Electricity price convergence in Europe: geographical versus generation structure proximity

Monika Papież[1], Michał Rubaszek[2], Sławomir Śmiech[1], Kornelia Kłopecka[1], Dawid Bonar[1]

[1]Krakow University of Economics
[2]SGH Warsaw School of Economics

11 December

Energy Finance Christmas Workshop (EFC25)

This research was financed by the National Science Centre (NCN) in Poland, grant no. 2023/51/B/HS4/01182.

Agenda

Motivation

1. The Single European Act of 1986, EU Directives No. 96/92/EC, 2003/54/EC, 2009/72/EC, and 2019/944/EC.
2. The integration of the European electricity market is an important issue for at least three reasons:
   - energy security,
   - the environment,
   - costs.
3. The electricity market is still far from complete integration.

Literature review

Authors	Area, Time period, Data type	Methodology	Conclusions
Telatar i Yaşar (2020)	EU; annual prices; 2003–2017	Beta and sigma convergence	No convergence
Cassetta et al. (2022a)	EU; annual prices; 2008–2018 (households, industry)	Beta and sigma convergence	Weak beta convergence, no sigma convergence
Casetta et al. (2022b)	EU; annual prices; 2008–2021 (households, industry)	Club convergence	Existence of multiple convergence clubs
Bhattacharya et al. (2023)	Europe; annual prices; 1995–2019	Club convergence	Existence of multiple convergence clubs
Gugler et al. (2018)	Europe; hourly spot prices; 2010–2015	Cointegration, ECM	Limited convergence
Du and Lai (2017)	4 countries (DE, FR, AT, CH); daily day-ahead prices; 2006–2014	Coupula models	Strong price linkages
Kartepe (2024)	Europe; monthly spot prices; 2013–2021	Stationary tests with structural breaks	Limited convergence

Literature review

Authors	Area, Time period, Data type	Methodology	Conclusions
Bunn i Gianfreda (2010)	5 countries (DE, FR, NE, ES, UK); 2001–2005	Cointegration	Convergence depends on the capacity of interconnections, and to a lesser extent on geographical proximity
De Menezes and Houllier (2016)	Europe: 9 spot markets, 4 futures; 2000–2013	Fraction integration	Cross-border interconnections and geographical distance are important for price integration
Montoya et al.a (2020)	UK, NE, FR; 2013–2018	Authorship indicators	Convergence depends on coupling and the capacity of interconnections
Hirth (2018)	DE, SE; 2008–2015	Structural model	The increase in renewable energy lowers wholesale prices
Chen et al. (2021)	26 European countries; 2020	Cluster analysis	Similarity of energy mix reduces price differences
De Menezes et al. (2016)	UK, FR, Nordpool; 2005–2013	Cointegration	Rising CO_2 emission costs increase price differences; gas promotes price interdependence

Research Objective

- The objective of this study is to identify the factors that influence the convergence of electricity prices in Europe, with particular attention to geographic and structural aspects.

Contribution to the Literature

1. Comparison of two key dimensions of electricity price convergence: geographical proximity and structural similarity.
2. Applying Random Forest Models.
3. Division into two subperiods:
   - 2016–2019
   - 2020–2024
4. Analysis of determinants divided into five categories (Transmission capacity, Electricity generation structure, Political factors, Electricity system size, and Geographical factors).

Data

- 23 European countries: Austria (AT), Belgium (BE), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Italy (IT), Latvia (LV), Lithuania (LT), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH).
- Time period: 01/01/2016 – 31/12/2024
- Division into two subperiods:
  1. 01/01/2016 – 31/12/2019
  2. 01/01/2020 – 31/12/2024
- Hourly day-ahead electricity prices (€/MWh) obtained from Ember [1]

[1] https://ember-energy.org/data/european-wholesale-electricity-price-data/

Methodology - Convergence indicator

$$CI_{1_{i,j}} = \frac{1}{T}\sum_{t=1}^{T} I\left(\frac{|P_{i,t} - P_{j,t}|}{\frac{|P_{i,t}|+|P_{j,t}|}{2}} \leq 0.02\right)$$

- T is the number of hours
- $P_{i,t}$ and $P_{j,t}$ are the hourly day-ahead electricity prices (€/MWh) in countries i and j at time t.
- $I(\cdot)$ takes the value 1 if the relative price difference is $\leq 2\%$, and 0 otherwise.

Methodology - Convergence determinants (1/3)

Variable symbol	Description of the variable	Data source
	Transmission capacity	ENTSO-E / Ember Energy
EXP_I	$\text{EXP\_I} = \frac{1}{M}\sum_{m=1}^{M}\frac{\text{EXP}_{i,m}+\text{EXP}_{j.m}}{I_{i,m}+I_{j.m}}$	
I_GEN	$I_{\text{GEN}} = \frac{1}{M}\sum_{m=1}^{M}\frac{(I_{i,m}+I_{j,m})\cdot 24\cdot\frac{365}{12}}{(GEN_{i,m}+GEN_{j,m})\cdot 10^6}$	
	Electricity generation structure	Ember Energy
HHI	$HHI = HHI_F + HHI_N + HHI_H + HHI_R$	
HHI_F	$HHI_F = \frac{1}{M}\sum_{m=1}^{M}\lvert Fossil_{i,m} - Fossil_{j,m}\rvert^2$	
HHI_N	$HHI_N = \frac{1}{M}\sum_{m=1}^{M}\lvert Nuclear_{i,m} - Nuclear_{j,m}\rvert^2$	
HHI_H	$HHI_H = \frac{1}{M}\sum_{m=1}^{M}\lvert Hydro_{i,m} - Hydro_{j,m}\rvert^2$	
HHI_R	$HHI_R = \frac{1}{M}\sum_{m=1}^{M}\lvert RES_{i,m} - RES_{j,m}\rvert^2$	

Methodology - Convergence determinants (2/3)

	Political factors	Ember Energy
CO2_d	$CO2_d = \frac{1}{M}\sum_{m=1}^{M} \lvert CO2_{i,m} - CO2_{j,m} \rvert$	
CO2_s	$CO2_s = \frac{1}{M}\sum_{m=1}^{M} (CO2_{i,m} + CO2_{j,m})$	
CO2_BC	$CO2_{BC} = \frac{CO2_d}{CO2_s}$	
	Electricity system size	Ember Energy
GEN_d	$GEN_d = \frac{1}{M}\sum_{m=1}^{M} \lvert GEN_{i,m} - GEN_{j,m} \rvert$	
GEN_s	$GEN_s = \frac{1}{M}\sum_{m=1}^{M} (GEN_{i,m} + GEN_{j,m})$	
GEN_BC	$GEN_{BC} = \frac{GEN_d}{GEN_s}$	

Methodology - Convergence determinants (3/3)

	Geographical factors	European Commission
CWE	Both countries are in Central Western Europe (AT, BE, CH, DE, FR, NL)	
CEE	Both countries are in Central Eastern Europe (CZ, HU, PL, RO, SI, SK)	
NORD	Both countries are in Northern Europe (DK, EE, FI, LT, LV, NO, SE)	
CWE_CEE	One country is in CWE, the other in CEE	
CWE_NORD	One country is in CWE, the other in NORD	
CEE_NORD	One country is in CEE, the other in NORD	

Random Forest

- Ensemble algorithm combining multiple decision trees.
- Reduces variance and the risk of overfitting.
- Parameter optimization:
  - number of trees,
  - tree depth,
  - number of randomly selected variables at each split,
  - minimum node size.

Random Forest - MDA and SHAP

1. Mean Decrease Accuracy (MDA)
    - Measure variable importance in the model.
    - Evaluates how accuracy decreases when a given variable is permuted.
    - The greater the decrease in accuracy, the more important the variable.
2. SHAP values
    - Explains the contribution of each variable to the model prediction.
    - Based on game theory (Shapley values).
    - Allows us to understand not only which variable matters, but also how it affects the outcome.

Density plot of Convergence Indicator

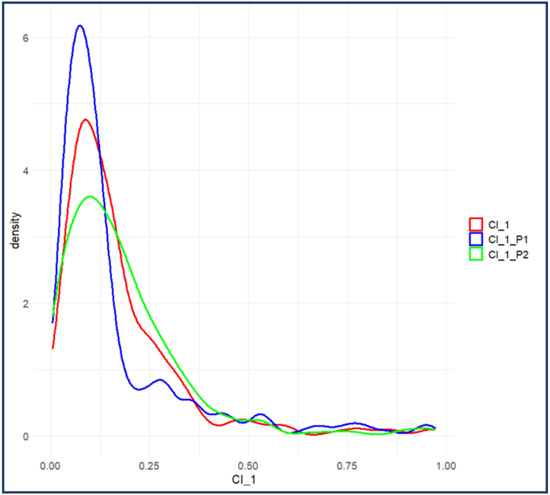

Figure: Density plot of CI_1 *measure*

Corrplot

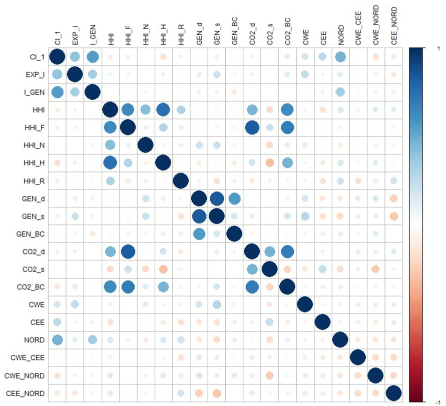

Figure: Correlation analysis between the determinants of electricity price convergence and the convergence indicator (CI_1): 2016–2024.

Importance and SHAP values: 2016–2024

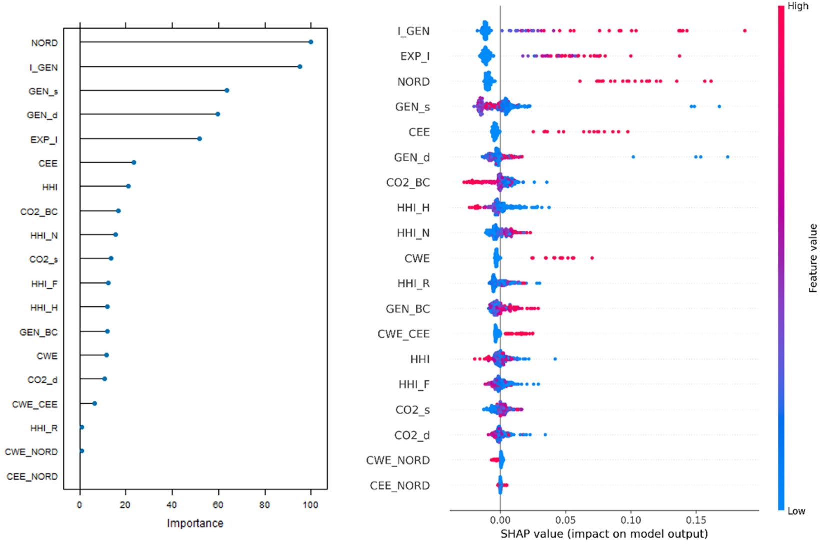

Figure: Importance plot and SHAP values: 2016–2024.

Sub-periods importance

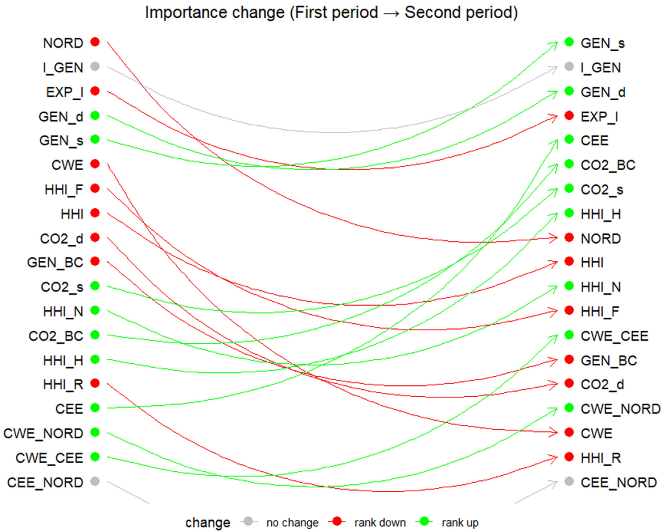

Figure: Comparison of changes in the importance of determinants between the first and second sub-period for the CI_1 measure.

Summary

- Cross-border infrastructure – transmission capacity remains a key factor supporting market integration, both in times of stability and during crises (COVID-19, gas crisis, war in Ukraine).
- Regional nature of convergence – electricity prices converge mainly within regions (Northern and Central-Eastern Europe), while interregional integration plays a much smaller role.
- Importance of system size – smaller countries, more strongly linked with larger partners, are more prone to price synchronization, whereas large markets remain relatively self-sufficient and less integrated.
- Environmental factors – since 2020, CO_2 emissions have become increasingly important; Similar emission intensity supports convergence, while rising emission costs may deepen the differences between low- and high-emission systems.
- Energy mix – similarities in hydropower and fossil fuels foster convergence, while differences in the share of renewable energy and nuclear energy can also stimulate integration.
- Changing importance of determinants over time – in 2016–2019, infrastructure and regional factors dominated, while in 2020-2024 structural differences (system size, emissions, mix concentration) played a greater role. This indicates that price convergence in the EU is neither linear nor uniform, but depends on crises and structural conditions.

Policy implication

- Priority for cross-border infrastructure – development and modernization of cross-border connections as a key condition for price convergence during periods of stability and crises.
- Strengthening regional cooperation – deepening integration within existing initiatives (NORD Pool, 4M, CEE) as a transitional step toward full market integration; the CEE region as a strategic 'bridge' between east and west.
- Support for smaller systems – investments in infrastructure, access to shared trading platforms, and ensuring active cross-border cooperation from larger markets.
- Coordination of climate and energy policy – harmonization of decarbonization pathways and integration of CO costs in market mechanisms, including joint investments in renewable energy sources (RES).
- Diversification of the energy mix – promoting diverse sources, especially renewable energy and nuclear energy, to increase resilience and foster market integration.
- Regulatory flexibility – adapting policy to changing technological, environmental, and geopolitical conditions through mechanisms that allow rapid responses.

Bibliography

- Bhattacharya, M., Inekwe, J. N., Liddle, B. (2023). The role of renewable energy sources in residential electricity prices: A club convergence analysis across selected European countries. Applied Economics, 55(44), 5157–5171. https://doi.org/10.1080/00036846.2022.2137294
- Bunn, D. W., Gianfreda, A. (2010). Integration and shock transmissions across European electricity forward markets. Energy Economics, 32(2), 278–291. https://doi.org/10.1016/j.eneco.2009.09.005
- Cassetta, E., Nava, C. R., Zoia, M. G. (2022a). A three-step procedure to investigate the convergence of electricity and natural gas prices in the European Union. Energy Economics, 105, 105697. https://doi.org/10.1016/j.eneco.2021.105697
- Cassetta, E., Nava, C. R., Zoia, M. G. (2022b). EU electricity market integration and cross-country convergence in residential and industrial end-user prices. Energy Policy, 165, 112934. https://doi.org/10.1016/j.enpol.2022.112934
- Chen, Q., Balian, A., Kyzym, M., Salashenko, T., Gryshova, I., Khaustova, V. (2021). Electricity markets instability: Causes of price dispersion. Sustainability (Switzerland), 13(22). https://doi.org/10.3390/su132212343
- de Menezes, L. M., Houllier, M. A. (2016). Reassessing the integration of European electricity markets: A fractional cointegration analysis. Energy Economics, 53, 132–150. https://doi.org/10.1016/j.eneco.2014.10.021
- de Menezes, L. M., Houllier, M. A., Tamvakis, M. (2016). Time-varying convergence in European electricity spot markets and their association with carbon and fuel prices. Energy Policy, 88, 613–627. https://doi.org/10.1016/j.enpol.2015.09.008
- Du, J., Lai, K. K. (2017). Modeling Dependence between European Electricity Markets with Constant and Time-varying Copulas. Procedia Computer Science, 122, 94–101. https://doi.org/10.1016/J.PROCS.2017.11.346
- Gugler, K., Haxhimusa, A., Liebensteiner, M. (2018). Integration of European Electricity Markets: Evidence from Spot Prices. The Energy Journal, 39(2suppl), 41–66. https://doi.org/10.5547/01956574.39.SI2.kgug
- Hirth, L. (2018). What Caused the Drop in European Electricity Prices? A Factor Decomposition Analysis. The Energy Journal, 39(1), 143–158. https://doi.org/10.5547/01956574.39.1.lhir
- IMF. (2025). Integrating the EU Energy Market to Foster Growth and Resilience. https://www.imf.org/en/News/Articles/2025/01/13/sp-integrating-the-eu-energy-market-to-foster-growth-and-resilience
- Karatepe, S. (2024). Convergence of wholesale electricity prices across European markets: are we there yet? Toplum Ekonomi ve Yönetim Dergisi, 5(1), 1–14. https://doi.org/10.58702/teyd.1357334
- Montoya, L. G., Guo, B., Newbery, D., Dodds, P. E., Lipman, G., Castagneto Gissey, G. (2020). Measuring inefficiency in international electricity trading. Energy Policy, 143. https://doi.org/10.1016/j.enpol.2020.111521
- Telatar, M. E., Yaşar, N. (2020). The Convergence of Electricity Prices for European Union Countries. In Regulations in the Energy Industry (pp. 55–63). Springer International Publishing. https://doi.org/10.1007/978-3-030-32296-04