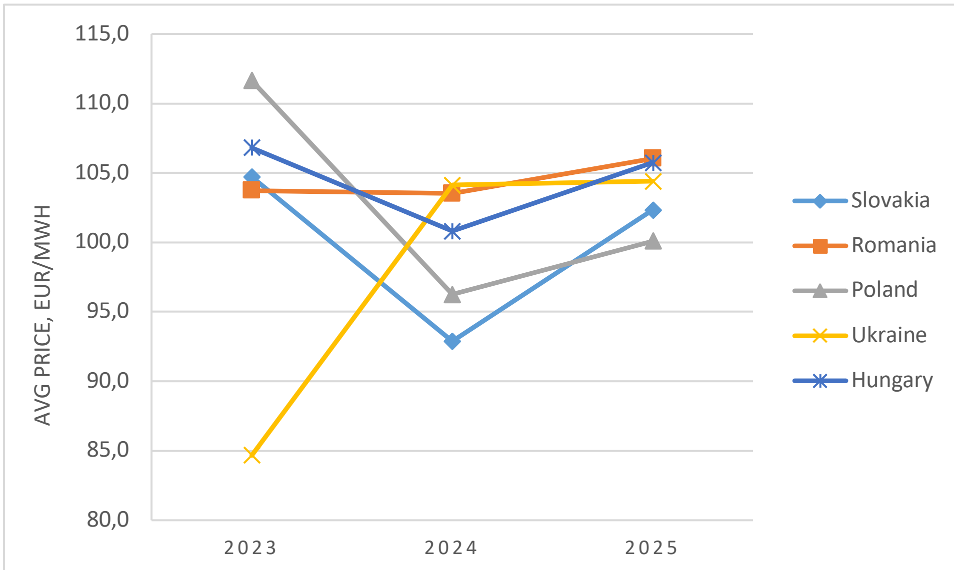
Source: Market Operator

The figure shows the average annual electricity prices for DAM on European spot markets. In 2024, the highest DAM prices were recorded in Italy, Romania and Ukraine. On the other hand, the lowest prices were recorded in Sweden, Norway and Finland. These three countries have an advantage due to their relatively large volumes of inexpensive hydroelectricity.

The map also shows a geographical pattern, with countries in northern and western Europe generally having lower electricity prices, while countries in the east, south-east of Europe and in the Mediterranean region tend to have higher electricity prices, mainly due to their generation mix and dependence on imports.

Also, on the figure below we can see comparable analysis 2024 vs 2025-year prices on the DAM in Ukraine.

Figure 6. Average price on DAM



Source: Own calculations

Between 2023 and 2025, average prices on the day-ahead market in Ukraine rose from €84.7/MWh to €104.4/MWh, moving from a clear discount compared to neighboring EU markets to near parity. By 2024, the gap had narrowed as Ukraine's average (96.3) moved closer to regional levels, and by 2025, prices had converged even further, with all markets reaching nearly identical levels of €100–106/MWh. This trend indicates a strengthening of price integration between the Ukrainian and ENTSO-E markets.

In November 2023, the Ukrainian energy regulator (NEURC) issued Resolution № 2099, setting the following maximum price caps on the day-ahead and intraday electricity markets:

- 00:00–07:00 and 23:00–24:00 – UAH 3,000/MWh
- 07:00–08:00 and 11:00–17:00 – UAH 5,600/MWh
- 08:00–11:00 – UAH 6,900/MWh

- 17:00–23:00 – UAH 7,500/MWh
- The minimum price cap was set at UAH 10/MWh

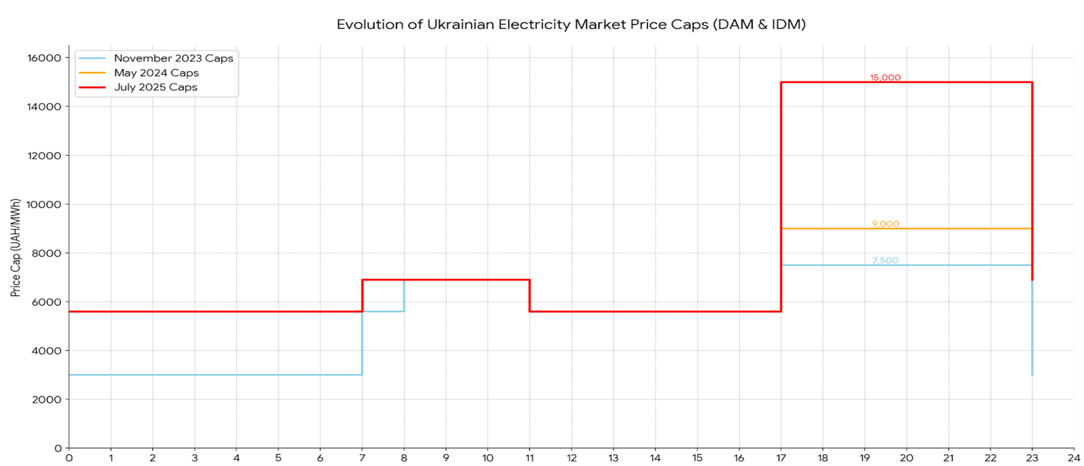
Then, in May 2024, via Resolution № 949 (effective from 31 May 2024), NEURC raised these price caps:

- 00:00–07:00 and 11:00–17:00 – UAH 5,600/MWh
- 07:00–11:00 and 23:00–24:00 – UAH 6,900/MWh
- 17:00–23:00 – UAH 9,000/MWh
- Minimum price cap remained unchanged at UAH 10/MWh

According to Resolution № 1133 adopted on 25 July 2025, effective from 31 July:

- Evening peak hours (17:00–23:00) on DAM & IDM were raised to UAH 15,000/MWh
- All other time intervals remained at their existing levels

Figure 7. Price caps on DAM and IDM.



Source: Own graph

As these regulations raised the upper price limits, they also allowed market participants to increase the amount of money that can be paid at spot prices.

Import and Export

The Ukrainian electricity trading system is an important tool for maintaining the country's national energy security, ensuring a stable pricing environment for electricity, and further integration into the European energy system. Since the emergency synchronisation of the Ukrainian power system with the Continental Europe Synchronous Area (CESA) in March 2022, cross-border electricity exchange has been an important tool for balancing domestic supply and demand and generating revenue from electricity exports.

Cross-border interconnection plays several roles within the current structure of the Ukrainian power system. First, the CBI serves as a balancing mechanism. It allows electricity to be imported into Ukraine during periods of high domestic demand, power blackouts, and when the amount of renewable electricity generated falls below expectations. Second, the CBI provides a method of raising revenue by exporting electricity to other countries, especially during periods of high domestic production relative to domestic consumption.

The maximum hourly capacity for electricity exports from Ukraine to the EU was increased from 650 MW to 900 MW in July 2025. Monthly capacity availability assessments are carried out by the Regional Coordination Centre (RCC) for each member country in the region to ensure that all available capacities comply with the technical requirements of the regional electricity grid.

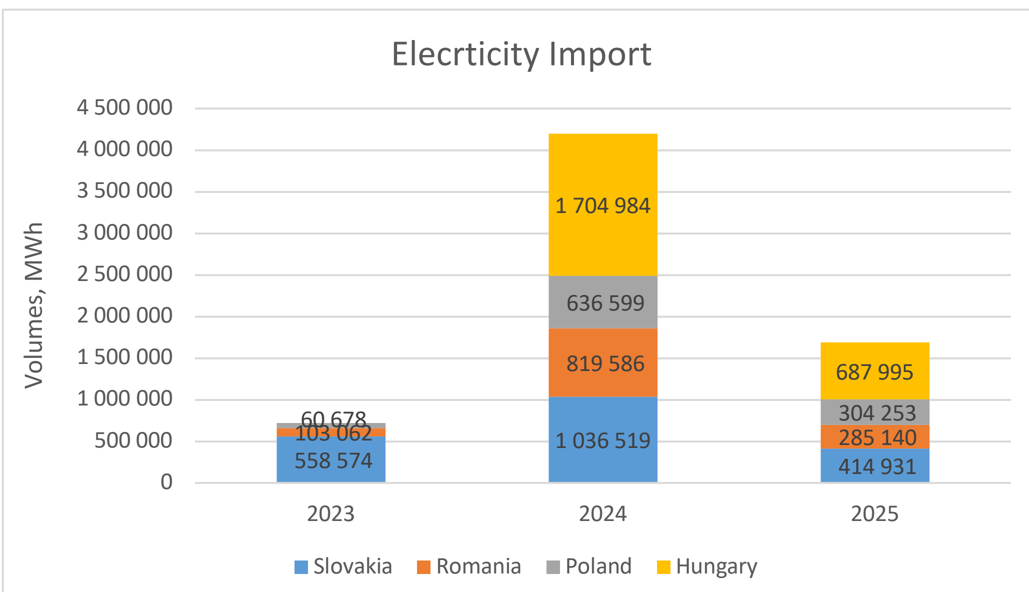
Imports in 2023 were minimal, amounting to less than 0.8 TWh. The main importer was Slovakia (558,574 MWh), with slightly smaller volumes coming from Hungary, Romania and Poland.

In 2024, imports rose sharply to over 4.1 TWh. This was due to a significant increase in supplies from Hungary (1.70 TWh) combined with larger contributions from Slovakia (1.04 TWh) and Romania (0.82 TWh), as well as 0.64 TWh from Poland. The sharp increase was caused by problems with the supply of domestically produced electricity due to missile attacks.

As of August 2025, imports amounted to 1.69 TWh. Imports from Hungary (0.69 TWh) again accounted for the largest share of imports for the year. The next largest suppliers were Slovakia (0.41 TWh), Poland (0.30 TWh) and Romania (0.28 TWh).

The data shows that import dependence reached its peak in 2024, when Hungary became the main supplier and in 2025 imports for these eight months already significantly exceeded the volumes compared to 2023.

Figure 8. Electricity Import to Ukraine



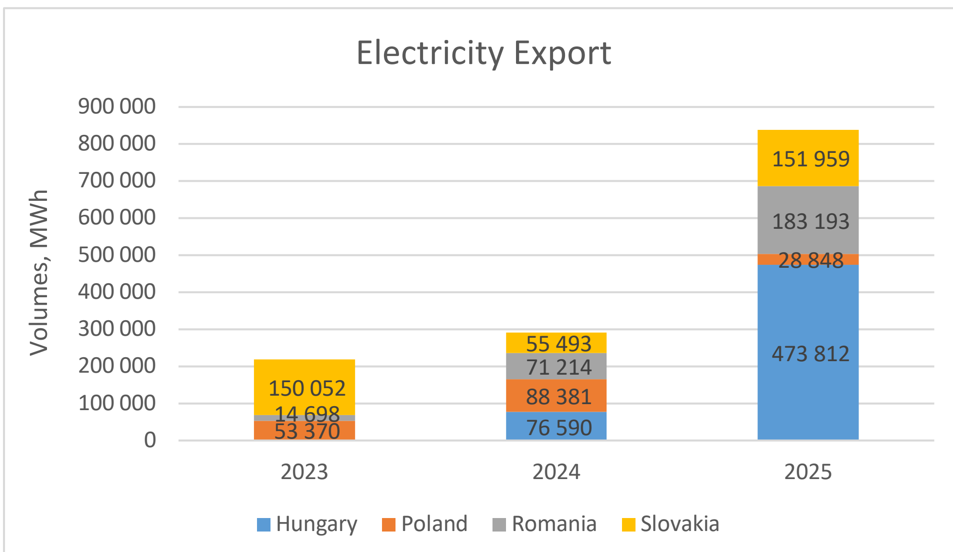
In 2023 Slovakia was the largest market for electricity from the region accounting for approximately 150,052 MWh, which was around 70% of total exports. The total volume of electricity exported to the EU in 2023 was approximately 0.22 TWh.

The total volume of electricity exported to the EU region in 2024 was approximately 0.29 TWh. Poland accounted for most of this volume (88,381 MWh). However, if you look at the graph, the volumes are distributed almost equally.

As of August 20205, the total volume of electricity exported to the EU region was approximately 0.84 TWh. Exports to Hungary increased sharply, while exports to Romania and Slovakia were also higher than in previous years.

Overall, the data shows that Hungary has become the main export market since 2024.

Figure 9. Electricity Export to Ukraine



Source: Own calculations

Related studies

Suryanto et al (2022) is a useful study to use as a basis for my work, as it applies VECM to examine both short-term and long-term relationships in the electricity sector. Although Suryanto et al (2022) focuses directly on electricity consumption and human development in Asian developing countries. Testing for cointegration, interpreting error correction terms, and examining lag effects can be directly applied to my research on electricity price trends in Ukraine and Hungary.

Stanciu and Mitu (2025) use a vector error correction model (VECM) for daily wholesale electricity prices for the following day for 24 EU countries (from October 2017 to September 2024), which allowed them to identify seven regional price clusters. They found that EU electricity markets have both long-term equilibrium relationships and dynamic short-term price adjustments between them. Stanciu and Mitu's findings demonstrate how key market players, such as Germany and France, can act as central price setters for their regions, leading to higher prices within the interconnection of these regions. My research will directly apply Stanciu and Mitu's research, as they confirm that VECM can be applied to analyse interconnected electricity markets, provide an applicable methodology for capturing both long-term cointegration and short-term dynamics, and provide a comparative basis for determining whether Ukraine after integration into ENTSO-E will be part of specific regional price clusters and whether it will experience asymmetric price transmission from major EU market players.

Kornienko (2023) in his study examines the impact of russia's full-scale invasion on Ukraine's wholesale electricity market, focusing on price, supply and demand shocks on DAM and BCM. He uses ordinary least squares (OLS) regression models that include a war coefficient as well as Chow tests to identify significant changes in the volume of traded energy products (a 61% decrease for DAM; a 40% decrease for BCM), a decrease in the amount of energy supplied (37%) and consumed (62%) and price volatility due to regulatory impact through the setting of minimum price caps. The war damaged approximately 78% of thermal capacity and led to an almost complete collapse in industrial demand (a 65% decline in metallurgical production).

The study of Carr, Meissner & Zachmann (2024) research whether higher EU-to-Ukraine power exports raise neighbours' day-ahead prices. Using a power-system model (EU + Ukraine + Moldova) and three cross-border limits (0, 2200, 3000 MW) for Jan – Jun, it finds the effect is small. Letting exports rise from 0 to 2200 MW increase price a little (about 1% in Poland to ~11% in Slovakia), and going to 3000 MW adds only a bit more. Ukraine needs these imports because war damage removed much of its generation; imports helped avoid blackouts. More transfer capacity strongly helps Ukraine's security of supply and only slightly lifts prices in neighbouring markets.

3. METHODOLOGY

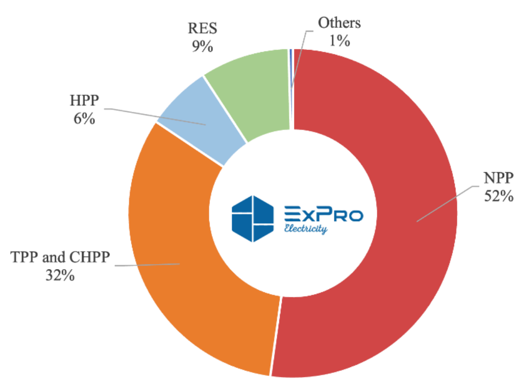
Structure of electricity production

In my opinion, the price on the electricity market strongly depends on the structure of production, so it is necessary to consider this in Ukraine and neighbouring countries and take it into account for further analysis.

In March 2025, Ukraine's electricity production was dominated by nuclear power plants (NPP), which accounted for 52% of total generation. Thermal and combined heat and power plants (TPP and CHPP) provided 32%, while renewable energy sources (RES) contributed 9% and hydropower plants (HPP) supplied 6%. Other sources made up just 1%.

This structure highlights Ukraine's strong reliance on nuclear generation, with thermal plants as the main secondary source, and a comparatively smaller share from renewables and hydropower.

Figure 10. Electricity production in Ukraine.

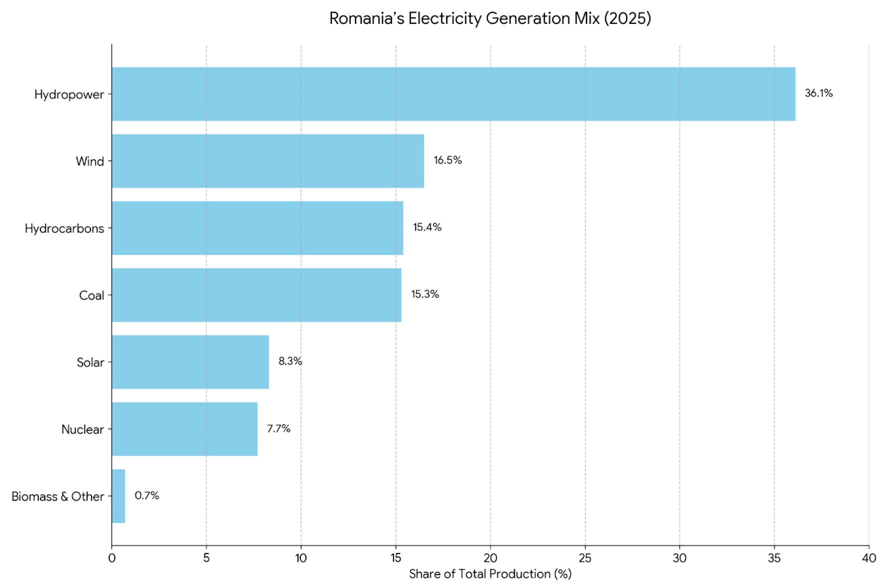


Source: ExPro Electricity

Romania's electricity generation is dominated by hydropower, which leads a diverse mix where renewables (hydro, wind, solar) account for over 60% of total production.

The remaining power comes from a balanced blend of fossil fuels (hydrocarbons and coal) and nuclear energy.

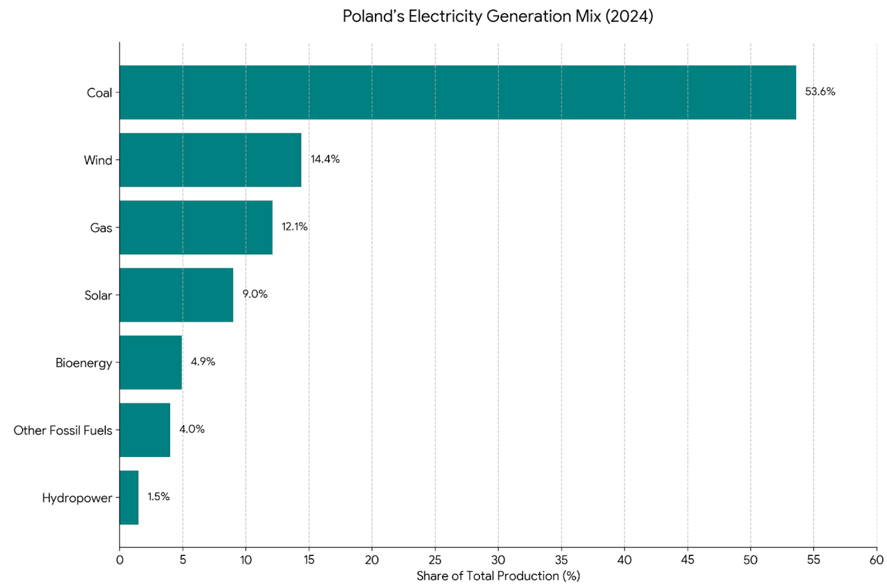
Figure 11. Electricity production in Romania.



Source: Own graph using data from International Trade Administration 2025

Poland's electricity generation is heavily dominated by coal, which provides over half of the country's power. While fossil fuels collectively account for nearly 70% of the total, wind and solar lead the country's growing renewable energy sector.

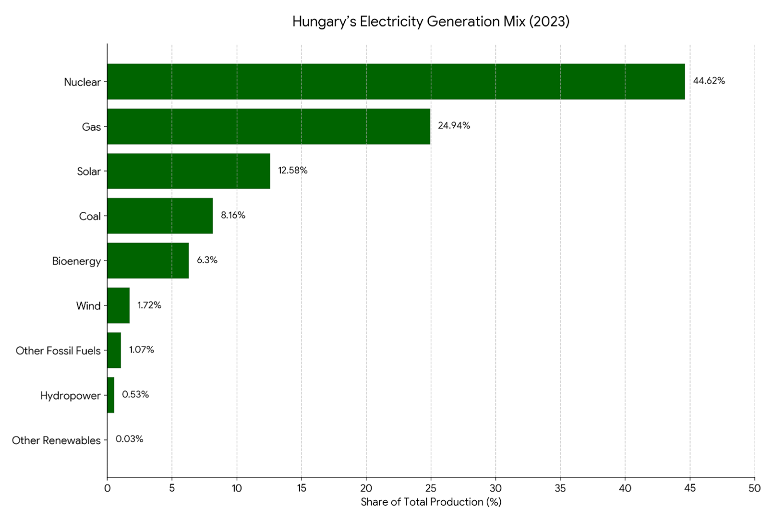
Figure 12. Electricity production in Poland.



Source: Own graph using data from Ember 2024

Hungary's electricity mix is dominated by nuclear power and gas, which together account for nearly 70% of its total generation. Solar stands out as the country's leading renewable energy source.

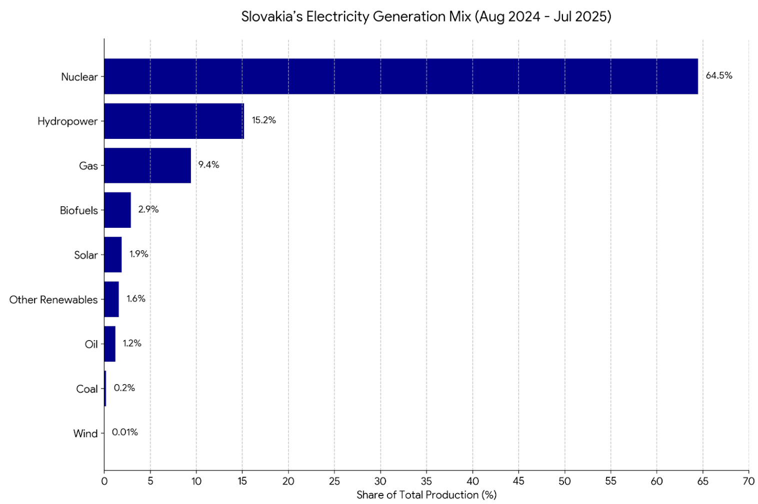
Figure 13. Electricity production in Hungary.



Source: Own graph using data from International Trade Administration 2023

Slovakia's electricity generation is overwhelmingly dominated by low-carbon sources, with nuclear power and hydropower together accounting for nearly 80% of the total mix. Fossil fuels, primarily gas, play a minimal supporting role.

Figure 14. Electricity production in Slovakia.



Source: Own graph using data from LowCarbonPower 2024-2025

Our generation structure is very similar to that of Hungary, so I would use it for further analysis.

VECM

This study uses a vector error correction model (VECM) because the variables considered – DAM prices and import and export volumes are non-stationary time series that are expected to be cointegrated. Cointegration means that these variables move together in the long run, reflecting the increasing integration of the Ukrainian and neighboring markets following the synchronization of the Ukrainian power system with ENTSO-E. The VECM model is particularly appropriate because it allows for the simultaneous estimation of the long-term equilibrium between prices and trade flows, as well as the short-term adjustments that occur when actual prices deviate from the equilibrium.

Let p_t^{UA} denote the hourly DAM price in Ukraine, p_t^{HU} the hourly DAM price in Hungary, IMP_t^{HU} the electricity imported by Ukraine from Hungary in hour, and EXP_t^{HU} the electricity exported by Ukraine to Hungary in hour. The model assumes these series are integrated of order one and cointegrated. I normalize the cointegration relation on p_t^{UA} and include standard seasonal controls for daily and weekly patterns.

So, the long-run relation will be as follows:

$$ECT_{t-1}^{HU} = p_{t-1}^{UA} - (\beta_0 + \beta_{HU}\, p_{t-1}^{HU} + \beta_{IMP}\, IMP_{t-1}^{HU} - \beta_{EXP}\, EXP_{t-1}^{HU})$$

Where $\beta_{HU} > 0$ captures long-run price pass-through from Hungary to Ukraine, then $\beta_{IMP} < 0$ is expected if imports eliminate the deficit and reduce the Ukrainian price in equilibrium, and $\beta_{EXP} > 0$ if exports restrict domestic supply and increase the equilibrium price.

And here is short-run error-correction model:

$$\Delta p_t^{UA} = \alpha ECT_{t-1}^{HU} + \sum_{i=1}^{p} \phi_i \Delta p_{t-i}^{UA} + \sum_{i=1}^{p} \gamma_i \Delta p_{t-i}^{HU} + \sum_{i=1}^{p} \delta_i \Delta IMP_{t-i}^{HU} - \sum_{i=1}^{p} \theta_i \Delta EXP_{t-i}^{HU} + \eta' H_t + \kappa' W_t + \varepsilon_t$$

Where:

- Δp_t^{UA} – hourly change in Ukraine's DAM price (dependent variable),
- αECT_{t-1}^{HU} – error correction term from the long-run equilibrium,
- $\sum_{i=1}^{p} \phi_i \Delta p_{t-i}^{UA}$ – short-run own lags of Ukraine's price,
- $\sum_{i=1}^{p} \gamma_i \Delta p_{t-i}^{HU}$ – short-run impact of Hungarian price changes,
- $\sum_{i=1}^{p} \delta_i \Delta IMP_{t-i}^{HU}$ – short-run effect of changes in imports from Hungary,
- $\sum_{i=1}^{p} \theta_i \Delta EXP_{t-i}^{HU}$ – short-run effect of changes in exports to Hungary,
- $\eta' H_t$ – hourly seasonal dummies,
- $\kappa' W_t$ – day-of-week seasonal dummies,
- ε_t – error term.

4. DATA

The empirical analysis in this study is based on hourly time series data covering the period from January 1, 2023, to August 2025. The dataset contains information on hourly wholesale electricity prices in Ukraine and neighboring EU markets (Poland, Hungary, Romania, Slovakia), as well as hourly import and export between Ukraine and neighboring ENTSO-E member states.

The data set has an hourly frequency. Such a high frequency allows for the analysis of short-term price dynamics and the rapid spread of shocks between markets. This is also necessary because prices vary greatly at different hours of the day, depending on consumption and demand.

The data on DAM prices in European countries were in euros, while the prices in Ukraine were given in UAH, so I took the average euro exchange rate for each year and multiplied it to ensure that all data was in the same currency. The information for all countries by year was separated, so I compiled it into a single dataset. Prices are measured in EUR/MWh.

Figure 15. Example of the collected data on 01.01.2023 for DAM prices

Energy Prices
Energy Prices [12.1.D]
01/01/2023 00:00 - 22/08/2025 11:00 (CET/CEST)

MTU	BZN|UA-IPS	BZN|HU	BZN|PL	BZN|RO	BZN|SK
	Without Sequence	Without Sequence	Without Sequence	Without Sequence	Without Sequence
	Day-ahead (EUR/MWh)	Day-ahead (EUR/MWh)	Day-ahead (EUR/MWh)	Day-ahead (EUR/MWh)	Day-ahead (EUR/MWh)
31/12/2022 23:00:00 - 01/01/2023 00:00:00	50,07	2,06	21,34	2,02	2,06
01/01/2023 00:00:00 - 01/01/2023 01:00:00	49,95	19,76	18,09	20,02	20,26
01/01/2023 01:00:00 - 01/01/2023 02:00:00	44,10	0,19	5,75	0,18	0,33
01/01/2023 02:00:00 - 01/01/2023 03:00:00	34,61	0,07	5,27	0,01	0,50
01/01/2023 03:00:00 - 01/01/2023 04:00:00	34,61	0,01	5,74	0,01	0,50
01/01/2023 04:00:00 - 01/01/2023 05:00:00	34,61	-0,77	5,22	0,01	0,10
01/01/2023 05:00:00 - 01/01/2023 06:00:00	44,10	0,01	6,14	0,01	0,72
01/01/2023 06:00:00 - 01/01/2023 07:00:00	66,42	-2,56	5,31	0,00	-2,45
01/01/2023 07:00:00 - 01/01/2023 08:00:00	66,42	0,02	5,99	0,01	0,04
01/01/2023 08:00:00 - 01/01/2023 09:00:00	66,42	0,30	6,63	0,29	0,48
01/01/2023 09:00:00 - 01/01/2023 10:00:00	66,42	0,95	6,64	0,93	1,19
01/01/2023 10:00:00 - 01/01/2023 11:00:00	66,42	1,60	5,17	1,57	1,91
01/01/2023 11:00:00 - 01/01/2023 12:00:00	66,42	2,32	8,53	2,27	2,74
01/01/2023 12:00:00 - 01/01/2023 13:00:00	66,42	2,43	10,72	2,40	2,79
01/01/2023 13:00:00 - 01/01/2023 14:00:00	86,67	2,56	14,06	2,49	2,76
01/01/2023 14:00:00 - 01/01/2023 15:00:00	99,90	9,96	56,41	9,70	9,96
01/01/2023 15:00:00 - 01/01/2023 16:00:00	99,90	23,87	91,66	23,86	23,87
01/01/2023 16:00:00 - 01/01/2023 17:00:00	99,90	36,54	97,81	36,54	36,54
01/01/2023 17:00:00 - 01/01/2023 18:00:00	99,90	46,03	102,08	46,03	46,03
01/01/2023 18:00:00 - 01/01/2023 19:00:00	99,90	53,35	106,34	53,22	53,68
01/01/2023 19:00:00 - 01/01/2023 20:00:00	99,90	54,95	108,73	54,95	54,95
01/01/2023 20:00:00 - 01/01/2023 21:00:00	98,12	49,08	106,65	49,06	49,11
01/01/2023 21:00:00 - 01/01/2023 22:00:00	98,12	44,32	107,42	44,27	44,43
01/01/2023 22:00:00 - 01/01/2023 23:00:00	48,92	45,96	103,81	45,96	45,96
01/01/2023 23:00:00 - 02/01/2023 00:00:00	50,07	35,00	90,35	35,00	35,00

Imports and exports were considered as separate variables rather than net flows, which made it possible to identify the asymmetric impact of inflows and outflows on domestic prices and measures in MWh.

Figure 16. Example of the collected data on 01.01.2023 for imports and exports

MTU	YEAR	IMPORT				EXPORT			
		BZN|HU	BZN|PL	BZN|RO	BZN|SK	BZN|HU	BZN|PL	BZN|RO	BZN|SK
01/01/2023 00:00:00 - 01/01/2023 01:00:00	2023	0	0	0	50	0	0	0	0
01/01/2023 01:00:00 - 01/01/2023 02:00:00	2023	0	0	0	185	0	0	0	0
01/01/2023 02:00:00 - 01/01/2023 03:00:00	2023	0	0	0	190	0	0	0	0
01/01/2023 03:00:00 - 01/01/2023 04:00:00	2023	0	0	0	190	0	0	0	0
01/01/2023 04:00:00 - 01/01/2023 05:00:00	2023	0	0	0	195	0	0	0	0
01/01/2023 05:00:00 - 01/01/2023 06:00:00	2023	0	0	0	195	0	0	0	0
01/01/2023 06:00:00 - 01/01/2023 07:00:00	2023	0	0	0	140	0	0	0	0
01/01/2023 07:00:00 - 01/01/2023 08:00:00	2023	0	0	0	160	0	0	0	0
01/01/2023 08:00:00 - 01/01/2023 09:00:00	2023	0	0	0	185	0	0	0	0
01/01/2023 09:00:00 - 01/01/2023 10:00:00	2023	0	0	0	165	0	0	0	0
01/01/2023 10:00:00 - 01/01/2023 11:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 11:00:00 - 01/01/2023 12:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 12:00:00 - 01/01/2023 13:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 13:00:00 - 01/01/2023 14:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 14:00:00 - 01/01/2023 15:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 15:00:00 - 01/01/2023 16:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 16:00:00 - 01/01/2023 17:00:00	2023	0	0	0	150	0	0	0	0
01/01/2023 17:00:00 - 01/01/2023 18:00:00	2023	0	0	0	0	0	0	0	0
01/01/2023 18:00:00 - 01/01/2023 19:00:00	2023	0	0	0	0	0	0	0	0
01/01/2023 19:00:00 - 01/01/2023 20:00:00	2023	0	0	0	0	0	0	0	0
01/01/2023 20:00:00 - 01/01/2023 21:00:00	2023	0	0	0	0	0	0	0	0
01/01/2023 21:00:00 - 01/01/2023 22:00:00	2023	0	0	0	0	0	0	0	0
01/01/2023 22:00:00 - 01/01/2023 23:00:00	2023	0	0	0	5	0	0	0	0
01/01/2023 23:00:00 - 02/01/2023 00:00:00	2023	0	0	0	0	0	0	0	0

The DAM prices are sourced from the ENTSO-E Transparency Platform. The import and export data are sourced from the Energy Map.

I downloaded all the data separately for every year and each country and then collected everything in two datasets.

For easier analysis in R code, I joined the tables and also a little bit changed the structure of the time column: deleted the period and the first hour only left.

Data Analysis

Table 2. Mean, minimum and maximum of price on DAM, EUR/MWh over the period

	Mean	Minimum	Maximum
Ukraine	96.8	0.2	310.7

Hungary	104.3	-500.0	999.0
Poland	103.0	-133.0	630.2
Romania	104.2	-106.4	1021.6
Slovakia	99.6	-202.7	850.0

The table summarizes the mean, minimum, and maximum hourly DAM prices for Ukraine and four neighboring EU bidding zones – Hungary, Poland, Romania, and Slovakia – over the observation period.

The highest average hourly DAM price was in Hungary (104.3 EUR/MWh), closely followed by Romania (104.2) and Poland (103.0). Ukraine's mean price (96.8) was the lowest among all markets, slightly below Slovakia (99.6).

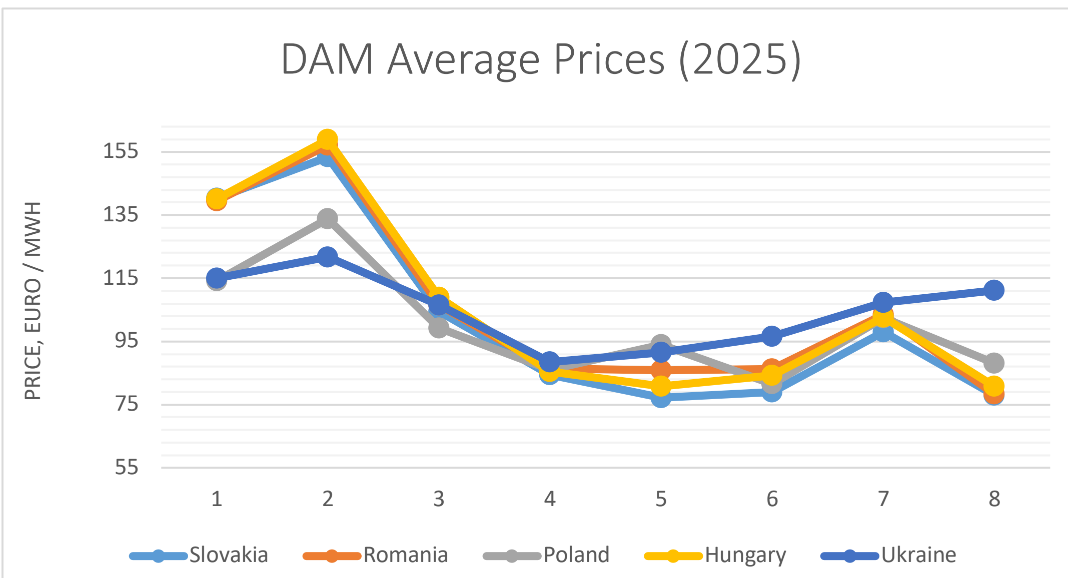
Negative prices on the following day occur when there is an excess of electricity at a certain time: demand is low, supply (wind/solar power plants or power plants that must operate continuously) is high, and some generators are too inflexible or expensive to shut down, so they offer a price below zero to avoid stopping and restarting. A negative price means that producers pay to feed electricity into the grid, while consumers and storage facilities are paid for consuming it, which is a strong signal to reduce production or increase demand. Typical responses include reducing the use of renewable energy sources, reducing the capacity of flexible installations, charging batteries, or shifting industrial loads.

The Ukrainian DAM has a regulatory minimum, so prices there do not fall below zero, but neighbors may experience negative hours. This minimum price creates an important dynamic in cross-border trade: when a neighbor's price is, for example, -10 euros/MWh, and the Ukrainian price remains at the minimum level of 0.2 euros/MWh, the Ukrainian market immediately becomes the most attractive place for this surplus electricity. The strong price difference encourages neighboring producers to maximize exports to the

Ukrainian grid, up to the limit of available cross-border capacity, with the flow directed from the cheaper market with a large surplus to the more expensive one (Ukraine).

Although importing this electricity helps neighbors reduce their surplus supply, it puts significant pressure on the Ukrainian transmission system operator (TSO). Since the Ukrainian market cannot naturally absorb this surplus due to a strong negative price signal (i.e., paying batteries or large industrial consumers to increase consumption), the Ukrainian TSO may be forced to initiate internal restrictions on domestic production to maintain balance in the grid. In essence, the regulatory minimum price shifts the problem of managing regional surpluses, at least in part, to the Ukrainian system, making it the key recipient of external energy surpluses.

Figure 17. Average price on DAM, 2025



Source: Own calculations

All five markets start the year with high figures in January-February (Hungary and Romania reach a peak of ~155-160 EUR/MWh), and then fall sharply in March-April to ~85-95 EUR/MWh. Prices reach their lowest point in May-June (≈75-90), recover in

July, and diverge in August. Romania and Hungary fall to ~80, Poland and Slovakia remain at ~85-90, and Ukraine remains raise to ~114.

5. RESULTS

Before evaluating the model, several diagnostic tests were performed to ensure that the properties of the time series data and the relationships between variables were consistent with the chosen econometric approach. These tests included stationarity testing, correlation analysis, multicollinearity diagnostics, and a test for heteroscedasticity.

5.1 Pre-estimation tests

First of all, the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test was applied to each of the four variables: Ukrainian market prices (pUA), Hungarian market prices (pHU), imports from Hungary (IMP_HU), and exports to Hungary (EXP_HU). Results indicate that for all variables, the null hypothesis of stationarity is rejected when testing the series in levels – the test statistics are far above the critical values at the 5% significance level. This means that the variables are non-stationary in levels.

Table 3. KPSS stationarity test results

Variable	KPSS Level (mu)	KPSS Level (tau)	KPSS Diff (mu)	KPSS Diff (tau)	Integration order
pUA	33.298	3.837	0.001	0.000	I(1)
pHU	4.109	4.225	0.001	0.000	I(1)
IMP_HU	35.015	9.299	0.001	0.001	I(1)
EXP_HU	41.394	8.703	0.007	0.002	I(1)

However, when the same test is applied to the first differences, the null hypothesis is no longer rejected, and the test statistics are close to zero. This confirms that all series are integrated of order one.

5.2 Lag Selection on Levels

Before estimating the VECM, it is necessary to determine the optimal lag length for the underlying VAR model in levels. The selection was based on four standard information criteria: Akaike Information Criterion (AIC), Hannan–Quinn Criterion (HQ), Schwarz Criterion (SC), and the Final Prediction Error (FPE).

Table 4. Lag Selection

Lag	**AIC(n)**	**HQ(n)**	**SC(n)**	**FPE(n)**
1	28.396	28.399	28.403	2.149e+12
2	28.065	28.069	28.078	1.544e+12
3	28.016	28.022	28.034	1.469e+12
4	27.984	27.992	28.008	1.424e+12
5	27.971	27.981	28.001	1.405e+12
6	27.954	27.965	27.989	1.381e+12
7	27.926	27.940	27.967	1.344e+12
8	27.908	27.923	27.954	1.319e+12
9	27.882	27.899	27.933	1.285e+12
10	27.872	27.891	27.929	1.273e+12
11	27.857	27.878	27.920	1.254e+12
12	27.831	27.853	27.900	1.222e+12
13	27.809	27.833	27.883	1.195e+12
14	27.792	27.818	27.872	1.175e+12
15	27.781	27.808	27.866	1.162e+12
16	27.764	27.793	27.854	1.142e+12
17	27.708	27.739	27.804	1.081e+12
18	27.664	27.697	27.766	1.036e+12
19	27.578	27.613	27.685	9.485e+11
20	27.499	27.535	27.611	8.757e+11
21	27.373	27.412	27.491	7.761e+11
22	27.179	27.219	27.303	6.363e+11
23	26.981	27.023	27.109	5.222e+11
24	26.817	26.861	26.932	4.431e+11

According to the Schwarz criterion (SC), the optimal lag length is p = 24. This choice is also supported by AIC and FPE, which reach their minimum values at lag 24.

Using 24 lags ensures that the model captures the relevant short-term dynamics while avoiding residual autocorrelation, which is particularly important for high-frequency electricity price data.

5.3 Johansen Const Cointegration Test

To assess the presence of long-run equilibrium relationships between the variables pUA, pHU, IMP_HU, and EXP_HU, the Johansen cointegration test was performed using the trace statistic approach without a linear trend and with a constant in the cointegration equation.

Eigenvalues (λ): The values are all positive but relatively small. This suggests that while long-run relationships exist. The connections are not exceptionally strong, implying a moderate return to equilibrium when deviations occur.

Table 5. Eigenvalues

	pUA	pHU	IMP_HU	EXP_HU
λ	0.004	0.002	0.0007	0.0005

Since the 5% significance level leads to a contradictory result, the conclusion is based on the 1% level. The procedure identifies the cointegrating rank as the first null hypothesis that is not rejected.

Therefore, the test indicates a cointegrating rank of r = 3. This is a strong and meaningful result. It implies that system of four variables, there are three distinct, stable long-run equilibrium relationships. This suggests a high degree of integration and interdependence between these market variables, meaning they do not move independently of one another in the long run.

Table 6. Trace Test results

Null Hypothesis	Trace Statistic	10% CV	5% CV	1% CV	Decision (1% level)
r ≤ 3	10.53	6.50	8.18	11.65	Don't reject H0
r ≤ 2	27.48	15.66	17.95	23.52	Reject H0
r ≤ 1	78.79	28.71	31.52	37.22	Reject H0
r = 0	181.32	45.23	48.28	55.43	Reject H0

Cointegration Vectors (β): Following the Johansen trace test, which determined a cointegrating rank of r=3, the first three columns of the matrix are relevant. Each of these columns is a "cointegrating vector" and defines the specific coefficients for one of the three distinct long-run equilibrium relationships identified in the system. The vectors are normalized so that the coefficient for the Ukrainian price (pUA) is set to 1.0. These three vectors form the basis for constructing the three Error Correction Terms (ECTs) used in the final VECM.

Table 7. Cointegration Vectors (β) - normalized on pUA

	pUA	pHU	IMP_HU	EXP_HU
pUA	1.00	1.00	1.00	1.00
pHU	-0.64	0.30	0.41	-0.30
IMP_HU	-0.09	-0.16	0.41	0.26
EXP_HU	-0.12	0.05	-0.63	1.79

Loading Matrix (α): Each coefficient in this matrix measures how quickly and strongly a variable (row) responds to a deviation from a specific long-run equilibrium (column). The most critical coefficient s in the first row and first column, which has a value of -0.030. This is the adjustment coefficient for the Ukrainian price in response to a disequilibrium in the first cointegrating relationship.

Table 8. Loading Matrix (α)

	pUA	pHU	IMP_HU	EXP_HU
ΔpUA	-0.030	-0.006	-0.004	-0.0009
ΔpHU	-0.040	-0.026	-0.003	-0.0008
ΔIMP_HU	0.078	0.067	-0.011	-0.004
ΔEXP_HU	-0.002	-0.002	0.003	-0.004

The negative sign confirms the existence of a stable error-correction mechanism. It means that when the Ukrainian price is "too high" (above its long-run equilibrium value), it will adjust downwards in the next period (hour) to return to the equilibrium.

The magnitude (0.030) indicates that approximately 3% of any deviation from this long-run equilibrium is corrected by the Ukrainian price within the next hour.

5.4 Short-run VECM

The estimated short-run Vector Error Correction Model (VECM) was based on the optimal lag order p = 24. The results are provided in the Table 9.

The estimation used N=22964 valid observations. The model explains all the hour-to-hour moves, adjusted R^2 = 0.64, residual s.e. = 14.75.

The regression output details the short-run dynamics of the VECM for the change in DAM. The most critical finding is the validation of the long-run cointegrating relationship. The coefficient for the primary ECT_lag1_1 is highly statistically significant ($p < 2e-16$) and has the correct negative sign (-0.055). This provides strong evidence of a functioning error-correction mechanism, indicating that when the Ukrainian price deviates from the main long-run equilibrium, 5.5% of this disequilibrium is corrected within the subsequent hour. The other two error correction terms, ECT_lag1_2 and ECT_lag1_3, are also highly significant, demonstrating a complex adjustment process where the Ukrainian price simultaneously responds to all three identified long-run relationships.

Beyond the long-run adjustment, the model captures significant short-run dynamics. The lagged values of Ukrainian price changes are all highly significant, indicating strong autoregressive properties. Furthermore, numerous lags of Hungarian price changes, import changes, and export changes are also statistically significant, confirming that short-term shocks in the Hungarian market and fluctuations in cross-border trade have a direct and immediate impact on Ukrainian price formation.

The 24-hour lag and the 48-hour lag are both highly significant, validating the use of a 24-lag structure to capture daily cycles. This strong seasonality is further confirmed by the high significance of all and day-of-week dummy variables, which effectively model the pronounced intra-day price spikes and the systematic price differences across the week.

5.5 Serial correlation diagnostics

To check the serial correlation, I did two tests: Durbin-Watson and Breusch-Godfrey test for serial correlation of order up to 24.

Table 10. Durbin-Watson test

DW	p-value
2.027	0.476

Durbin–Watson (DW = 2.027, p = 0.476) does not reject the null hypothesis, so there is no first-order autocorrelation. This is good because there is no direct AR (1) in the residuals.

Table 11. Breusch-Godfrey test

LM test	p-value	df
421.84	< 2.2e-16	24

At the same time, Breusch–Godfrey reveals autocorrelation of higher orders (up to 24 lags). This is typical for hourly data and the residuals often contain daily rhythms that are not removed by the DW test. The point coefficients of the model can be interpreted, but the usual OLS standard errors are underestimated.

5.6 HAC (Newey–West) robust inference

For correct t-statistics and p-values, I use HAC (Newey–West).

The estimation results of the short-run equation for Ukraine using HAC (Newey–West) robust standard errors that are provided in Table 12 confirm that the model's structure and the significance of the main variables remained stable.

All lags of the changes in Ukrainian prices remained highly significant, indicating strong inertia in domestic price dynamics. The influence of Hungarian prices, as well as Hungary's import and export indicators, also remained significant and mostly negative, suggesting a short-term interdependence between the two markets.

The coefficient of the error correction term (ECT) is negative and statistically significant, which confirms the existence of a mechanism that restores the system to its long-run equilibrium.

All hourly and day-of-week dummy variables retained their significance, reflecting the seasonal nature of price fluctuations.

Overall, the HAC model results demonstrate high robustness of the estimates and confirm the reliability of the identified relationships.

6. CONCLUSIONS AND RECOMMENDATIONS

The VECM model was applied to hourly data for the period from 1 January 2023 to August 2025. The analysis focused on Hungary as a key neighbouring market, given its similarity to Ukraine in terms of generation structure.

The results of the Johansen cointegration test indicate that there are three long-term equilibrium relationships among the variables of interest: the price in Ukraine, the price in Hungary, the volume of imports from Hungary to Ukraine and the volume of exports from Ukraine to Hungary. This study provides solid empirical evidence that the Ukrainian market has become fully integrated into regional European Union markets. Therefore, the long-run dynamics of the price in Ukraine will likely be strongly influenced by regional EU market developments.

The assessment process using the vector error correction model (VECM) provided a statistically significant and correctly signed error correction term (ECT_lag1_1), showing that there's a working market arbitrage mechanism. In particular, the results show that approximately 5.5% of price deviations in Ukraine from its long-term equilibrium (determined by Hungarian prices and trade volumes) are corrected within one hour. Thus, the market reacts to deviations and adjusts the price to its long-term equilibrium.

The short-run dynamics analysis indicates that the hourly price changes in Ukraine are impacted by both long-run trend effects and by immediate shocks:

1. Price inertia: Hourly price changes in Ukraine showed a high level of stability due to a strong autoregressive effect, so previous hourly price changes had a statistically significant impact on the current hourly price.
2. Seasonality: As expected, the results showed that daily and weekly cycles play a major role in determining the hourly price. All hourly and daily variables showed very strong statistical significance and showed pronounced consumption peaks

during certain hours of the day and weeks, as well as price differences between these periods.

The study discovered a significant regulatory asymmetry. Ukraine has minimal price caps, but neighboring markets may face significant negative prices. The Ukrainian market is the most attractive destination for imports, when there is excess generation in the EU, and prices become negative due to the fact that the Ukrainian price can't fall below zero. The Ukrainian transmission system operator must manage this surplus and reduce domestic generation to maintain balance due to import pressure.

Based on these findings, some recommendations can be formulated for regulators, market participants and future research.

Given the proven high level of market integration and price convergence, further harmonisation of Ukrainian market rules with ENTSO-E rules is crucial. This applies in particular to the revision of price cap mechanisms to avoid regulatory arbitrage.

Regulators should conduct a detailed analysis of the impact of the minimum price. While it may protect traditional electricity generation, it also prevents the market from responding adequately to regional supply surpluses and attracts excessive imports during periods of negative prices in the EU. Consideration should be given to introducing demand response mechanisms or energy storage systems that could economically absorb this surplus and cheap electricity.

As trade volumes directly affect prices, further investment in cross-border interconnections is key to strengthening energy security and market efficiency.

The high importance of hourly cycles and the significant increase in price constraints during evening peak hours highlight the growing economic value of flexible assets – highly manoeuvrable energy production and storage systems capable of responding quickly to price fluctuations.

For future research, the work should expand the VECM to simultaneously include all neighbouring markets (Poland, Slovakia, Romania) to create a comprehensive regional pricing model.

Also, to improve the explanatory power of the model in the short term, future research could add fundamental variables: forecasts of renewable energy production (especially wind and solar), demand and supply.

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ЗАКОН УКРАЇНИ Про внесення змін до деяких законів України щодо удосконалення умов підтримки виробництва електричної енергії з альтернативних джерел енергії.
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APPENDIX

Table 9. Short-run ΔpUA equation (OLS) results

Variable	Estimate	Std. Error	t-value	p-value	Significance
(Intercept)	-7.359	0.806	-9.134	< 2e-16	***
d_pUA_L1	-0.183	0.008	-23.334	< 2e-16	***
d_pUA_L2	-0.191	0.008	-24.286	< 2e-16	***
d_pUA_L3	-0.187	0.008	-23.935	< 2e-16	***
d_pUA_L4	-0.214	0.008	-27.521	< 2e-16	***
d_pUA_L5	-0.203	0.008	-26.275	< 2e-16	***
d_pUA_L6	-0.204	0.008	-26.415	< 2e-16	***
d_pUA_L7	-0.218	0.008	-28.498	< 2e-16	***
d_pUA_L8	-0.208	0.008	-27.434	< 2e-16	***
d_pUA_L9	-0.199	0.008	-26.426	< 2e-16	***
d_pUA_L10	-0.205	0.007	-27.498	< 2e-16	***
d_pUA_L11	-0.199	0.007	-26.93	< 2e-16	***
d_pUA_L12	-0.191	0.007	-26.02	< 2e-16	***
d_pUA_L13	-0.194	0.007	-26.656	< 2e-16	***
d_pUA_L14	-0.207	0.007	-28.735	< 2e-16	***
d_pUA_L15	-0.19	0.007	-26.69	< 2e-16	***
d_pUA_L16	-0.207	0.007	-29.38	< 2e-16	***
d_pUA_L17	-0.21	0.007	-30.275	< 2e-16	***
d_pUA_L18	-0.201	0.007	-29.401	< 2e-16	***
d_pUA_L19	-0.177	0.007	-26.202	< 2e-16	***
d_pUA_L20	-0.196	0.007	-29.558	< 2e-16	***
d_pUA_L21	-0.175	0.007	-26.867	< 2e-16	***
d_pUA_L22	-0.161	0.006	-25.032	< 2e-16	***
d_pUA_L23	-0.126	0.006	-20.061	< 2e-16	***
d_pUA_L24	0.268	0.007	39.83	< 2e-16	***
d_pHU_L1	0.007	0.005	1.515	0.130	
d_pHU_L2	0.005	0.005	0.971	0.332	
d_pHU_L3	-0.01	0.005	-1.995	0.046	*
d_pHU_L4	-0.008	0.005	-1.634	0.102	
d_pHU_L5	-0.006	0.005	-1.261	0.207	

d_pHU_L6	0.002	0.005	0.494	0.621	
d_pHU_L7	-0.008	0.005	-1.705	0.088	.
d_pHU_L8	-0.012	0.005	-2.523	0.012	*
d_pHU_L9	0.003	0.005	0.588	0.556	
d_pHU_L10	-0.008	0.005	-1.766	0.077	.
d_pHU_L11	-0.007	0.005	-1.407	0.159	
d_pHU_L12	-0.014	0.005	-2.889	0.004	**
d_pHU_L13	-0.006	0.005	-1.171	0.242	
d_pHU_L14	-0.011	0.005	-2.33	0.020	*
d_pHU_L15	-0.013	0.005	-2.755	0.006	**
d_pHU_L16	-0.021	0.005	-4.534	5.82e-06	***
d_pHU_L17	-0.008	0.005	-1.743	0.081	.
d_pHU_L18	-0.017	0.004	-3.835	0.0001	***
d_pHU_L19	-0.014	0.004	-3.218	0.001	**
d_pHU_L20	-0.016	0.004	-3.67	0.0002	***
d_pHU_L21	0.006	0.004	1.396	0.163	
d_pHU_L22	-0.005	0.004	-1.1	0.271	
d_pHU_L23	-0.002	0.004	-0.574	0.567	
d_pHU_L24	-0.005	0.004	-1.112	0.266	
d_IMP_HU_L1	-0.006	0.002	-3.671	0.0002	***
d_IMP_HU_L2	-0.008	0.002	-4.924	8.56e-07	***
d_IMP_HU_L3	-0.006	0.002	-3.706	0.0002	***
d_IMP_HU_L4	-0.007	0.002	-4.226	2.39e-05	***
d_IMP_HU_L5	-0.004	0.002	-2.328	0.020	*
d_IMP_HU_L6	-0.009	0.002	-5.221	1.79e-07	***
d_IMP_HU_L7	-0.009	0.002	-5.334	9.71e-08	***
d_IMP_HU_L8	-0.005	0.002	-3.045	0.002	**
d_IMP_HU_L9	-0.002	0.002	-1.415	0.157	
d_IMP_HU_L10	-0.005	0.002	-3.149	0.002	**
d_IMP_HU_L11	-0.004	0.002	-2.28	0.023	*
d_IMP_HU_L12	-0.002	0.002	-1.334	0.182	
d_IMP_HU_L13	-0.005	0.002	-2.779	0.005	**
d_IMP_HU_L14	-0.007	0.002	-3.94	8.19e-05	***
d_IMP_HU_L15	-0.003	0.002	-1.727	0.084	.
d_IMP_HU_L16	-0.006	0.002	-3.788	0.0001	***
d_IMP_HU_L17	-0.008	0.002	-4.94	7.86e-07	***
d_IMP_HU_L18	-0.007	0.002	-4.534	5.80e-06	***
d_IMP_HU_L19	-0.007	0.002	-4.299	1.72e-05	***

d_IMP_HU_L20	-0.007	0.002	-4.37	1.25e-05	***
d_IMP_HU_L21	-0.006	0.002	-4.084	4.45e-05	***
d_IMP_HU_L22	-0.004	0.002	-2.87	0.004	**
d_IMP_HU_L23	-0.004	0.002	-2.434	0.015	*
d_IMP_HU_L24	-0.003	0.002	-1.94	0.052	.
d_EXP_HU_L1	-0.016	0.004	-3.673	0.0002	***
d_EXP_HU_L2	-0.018	0.004	-4.271	1.96e-05	***
d_EXP_HU_L3	-0.008	0.004	-1.835	0.066	.
d_EXP_HU_L4	-0.008	0.004	-1.734	0.083	.
d_EXP_HU_L5	-0.013	0.004	-3.066	0.002	**
d_EXP_HU_L6	-0.017	0.004	-3.923	8.78e-05	***
d_EXP_HU_L7	-0.011	0.004	-2.451	0.014	*
d_EXP_HU_L8	-0.016	0.004	-3.487	0.0005	***
d_EXP_HU_L9	-0.012	0.005	-2.648	0.008	**
d_EXP_HU_L10	-0.011	0.005	-2.337	0.019	*
d_EXP_HU_L11	-0.017	0.005	-3.66	0.0003	***
d_EXP_HU_L12	-0.01	0.005	-2.236	0.025	*
d_EXP_HU_L13	-0.022	0.005	-4.82	1.44e-06	***
d_EXP_HU_L14	-0.017	0.005	-3.688	0.0002	***
d_EXP_HU_L15	-0.014	0.004	-3.094	0.002	**
d_EXP_HU_L16	-0.018	0.004	-4.045	5.25e-05	***
d_EXP_HU_L17	-0.008	0.004	-1.692	0.091	.
d_EXP_HU_L18	0.002	0.004	0.38	0.704	
d_EXP_HU_L19	-0.001	0.004	-0.13	0.896	
d_EXP_HU_L20	-0.003	0.004	-0.619	0.536	
d_EXP_HU_L21	-0.007	0.004	-1.555	0.120	
d_EXP_HU_L22	0.008	0.004	1.842	0.066	.
d_EXP_HU_L23	-0.013	0.004	-3.059	0.002	**
d_EXP_HU_L24	-0.008	0.004	-1.909	0.056	.
d_pUA_L48	0.158	0.006	25.82	< 2e-16	***
d_pHU_L48	0.003	0.004	0.645	0.519	
d_IMP_HU_L48	0	0.001	0.2	0.841	
d_EXP_HU_L48	0.015	0.004	3.832	0.0001	***
ECT_lag1_1	-0.055	0.005	-10.583	< 2e-16	***
ECT_lag1_2	0.016	0.003	5.506	3.71e-08	***
ECT_lag1_3	0.004	0.001	5.483	4.22e-08	***
hour_f0	11.324	0.806	14.049	< 2e-16	***
hour_f1	12.417	0.876	14.17	< 2e-16	***

hour_f2	10.254	0.91	11.273	< 2e-16	***
hour_f3	9.09	0.935	9.722	< 2e-16	***
hour_f4	9.741	0.954	10.206	< 2e-16	***
hour_f5	10.941	0.986	11.095	< 2e-16	***
hour_f6	10.996	0.969	11.344	< 2e-16	***
hour_f7	23.99	0.989	24.138	< 2e-16	***
hour_f8	16.005	0.93	17.209	< 2e-16	***
hour_f9	12.961	0.878	14.765	< 2e-16	***
hour_f10	9.746	0.855	11.401	< 2e-16	***
hour_f11	9.087	0.833	10.904	< 2e-16	***
hour_f12	11.145	0.86	12.954	< 2e-16	***
hour_f13	12.061	0.883	13.653	< 2e-16	***
hour_f14	13.094	0.931	14.065	< 2e-16	***
hour_f15	12.1	0.973	12.434	< 2e-16	***
hour_f16	13.138	0.969	13.558	< 2e-16	***
hour_f17	23.06	0.995	23.174	< 2e-16	***
hour_f18	17.311	0.953	18.172	< 2e-16	***
hour_f19	17.217	0.934	18.427	< 2e-16	***
hour_f20	15.856	0.908	17.467	< 2e-16	***
hour_f21	18.109	0.871	20.797	< 2e-16	***
hour_f22	17.257	0.803	21.486	< 2e-16	***
hour_f23	NA	NA	NA	NA	
dow_f2	-2.381	0.383	-6.223	4.96e-10	***
dow_f3	-2.62	0.384	-6.82	9.33e-12	***
dow_f4	-2.749	0.387	-7.106	1.23e-12	***
dow_f5	-3.218	0.391	-8.228	< 2e-16	***
dow_f6	-4.073	0.399	-10.214	< 2e-16	***
dow_f7	-4.112	0.393	-10.471	< 2e-16	***
Signif. codes	'***' 0.001	'**' 0.01	'*' 0.05	'.' 0.1	
Residual standard error: 14.75 on 22964 degrees of freedom					
Multiple R-squared: 0.674, Adjusted R-squared: 0.672					
F-statistic: 359.2 on 132 and 22964 DF, p-value: < 2.2e-16					

Table 12. HAC (Newey–West) results

Variable	Estimate	Std. Error	t-value	p-value	Significance
(Intercept)	-7.359	0.895	-8.227	< 2.2e-16	***
d_pUA_L1	-0.183	0.011	-17.113	< 2.2e-16	***
d_pUA_L2	-0.191	0.010	-18.187	< 2.2e-16	***
d_pUA_L3	-0.187	0.010	-18.869	< 2.2e-16	***
d_pUA_L4	-0.214	0.010	-21.525	< 2.2e-16	***
d_pUA_L5	-0.203	0.010	-20.949	< 2.2e-16	***
d_pUA_L6	-0.204	0.010	-20.291	< 2.2e-16	***
d_pUA_L7	-0.218	0.010	-21.206	< 2.2e-16	***
d_pUA_L8	-0.208	0.010	-20.931	< 2.2e-16	***
d_pUA_L9	-0.199	0.010	-20.126	< 2.2e-16	***
d_pUA_L10	-0.205	0.010	-20.728	< 2.2e-16	***
d_pUA_L11	-0.199	0.010	-20.323	< 2.2e-16	***
d_pUA_L12	-0.191	0.010	-19.281	< 2.2e-16	***
d_pUA_L13	-0.194	0.010	-20.224	< 2.2e-16	***
d_pUA_L14	-0.207	0.010	-21.699	< 2.2e-16	***
d_pUA_L15	-0.190	0.010	-19.314	< 2.2e-16	***
d_pUA_L16	-0.207	0.010	-21.419	< 2.2e-16	***
d_pUA_L17	-0.210	0.010	-20.846	< 2.2e-16	***
d_pUA_L18	-0.201	0.010	-21.075	< 2.2e-16	***
d_pUA_L19	-0.177	0.010	-18.598	< 2.2e-16	***
d_pUA_L20	-0.196	0.009	-21.654	< 2.2e-16	***
d_pUA_L21	-0.175	0.009	-19.323	< 2.2e-16	***
d_pUA_L22	-0.161	0.009	-18.065	< 2.2e-16	***
d_pUA_L23	-0.126	0.010	-12.801	< 2.2e-16	***
d_pUA_L24	0.268	0.012	21.785	< 2.2e-16	***
d_pHU_L1	0.007	0.004	1.725	0.084	.
d_pHU_L2	-0.005	0.005	-1.042	0.297	
d_pHU_L3	-0.010	0.005	-1.936	0.053	.
d_pHU_L4	-0.008	0.005	-1.707	0.088	.
d_pHU_L5	-0.006	0.005	-1.258	0.208	
d_pHU_L6	0.002	0.005	0.507	0.612	
d_pHU_L7	-0.008	0.005	-1.772	0.076	.
d_pHU_L8	-0.012	0.005	-2.621	0.009	**
d_pHU_L9	-0.003	0.005	-0.576	0.564	
d_pHU_L10	-0.008	0.005	-1.596	0.110	

d_pHU_L11	-0.007	0.005	-1.345	0.179	
d_pHU_L12	-0.014	0.005	-2.747	0.006	**
d_pHU_L13	-0.006	0.006	-0.964	0.335	
d_pHU_L14	-0.011	0.005	-2.113	0.035	*
d_pHU_L15	-0.013	0.005	-2.505	0.012	*
d_pHU_L16	-0.021	0.005	-4.343	0.000	***
d_pHU_L17	-0.008	0.005	-1.584	0.113	
d_pHU_L18	-0.017	0.005	-3.392	0.001	***
d_pHU_L19	-0.014	0.005	-3.004	0.003	**
d_pHU_L20	-0.016	0.005	-3.347	0.001	***
d_pHU_L21	0.006	0.004	1.434	0.152	
d_pHU_L22	-0.005	0.004	-1.291	0.197	
d_pHU_L23	-0.002	0.003	-0.709	0.478	
d_pHU_L24	0.005	0.004	1.227	0.220	
d_IMP_HU_L1	-0.006	0.002	-3.459	0.001	***
d_IMP_HU_L2	-0.008	0.002	-4.708	0.000	***
d_IMP_HU_L3	-0.006	0.002	-3.498	0.000	***
d_IMP_HU_L4	-0.007	0.002	-4.120	0.000	***
d_IMP_HU_L5	-0.004	0.002	-2.068	0.039	*
d_IMP_HU_L6	-0.009	0.002	-4.562	0.000	***
d_IMP_HU_L7	-0.009	0.002	-4.776	0.000	***
d_IMP_HU_L8	-0.005	0.002	-2.713	0.007	**
d_IMP_HU_L9	-0.002	0.002	-1.267	0.205	
d_IMP_HU_L10	-0.005	0.002	-2.647	0.008	**
d_IMP_HU_L11	-0.004	0.002	-2.022	0.043	*
d_IMP_HU_L12	-0.002	0.002	-1.184	0.237	
d_IMP_HU_L13	-0.005	0.002	-2.361	0.018	*
d_IMP_HU_L14	-0.007	0.002	-3.343	0.001	***
d_IMP_HU_L15	-0.003	0.002	-1.481	0.139	
d_IMP_HU_L16	-0.006	0.002	-3.236	0.001	**
d_IMP_HU_L17	-0.008	0.002	-4.304	0.000	***
d_IMP_HU_L18	-0.007	0.002	-4.117	0.000	***
d_IMP_HU_L19	-0.007	0.002	-3.751	0.000	***
d_IMP_HU_L20	-0.007	0.002	-3.953	0.000	***
d_IMP_HU_L21	-0.006	0.002	-3.682	0.000	***
d_IMP_HU_L22	-0.004	0.002	-2.645	0.008	**
d_IMP_HU_L23	-0.004	0.002	-2.277	0.023	*

d_IMP_HU_L24	-0.003	0.002	-1.780	0.075	.
d_EXP_HU_L1	-0.016	0.005	-3.228	0.001	**
d_EXP_HU_L2	-0.018	0.004	-4.057	0.000	***
d_EXP_HU_L3	-0.008	0.005	-1.717	0.086	.
d_EXP_HU_L4	-0.008	0.005	-1.653	0.098	.
d_EXP_HU_L5	-0.013	0.005	-2.746	0.006	**
d_EXP_HU_L6	-0.017	0.006	-2.911	0.004	**
d_EXP_HU_L7	-0.011	0.005	-2.018	0.044	*
d_EXP_HU_L8	-0.016	0.005	-2.980	0.003	**
d_EXP_HU_L9	-0.012	0.005	-2.266	0.023	*
d_EXP_HU_L10	-0.011	0.005	-1.967	0.049	*
d_EXP_HU_L11	-0.017	0.005	-3.286	0.001	**
d_EXP_HU_L12	-0.010	0.005	-2.123	0.034	*
d_EXP_HU_L13	-0.022	0.005	-4.585	0.000	***
d_EXP_HU_L14	-0.017	0.005	-3.405	0.001	***
d_EXP_HU_L15	-0.014	0.005	-2.626	0.009	**
d_EXP_HU_L16	-0.018	0.005	-3.572	0.000	***
d_EXP_HU_L17	-0.008	0.006	-1.346	0.178	
d_EXP_HU_L18	0.002	0.005	0.347	0.729	
d_EXP_HU_L19	-0.001	0.005	-0.117	0.907	
d_EXP_HU_L20	-0.003	0.005	-0.533	0.594	
d_EXP_HU_L21	-0.007	0.005	-1.386	0.166	
d_EXP_HU_L22	0.008	0.006	1.226	0.220	
d_EXP_HU_L23	-0.013	0.005	-2.574	0.010	*
d_EXP_HU_L24	-0.008	0.005	-1.650	0.099	.
d_pUA_L48	0.158	0.011	14.495	< 2.2e-16	***
d_pHU_L48	0.003	0.004	0.680	0.497	
d_IMP_HU_L48	0.000	0.002	0.189	0.850	
d_EXP_HU_L48	0.015	0.005	2.937	0.003	**
ECT_lag1_1	-0.055	0.005	-10.169	< 2.2e-16	***
ECT_lag1_2	0.016	0.003	5.670	0.000	***
ECT_lag1_3	0.004	0.001	4.498	0.000	***
hour_f0	11.324	0.922	12.279	< 2.2e-16	***
hour_f1	12.417	0.908	13.675	< 2.2e-16	***
hour_f2	10.254	0.928	11.048	< 2.2e-16	***
hour_f3	9.090	0.916	9.924	< 2.2e-16	***
hour_f4	9.741	0.927	10.513	< 2.2e-16	***

hour_f5	10.941	0.995	10.992	< 2.2e-16	***
hour_f6	10.996	1.012	10.867	< 2.2e-16	***
hour_f7	23.891	1.199	19.925	< 2.2e-16	***
hour_f8	16.005	1.037	15.433	< 2.2e-16	***
hour_f9	12.961	0.990	13.091	< 2.2e-16	***
hour_f10	9.746	0.969	10.060	< 2.2e-16	***
hour_f11	9.087	0.917	9.915	< 2.2e-16	***
hour_f12	11.145	0.883	12.621	< 2.2e-16	***
hour_f13	12.061	0.901	13.388	< 2.2e-16	***
hour_f14	13.094	0.960	13.636	< 2.2e-16	***
hour_f15	12.100	1.024	11.820	< 2.2e-16	***
hour_f16	13.138	1.051	12.506	< 2.2e-16	***
hour_f17	23.060	1.198	19.256	< 2.2e-16	***
hour_f18	17.311	1.066	16.233	< 2.2e-16	***
hour_f19	17.217	0.992	17.356	< 2.2e-16	***
hour_f20	15.856	0.908	17.457	< 2.2e-16	***
hour_f21	18.109	0.924	19.595	< 2.2e-16	***
hour_f22	17.257	1.056	16.348	< 2.2e-16	***
dow_f2	-2.381	0.398	-5.974	0.000	***
dow_f3	-2.620	0.393	-6.660	0.000	***
dow_f4	-2.749	0.400	-6.869	0.000	***
dow_f5	-3.218	0.400	-8.046	0.000	***
dow_f6	-4.073	0.441	-9.232	< 2.2e-16	***
dow_f7	-4.112	0.437	-9.419	< 2.2e-16	***
Signif. codes	'***' 0.001	'**' 0.01	'*' 0.05	'.' 0.1	