

Three Speeds of the Renewable Transition: Sectoral Asymmetry in EU-27 Renewable Energy Shares, 2004–2024*

Arkadiusz WEREMCZUK¹ and Mariusz GRĘBOWIEC²

¹Department Economics and Economic Policy, Warsaw University of Life Sciences, Warsaw, Poland,
<https://orcid.org/0000-0002-6839-8508>

²Department of Development and Marketing Policy, Warsaw University of Life Sciences, Warsaw, Poland,
<https://orcid.org/0000-0002-2631-3940>

Correspondence should be addressed to: Arkadiusz WEREMCZUK, arkadiusz_weremczuk@sggw.edu.pl

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Abstract

Has the renewable transition in the EU-27 advanced evenly across all final energy uses, or has it relied on one channel of decarbonisation more than others? Drawing on harmonised EUROSTAT SHARES statistics for a balanced panel of 27 Member States over 2004–2024 (567 country-year observations per sector), we compare renewable shares in electricity, transport, and heating and cooling at the level of the weighted EU-27 aggregate, the unweighted cross-country distribution, and the sectoral mix within each country, using five dispersion measures to distinguish relative from absolute heterogeneity. All three sectors progressed, but in different ways: electricity led the expansion (15.871% in 2004 to 47.500% in 2024 at the EU-27 aggregate), heating and cooling grew steadily (11.735% to 26.697%), and transport remained the binding constraint (1.432% to 11.204%). Proportional dispersion fell in every sector, yet absolute gaps widened: the frontier-laggard gap grew from 61.627 to 79.410 percentage points (pp) in electricity, from 6.288 to 25.463 pp in transport, and from 44.894 to 59.915 pp in heating and cooling, while the mean within-country gap between the strongest and weakest sector nearly doubled, from 19.753 to 38.898 pp. The EU transition has shared a direction without sharing a sectoral pattern, which matters for how aggregate success in renewable deployment is interpreted.

Keywords: European Green Deal; RED II; sectoral renewable shares; renewable electricity; renewable heating and cooling; renewable transport; EU-27 energy transition

Introduction

Two decades of ambitious regulation have reshaped Europe's energy system. The first Renewable Energy Directive, its recast as Directive (EU) 2018/2001 (RED II), and the European Green Deal, with its 55% emission-reduction target for 2030 and climate-neutrality goal for 2050, have locked renewable deployment into binding Union-wide rules (Bórawski et al., 2022; Hoicka et al., 2021; Nagaj et al., 2024; Pietzcker et al., 2021). The targets are common, but the routes are not: Member States have advanced along visibly uneven trajectories, raising the question of whether the transition is a coordinated common front or a process differentiated by sector and geography (Manowska et al., 2024; Perez et al., 2019; Renou-Maissant et al., 2022). Most econometric evidence approaches this question through aggregate convergence in the renewable share of gross final energy consumption. Work using β -, σ - and stochastic convergence typically finds catch-up by low-share countries and falling cross-sectional dispersion in log-shares (Berk et al., 2020; Butnaru et al., 2020; Jankiewicz, 2021; Maza et al., 2010). Club-convergence studies complicate this picture, rejecting a single steady state for the EU-28 and EU-15 and identifying several clubs with distinct long-run shares, tied to income, energy dependence and historical energy mixes (Kasman & Kasman, 2019; Popescu & Covrig, 2023; Presno & Landajo, 2021; Saba & Ngepah,

2022). This coexistence of proportional homogenisation and persistent stratification in levels has rarely been examined sector by sector. The sectoral architecture has received much less attention, even though electricity, heating and cooling, and transport have clearly followed different paths (Kacperska et al., 2021; Matuszewska-Janica et al., 2021). Renewable electricity has been the most dynamic of the three: mature wind and solar, support schemes such as feed-in tariffs, premiums and auctions, and grid investment pushed renewables past fossil fuels in EU power generation around 2020 (Arántegui & Jäger-Waldau, 2017; Bölük & Kaplan, 2021; Dolge & Blumberga, 2023; Domhnaill & Ryan, 2020; Halkos & Tsirivis, 2023; Scarlat et al., 2022; Shivakumar et al., 2019; Yu et al., 2021). Renewable heating and cooling has grown less spectacularly but remains structurally embedded where biomass and district heating are well established, as in Sweden, Latvia and Finland (Bertelsen & Mathiesen, 2020; Cansino et al., 2011; Connolly et al., 2014). Across much of Western Europe it is held back by building-stock inertia, slow equipment turnover and persistent fossil-fuel boilers (Abbasi et al., 2021; Maduta et al., 2023; Salim et al., 2024; Thomaßen et al., 2020), and RED accounting may favour inefficient biomass devices over efficient heat pumps (Braungardt et al., 2019; Fernandes et al., 2025; Rosenow et al., 2025). Transport is the bottleneck: it is the only major sector whose emissions remain above 1990 levels, and most Member States missed the 10% RES-T target under the first directive (Dolge et al., 2023; Haas & Sander, 2020; Nasiri et al., 2022). Thin charging and hydrogen networks, high technology costs, fragmented governance and uncertainty over biofuels, particularly indirect land-use change, all play a role (Ajanovic & Haas, 2021; Biresselioglu et al., 2018; D'Adamo et al., 2020; Mai-Moulin et al., 2021). RED II raised the transport sub-target to 14% by 2030, capped crop-based biofuels and prioritised advanced biofuels and electrification (Prussi et al., 2019; Skov & Schneider, 2022), but ambition still outruns delivery (Falanga et al., 2025; Milek et al., 2022). A parallel literature explains the cross-country spread through structural factors. The starting energy mix matters, as countries without domestic fossil reserves expand renewables faster (Papież et al., 2018), and so do income, investment intensity and financial development (Marra & Colantonio, 2022; Silva et al., 2023; Török & László, 2025; Tu et al., 2022). Institutions count as well: stable demand-pull policy speeds deployment, whereas fossil-fuel lobbying and fragmented governance slow it (Kitzing et al., 2012; Wang et al., 2024). A recurring paradox is that deployment converges while R&D and patenting concentrate in a few leader states (Grafström, 2018; Grafström et al., 2020; Kijek et al., 2021). Four gaps emerge. Convergence research has mostly stayed at the aggregate level, so it is unclear whether Union-level patterns hold within each sector. Much of the evidence stops around 2020, leaving the post-RED II and early Green Deal years largely unexamined. The 2021 SHARES revision, tied to the move from Directive 2009/28/EC to Directive (EU) 2018/2001, introduces a definitional break that comparative sectoral work has not yet confronted. Finally, the relative-versus-absolute distinction, well established for aggregate convergence, is rarely operationalised at the sectoral level with complementary dispersion measures. This paper addresses those gaps with a descriptive-comparative analysis of the EU-27 transition across its three principal sectors over 2004-2024. It extends the sectoral record to 2024, separates relative from absolute heterogeneity, introduces sectoral-dominance and within-country asymmetry indicators, and reads every result against the 2021 break by reporting the 2004-2020, 2021-2024 and full-sample horizons separately.

Materials and methods

The analysis draws on the harmonised EUROSTAT SHARES workbook for the current EU-27, which supplies, for each Member State and year, the numerators and denominators behind the three sectoral indicators: the renewable share in electricity (RES-E), in transport (RES-T) and in heating and cooling (RES-H&C). We reconstruct the shares as percentages and keep the observed window 2004-2024; post-2024 columns contain zero placeholders and are dropped. The result is a balanced panel of 27 countries over 21 years: 567 country-year observations per indicator and 1,701 in total. Membership is fixed to the present EU-27 (excluding the United Kingdom, the EFTA states and candidate countries), and the EU-27 aggregate is rebuilt from country-level numerators and denominators rather than taken from the EU-28 sheet. Because SHARES calculation rules follow Directive (EU) 2018/2001 from 2021 onward, we interpret 2021-2024 with care.

Let $r^{(s)}_{it} \in [0, 1]$ be the renewable share, as a fraction, in sector s for country i in year t , with $s \in \{E, T, H\}$ for electricity, transport, and heating and cooling. Shares are expressed in percent,

$$P^{(s)}_{it} = 100 \cdot r^{(s)}_{it}, \quad (1)$$

and endpoint changes are reported in percentage points (pp). The three indicators are not additive: each has its own sector-specific denominator, so they measure within-sector penetration rather than components of total RES. The sectoral series contain exact zeros in the early years (RES-E for Malta in 2004; RES-T for Cyprus in 2004), so we avoid logarithmic and logit transforms and work in levels, which preserves the meaning of penetration and avoids ad hoc continuity corrections.

For each sector and year the weighted EU-27 aggregate is

$$P_{EU,t}^{(s)} = 100 \cdot (\sum_i N_{it}^{(s)}) / (\sum_i D_{it}^{(s)}), \quad (2)$$

N and D being the country numerators and denominators. Alongside it we compute the unweighted cross-country mean $\bar{P}_t$ and median across the 27 states. Dispersion is summarised by five indicators — the population standard deviation, the coefficient of variation, the interquartile range, the median absolute deviation, and the frontier-laggard gap:

$$\sigma_t = \sqrt{(1/n) \sum_i (P_{it} - \bar{P}_t)^2}, \quad (3)$$

$$CV_t = \sigma_t / \bar{P}_t, \quad (4)$$

$$IQR_t = Q_{3,t} - Q_{1,t}, \quad (5)$$

$$MAD_t = \text{median}_i |P_{it} - \text{median}_j P_{jt}|, \quad (6)$$

$$G_t = \max_i P_{it} - \min_i P_{it}. \quad (7)$$

Using several measures at once separates relative compression (a falling CV) from absolute stratification (a stable or rising σ , IQR or G). Because the transport mean is very small in the early years, its CV is numerically unstable and is treated as supplementary rather than diagnostic.

The dominant sector in each country-year is

$$D_{it} = \text{argmax}_{s \in \{E,T,H\}} P_{it}^{(s)}, \quad (8)$$

and the annual count of countries in which sector s leads is

$$n_t^{(s)} = \sum_i 1 \{ D_{it} = s \}. \quad (9)$$

Within-country asymmetry is the spread between a country's strongest and weakest sector,

$$A_{it} = \max_s P_{it}^{(s)} - \min_s P_{it}^{(s)}, \quad (10)$$

whose cross-country mean indicates whether national profiles grew more balanced or more uneven:

$$\bar{A}_t = (1/n) \sum_i A_{it}. \quad (11)$$

Given the 2021 revision, results are reported for the full period (2004-2024), the pre-break period (2004-2020) and the post-break period (2021-2024). The full window anchors the long-run reading, while 2021-2024 is treated as indicative because it opens with a definitional discontinuity. Robustness rests on three rules: a conclusion counts only if it appears in both the weighted aggregate and the unweighted distribution; heterogeneity is judged with several dispersion measures; and endpoint comparisons are run for both 2004 vs 2024 and 2004 vs 2020, so the sector ranking never depends on the post-break window alone. The design is descriptive-comparative rather than causal: it characterises how the sectoral transition unfolded, not why.

Results

At the weighted EU-27 level every sector advanced. RES-E climbed from 15.871% in 2004 to 47.500% in 2024 (+31.629 pp), RES-T from 1.432% to 11.204% (+9.772 pp), and RES-H&C from 11.735% to 26.697% (+14.962 pp), making electricity the most dynamic channel. The unweighted statistics agree: mean RES-E rose from 16.532% to 45.020%, mean RES-T from 1.186% to 10.725%, and mean RES-H&C from 16.618% to 34.932%, with medians moving in the same way (Table 1). In the cross-country mean, heating slightly exceeded electricity in 2004; electricity overtook it in 2013 and pulled clearly ahead thereafter.

Table 1. EU-27 aggregate trajectories and unweighted cross-country central tendency, 2004 and 2024 (%).

Sector	Aggregate 2004	Aggregate 2024	Mean 2004	Mean 2024	Median 2004	Median 2024
Electricity	15.871	47.500	16.532	45.020	9.436	43.079
Transport	1.432	11.204	1.186	10.725	0.971	9.456
Heating & cooling	11.735	26.697	16.618	34.932	12.531	32.639

Source: own calculations based on the EUROSTAT SHARES workbook (2004-2024); the EU-27 aggregate is reconstructed from country-level numerators and denominators.

Rising averages did not close the gaps. In electricity the floor improved from 0.000% (Malta, 2004) to 10.655% (Malta, 2024) while the ceiling rose from 61.627% to 90.065% (Austria at both endpoints), so the frontier-laggard gap widened from 61.627 to 79.410 pp. In transport the minimum moved from 0.000% (Cyprus, 2004) to 0.936% (Croatia, 2024) and the maximum from 6.288% to 26.399% (Sweden at both), widening the gap from 6.288 to 25.463 pp. In heating the minimum rose from 1.035% (Malta) to 7.913% (Ireland) and the maximum from 45.929% to 67.828% (Sweden at both), widening the gap from 44.894 to 59.915 pp (Table 2). Broad improvement therefore coexisted with widening absolute disparities in every sector.

Table 2. Cross-country distribution of sectoral renewable shares, 2004 and 2024.

Sector	Min 2004	Code	Max 2004	Code	Min 2024	Code	Max 2024	Code
Electricity (%)	0.000	MT	61.627	AT	10.655	MT	90.065	AT
Transport (%)	0.000	CY	6.288	SE	0.936	HR	26.399	SE
Heating & cooling (%)	1.035	MT	45.929	SE	7.913	IE	67.828	SE

Source: own calculations based on the EUROSTAT SHARES workbook (2004-2024). Code denotes the ISO 3166-1 alpha-2 country code of the country recording the minimum or maximum.

The two faces of heterogeneity pull in opposite directions. The coefficient of variation fell sharply in every sector, from 1.004 to 0.446 in electricity, from 1.147 to 0.477 in transport, and from 0.796 to 0.494 in heating, so countries grew more alike in proportional terms. Measured in percentage points, however, they drifted further apart: the standard deviation rose from 16.603 to 20.071 pp in electricity, from 1.360 to 5.121 pp in transport, and from 13.222 to 17.241 pp in heating, the frontier-laggard gap moved the same way, and for transport and heating the interquartile range also widened (Table 3). Relative compression thus coexisted with persistent absolute stratification.

Table 3. Dispersion dynamics by sector, selected years (SD reported as the population standard deviation).

Year	Sector	SD (pp)	CV	IQR (pp)	MAD (pp)
2004	Electricity	16.603	1.004	23.875	7.722
2004	Transport	1.360	1.147	0.922	0.529
2004	Heating & cooling	13.222	0.796	20.033	7.970
2020	Electricity	18.818	0.534	22.179	12.029
2020	Transport	4.724	0.453	2.152	1.210
2020	Heating & cooling	16.757	0.542	20.666	11.602
2021	Electricity	18.761	0.525	23.634	13.563
2021	Transport	4.772	0.510	3.103	1.626
2021	Heating & cooling	16.813	0.538	24.011	12.739
2024	Electricity	20.071	0.446	24.089	12.435
2024	Transport	5.121	0.477	4.247	1.895
2024	Heating & cooling	17.241	0.494	28.661	12.451

Source: own calculations based on the EUROSTAT SHARES workbook (2004-2024).

National trajectories confirm the divergence. In electricity the largest gains went to Denmark (+55.902 pp), the Netherlands (+46.099 pp) and Lithuania (+45.400 pp), the smallest to Slovakia (+9.507 pp), Latvia (+9.556 pp) and Malta (+10.655 pp). In transport the leaders were Sweden (+20.111 pp), Finland (+19.261 pp) and the Netherlands (+19.232 pp), while Croatia (−0.059 pp), Greece (+3.785 pp), Poland (+4.452 pp) and Czechia (+4.540 pp) barely moved, which underlines transport's structural constraint. In heating the strongest gains were Malta (+58.174 pp), Denmark (+35.918 pp) and Cyprus (+32.327 pp), the weakest Ireland (+5.041 pp), Croatia (+5.399 pp) and Belgium (+8.332 pp). Some countries advanced mainly through electricity, others mainly through heating; transport rarely led. The dominance pattern sharpens the point. In 2004 electricity was the strongest sector in 15 of the 27 states and heating in the remaining 12; transport led nowhere. By 2024 electricity led in 19 states, heating in 8, and transport still in none. This shift was accompanied by a steep rise in within-country asymmetry: the mean gap between a country's strongest and weakest sector grew from 19.753 pp in 2004 to 38.898 pp in 2024 (Table 4).

Table 4. Sectoral dominance and within-country asymmetry, selected years.

Year	Electricity dominant	Transport dominant	Heating & cooling dominant	Mean within-country asymmetry (pp)
2004	15	0	12	19.753
2020	17	0	10	31.006
2021	16	0	11	32.273
2024	19	0	8	38.898

Source: own calculations based on the EUROSTAT SHARES workbook (2004-2024).

The 2020-to-2021 boundary brings visible reshuffling, which matters for short-window comparisons. At the aggregate level, electricity edged up from 37.408% to 37.793% and heating from 22.983% to 23.033%, while transport fell from 10.253% to 9.051%. Between 2020 and 2021, electricity declined in 12 countries, transport in 22 and heating in 10. Some moves were large: in electricity Austria fell by 4.196 pp while Denmark rose by 7.858 pp; in transport Ireland fell by 5.541 pp while Finland rose by 5.988 pp; in heating Bulgaria fell by 7.323 pp while Malta rose by 9.579 pp. Because the SHARES revision begins in 2021, these one-year changes are not purely structural.

Discussion

Overall, the transition is broad but lopsided. The main finding is not that shares rose in all three sectors, but that the sectors followed different logics: electricity drove the expansion, heating provided a stable base, and transport lagged. This extends the convergence literature, which has mostly worked with aggregate RES and repeatedly found proportional convergence alongside persistent stratification in levels (Kasman & Kasman, 2019; Presno & Landajo, 2021; Saba & Ngepah, 2022). What is new is that this tension also operates inside the transition. In aggregate the EU moves in a shared pro-renewable direction; decomposed by sector, the idea of a single homogeneous pathway weakens. Some countries advanced through electricity, others retained strong heating positions, and transport seldom led; rising within-country asymmetry shows that the change was less a balanced three-sector transformation than an increasingly differentiated restructuring. Electricity's lead deserves emphasis. It had the most favourable conditions: mature technologies, scalable infrastructure, well-designed support and high policy visibility. By 2024 it led in a clear majority of Member States, so EU renewable success has been shaped disproportionately by one sector. This, however, is not the same as an integrated transition. Heating kept a broad role throughout: it slightly exceeded electricity in average country terms in 2004 and still led in a sizeable group of states in 2024. Its growth was quieter, but its breadth points to a more distributed base. Transport remained the binding constraint. It improved from a low base but stayed the weakest sector in aggregate and cross-country terms, never led in any Member State at either endpoint, and kept a stubbornly uneven distribution. The asymmetry is structural: the EU accelerated deployment, but not evenly across the sectors that decarbonisation requires. The split between relative and absolute heterogeneity is a further key result. Falling coefficients of variation indicate that Member States grew more alike in proportional terms; the simultaneous rise in standard deviations and frontier-laggard gaps shows that this compression did not equalise levels. The transition became more general without becoming equal, the pattern expected when leaders keep adding gains from already high bases. The 2021 break warrants caution. Because the SHARES revision aligned the methodology with Directive (EU) 2018/2001, post-2020 figures may mix genuine change with a definitional shift, and the sectors differ in their sensitivity to it. The full-period reading is therefore the most reliable basis for structural assessment, while 2021-2024 is best treated as indicative. Several limitations bound the claims. The study is descriptive-comparative, not causal: it maps the structure and asymmetry of sectoral development without attributing them to drivers such as investment, regulation, technology costs or infrastructure. The indicators are non-additive, as each rests on a sector-specific denominator, and annual shares say little about within-year volatility or short-run policy timing. These limits suggest natural extensions: conditional or club-convergence designs, sector-specific panel models, and covariates for infrastructure, technology mix and institutional capacity.

Conclusions

This study tracked the sectoral path of EU-27 renewable development over 2004-2024 across the weighted aggregate, the unweighted cross-country distribution and the within-country mix. Four conclusions follow. First, all three sectors advanced, but unevenly: electricity was the engine of expansion, heating a broad and stable base, and transport the laggard throughout. Second, the transition grew more asymmetric rather than less; by 2024 electricity led in 19 of 27 states, transport in none, and the average within-country gap between the strongest and weakest sector nearly doubled. Third, relative improvement did not bring level equalisation, as proportional

dispersion fell in every sector while absolute gaps widened at the endpoints; the transition is broad progress over persistent structural inequality rather than uniform sectoral harmonisation. Fourth, aggregate success can mask internal imbalance: an electricity-led Union has not yet achieved balanced decarbonisation across all final energy uses. In policy terms, common EU targets appear to have supported diffusion and proportional catch-up, but narrowing absolute gaps in laggard countries, especially in transport and in heating outside the biomass-and-district-heating cluster, will require more differentiated, capacity- and infrastructure-oriented action. Extending the record to 2024 shows that broad renewable progress can coexist with durable sectoral and cross-country asymmetries: the depth of the transition depends not only on how much renewable energy grows, but on where in the energy system that growth occurs.

References

- Abbasi, M., Abdullah, B., Ahmad, M., Rostami, A., & Cullen, J. (2021). Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology. *Sustainable Energy Technologies and Assessments*, 48, 101630. <https://doi.org/10.1016/j.seta.2021.101630>
- Ajanovic, A., & Haas, R. (2021). Renewable energy systems implementation in road transport: Prospects and impediments. *Renewable Energy and Environmental Sustainability*, 6, 39. <https://doi.org/10.1051/rees/2021042>
- Arántegui, R. L., & Jäger-Waldau, A. (2017). Photovoltaics and wind status in the European Union after the Paris Agreement. *Renewable and Sustainable Energy Reviews*, 81, 2460-2471. <https://doi.org/10.1016/j.rser.2017.06.052>
- Berk, I., Kasman, A., & Kilinc, D. (2020). Towards a common renewable future: The System-GMM approach to assess the convergence in renewable energy consumption of EU countries. *Energy Economics*, 87, 103922. <https://doi.org/10.1016/j.eneco.2018.02.013>
- Bertelsen, N., & Mathiesen, B. V. (2020). EU-28 residential heat supply and consumption: Historical development and status. *Energies*, 13(8), 1894. <https://doi.org/10.3390/en13081894>
- Biresselioglu, M. E., Kaplan, M. D., & Yilmaz, B. K. (2018). Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes. *Transportation Research Part A: Policy and Practice*, 109, 1-13. <https://doi.org/10.1016/j.tra.2018.01.017>
- Bölük, G., & Kaplan, R. (2021). Effectiveness of renewable energy incentives on sustainability: Evidence from dynamic panel data analysis for the EU countries and Turkey. *Environmental Science and Pollution Research*, 29, 26613-26630. <https://doi.org/10.1007/s11356-021-17801-y>
- Bórawski, P., Wyszomierski, R., Beldycka-Bórawska, A., Mickiewicz, B., Kalinowska, B., Dunn, J. W., & Rokicki, T. (2022). Development of renewable energy sources in the European Union in the context of sustainable development policy. *Energies*, 15(4), 1545. <https://doi.org/10.3390/en15041545>
- Braungardt, S., Bürger, V., Zieger, J., & Bosselaar, L. (2019). How to include cooling in the EU Renewable Energy Directive? Strategies and policy implications. *Energy Policy*, 129, 260-267. <https://doi.org/10.1016/j.enpol.2019.02.027>
- Butnaru, G. I., Haller, A. P., Clipa, R. I., Ștefănică, M., & Ifrim, M. (2020). The nexus between convergence of conventional and renewable energy consumption in the present European Union states. *Energies*, 13(20), 5272. <https://doi.org/10.3390/en13205272>
- Cansino, J. M., Pablo-Romero, M. del P., Román, R., & Yñiguez, R. (2011). Promoting renewable energy sources for heating and cooling in EU-27 countries. *Energy Policy*, 39(6), 3803-3812. <https://doi.org/10.1016/j.enpol.2011.04.010>
- Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P. A., & Nielsen, S. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy*, 65, 475-489. <https://doi.org/10.1016/j.enpol.2013.10.035>

- D'Adamo, I., Falcone, P. M., Gastaldi, M., & Morone, P. (2020). RES-T trajectories and an integrated SWOT-AHP analysis for biomethane: Policy implications to support a green revolution in European transport. *Energy Policy*, 138, 111220. <https://doi.org/10.1016/j.enpol.2019.111220>
- Dolge, K., Barisa, A., Kirsanovs, V., & Blumberga, D. (2023). The status quo of the EU transport sector: Cross-country indicator-based comparison and policy evaluation. *Applied Energy*, 334, 120700. <https://doi.org/10.1016/j.apenergy.2023.120700>
- Dolge, K., & Blumberga, D. (2023). Transitioning to clean energy: A comprehensive analysis of renewable electricity generation in the EU-27. *Energies*, 16(18), 6415. <https://doi.org/10.3390/en16186415>
- Domhnaill, C., & Ryan, L. (2020). Towards renewable electricity in Europe: Revisiting the determinants of renewable electricity in the European Union. *Renewable Energy*, 154, 955-965. <https://doi.org/10.1016/j.renene.2020.03.084>
- Falanga, A., Picone, M., Greco, F., & Carteni, A. (2025). A roadmap to low-carbon freight transport: A review of EU directives and regulations. *WSEAS Transactions on Power Systems*, 20, 90-105. <https://doi.org/10.37394/232016.2025.20.11>
- Fernandes, J., Rémedios, S., Gérard, F., Bačan, A., Stroleny, M., Drosou, V., & Christodoulaki, R. (2025). The decarbonisation of heating and cooling following EU directives. *Energies*, 18(13), 3432. <https://doi.org/10.3390/en18133432>
- Grafström, J. (2018). Divergence of renewable energy invention efforts in Europe: An econometric analysis based on patent counts. *Environmental Economics and Policy Studies*, 20, 829-859. <https://doi.org/10.1007/s10018-018-0216-y>
- Grafström, J., Söderholm, P., Gawel, E., Lehmann, P., & Strunz, S. (2020). Government support to renewable energy R&D: Drivers and strategic interactions among EU Member States. *Economics of Innovation and New Technology*, 32(1), 1-24. <https://doi.org/10.1080/10438599.2020.1857499>
- Haas, T., & Sander, H. (2020). Decarbonizing transport in the European Union: Emission performance standards and the perspectives for a European Green Deal. *Sustainability*, 12(20), 8381. <https://doi.org/10.3390/su12208381>
- Halkos, G., & Tsirivis, A. (2023). Sustainable development of the European electricity sector: Investigating the impact of electricity price, market liberalization and energy taxation on RES deployment. *Energies*, 16(14), 5567. <https://doi.org/10.3390/en16145567>
- Hoicka, C. E., Lowitzsch, J., Brisbois, M. C., Kumar, A., & Camargo, L. R. (2021). Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3729512>
- Jankiewicz, M. (2021). The convergence of energy use from renewable sources in the European countries: Spatio-temporal approach. *Energies*, 14(24), 8378. <https://doi.org/10.3390/en14248378>
- Kacperska, E., Łukasiewicz, K., & Pietrzak, P. (2021). Use of renewable energy sources in the European Union and the Visegrad Group countries — Results of cluster analysis. *Energies*, 14(18), 5680. <https://doi.org/10.3390/en14185680>
- Kasman, A., & Kasman, S. (2019). Convergence of renewable energy consumption in the EU-15: Evidence from stochastic and club convergence tests. *Environmental Science and Pollution Research*, 27, 5901-5911. <https://doi.org/10.1007/s11356-019-07378-y>
- Kijek, T., Kijek, A., Bolibok, P., & Matras-Bolibok, A. (2021). The patterns of energy innovation convergence across European countries. *Energies*, 14(10), 2755. <https://doi.org/10.3390/en14102755>
- Kitzing, L., Mitchell, C., & Morthorst, P. E. (2012). Renewable energy policies in Europe: Converging or diverging? *Energy Policy*, 51, 192-201. <https://doi.org/10.1016/j.enpol.2012.08.064>
- Maduta, C., D'Agostino, D., Tsemekidi-Tzeiranaki, S., Castellazzi, L., Melica, G., & Bertoldi, P. (2023). Towards climate neutrality within the European Union: Assessment of the Energy Performance of

Buildings Directive implementation in Member States. *Energy and Buildings*, 301, 113716. <https://doi.org/10.1016/j.enbuild.2023.113716>

- Mai-Moulin, T., Hoefnagels, R., Grundmann, P., & Junginger, M. (2021). Effective sustainability criteria for bioenergy: Towards the implementation of the European Renewable Directive II. *Renewable and Sustainable Energy Reviews*, 138, 110645. <https://doi.org/10.1016/j.rser.2020.110645>
- Manowska, A., Bluszcz, A., Chomiak-Orsa, I., & Wowra, R. (2024). Towards energy transformation: A case study of EU countries. *Energies*, 17(7), 1778. <https://doi.org/10.3390/en17071778>
- Marra, A., & Colantonio, E. (2022). The institutional and socio-technical determinants of renewable energy production in the EU: Implications for policy. *Journal of Industrial and Business Economics*, 49, 267-299. <https://doi.org/10.1007/s40812-022-00212-6>
- Matuszewska-Janica, A., Żebrowska-Suchodolska, D., Ala-Karvia, U., & Hozer-Koćmiel, M. (2021). Changes in electricity production from renewable energy sources in the European Union countries in 2005-2019. *Energies*, 14(19), 6276. <https://doi.org/10.3390/en14196276>
- Maza, A., Hierro, M., & Villaverde, J. (2010). Renewable electricity consumption in the EU-27: Are cross-country differences diminishing? *Renewable Energy*, 35(9), 2094-2101. <https://doi.org/10.1016/j.renene.2010.02.012>
- Miłek, D., Nowak, P., & Latosińska, J. (2022). The development of renewable energy sources in the European Union in the light of the European Green Deal. *Energies*, 15(15), 5576. <https://doi.org/10.3390/en15155576>
- Nagaj, R., Gajdzik, B., Wolniak, R., & Grebski, W. (2024). The impact of deep decarbonization policy on the level of greenhouse gas emissions in the European Union. *Energies*, 17(5), 1245. <https://doi.org/10.3390/en17051245>
- Nasiri, E., Rocha-Meneses, L., Inayat, A., & Kikas, T. (2022). Impact of policy instruments in the implementation of renewable sources of energy in selected European countries. *Sustainability*, 14(10), 6314. <https://doi.org/10.3390/su14106314>
- Papież, M., Śmiech, S., & Frodyma, K. (2018). Determinants of renewable energy development in the EU countries: A 20-year perspective. *Renewable and Sustainable Energy Reviews*, 91, 918-934. <https://doi.org/10.1016/j.rser.2018.04.075>
- Perez, M. dos S., Scholten, D., & Stegen, K. S. (2019). The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security. *Energy Strategy Reviews*, 26, 100415. <https://doi.org/10.1016/j.esr.2019.100415>
- Pietzcker, R. C., Osorio, S., & Rodrigues, R. (2021). Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. *Applied Energy*, 293, 116914. <https://doi.org/10.1016/j.apenergy.2021.116914>
- Popescu, C., & Covrig, M. (2023). Club convergence in energy transition of EU Member States. *SGEM International Multidisciplinary Scientific GeoConference EXPO Proceedings*. <https://doi.org/10.5593/sgem2023v/4.2/s19.19>
- Presno, M. J., & Landajo, M. (2021). EU-28's progress toward the 2020 renewable energy share: A club convergence analysis. *Environmental Science and Pollution Research*, 28, 66830-66844. <https://doi.org/10.1007/s11356-021-15084-x>
- Prussi, M., Padella, M., Conton, M., Postma, E. D., & Lonza, L. (2019). Review of technologies for biomethane production and assessment of EU transport share in 2030. *Journal of Cleaner Production*, 222, 565-572. <https://doi.org/10.1016/j.jclepro.2019.02.271>
- Renou-Maissant, P., Abdesselam, R., & Bonnet, J. (2022). Trajectories for energy transition in EU-28 countries over the period 2000-2019: A multidimensional approach. *Environmental Modeling and Assessment*, 27, 525-551. <https://doi.org/10.1007/s10666-022-09816-7>

- Rosenow, J., Gibb, D., & Thomas, S. (2025). From inefficient to efficient renewable heating: A critical assessment of the EU Renewable Energy Directive. *Sustainability*, 17(9), 4164. <https://doi.org/10.3390/su17094164>
- Saba, C. S., & Ngepah, N. (2022). Convergence in renewable energy sources and the dynamics of their determinants: An insight from a club clustering algorithm. *Energy Reports*, 8, 3483-3506. <https://doi.org/10.1016/j.egyr.2022.01.190>
- Salim, S., Luxembourg, S. L., Longa, F. D., & Van Der Zwaan, B. (2024). Decarbonisation scenarios for the European residential sector. *Building and Environment*, 267, 112408. <https://doi.org/10.1016/j.buildenv.2024.112408>
- Scarlat, N., Prussi, M., & Padella, M. (2022). Quantification of the carbon intensity of electricity produced and used in Europe. *Applied Energy*, 305, 117901. <https://doi.org/10.1016/j.apenergy.2021.117901>
- Shivakumar, A., Dobbins, A., Fahl, U., & Singh, A. (2019). Drivers of renewable energy deployment in the EU: An analysis of past trends and projections. *Energy Strategy Reviews*, 26, 100402. <https://doi.org/10.1016/j.esr.2019.100402>
- Silva, N., Fuinhas, J. A., Koengkan, M., Kazemzadeh, E., & Kaymaz, V. (2023). Renewable energy deployment in Europe: Do politics matter? *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-023-03839-0>
- Skov, I. R., & Schneider, N. (2022). Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states. *Energy Policy*, 168, 113121. <https://doi.org/10.1016/j.enpol.2022.113121>
- Thomaßen, G., Kavvadias, K., & Navarro, J. P. J. (2020). The decarbonisation of the EU heating sector through electrification: A parametric analysis. *Energy Policy*, 148, 111929. <https://doi.org/10.1016/j.enpol.2020.111929>
- Török, L., & László, T. (2025). Economic drivers of renewable energy growth in the European Union: Evidence from a panel data analysis (2015-2023). *Energies*, 18(13), 3363. <https://doi.org/10.3390/en18133363>
- Tu, Y.-X., Kubatko, O., Piven, V., Sotnyk, I., & Kurbatova, T. (2022). Determinants of renewable energy development: Evidence from the EU countries. *Energies*, 15(19), 7093. <https://doi.org/10.3390/en15197093>
- Wang, X., Jin, W., Qin, M., Su, C.-W., & Umar, M. (2024). Pushing forward the deployment of renewable energy: Do cross-national spillovers of policy instruments matter? *Energy*, 302, 131643. <https://doi.org/10.1016/j.energy.2024.131643>
- Yu, B., Fang, D., Yu, H., & Zhao, C. (2021). Temporal-spatial determinants of renewable energy penetration in electricity production: Evidence from EU countries. *Renewable Energy*, 180, 438-451. <https://doi.org/10.1016/j.renene.2021.08.079>