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Structural transformation: Testing convergence in energy, carbon emissions, innovation, and governance

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Abstract. The green transition has increasingly been conceptualised as a process of structural transformation encompassing energy systems, innovation capacity, carbon performance, and institutional governance. However, whether this transformation leads to convergence across countries or reinforces persistent structural divergence remains an open empirical question. This study examines convergence dynamics within the European green transition by analysing a balanced panel of 27 European Union member states and Ukraine over the period 2004–2023. The analysis applies complementary σ-convergence indicators and β-convergence regressions, including pooled, fixed-effects, and time-effects specifications, to distinguish between cross-country structural disparities and within-country adjustment dynamics. The results reveal asymmetric convergence patterns across transition dimensions. Renewable energy penetration and research and development intensity exhibit statistically significant convergence, reflecting coordinated policy frameworks and technological diffusion. In contrast, carbon emissions remain highly heterogeneous at the cross-country level, while institutional governance quality displays divergence in pooled specifications and only conditional convergence once country-specific effects are

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controlled for. Time-effects estimations further indicate that major systemic shocks, such as the global financial crisis and the COVID-19 pandemic, have significantly shaped convergence trajectories. The findings demonstrate that the green transition in EU unfolds as an institutionally mediated structural transformation, in which technological and innovation dimensions converge more rapidly than emissions and governance. This underscores the need for differentiated policy instruments and strengthened governance architectures to support balanced and resilient green transition pathways.

Keywords: green growth, structural transformation, convergence analysis, renewable energy, carbon emissions, innovation capacity, governance quality, European Union, sustainable development

JEL Classification: Q01, Q56, Q57

1. INTRODUCTION

Driven by climate change, resource constraints, and rising geopolitical uncertainty, countries are increasingly required to reconcile environmental sustainability with economic growth, energy security, and social stability. Far from being a purely environmental agenda, the green transition entails a fundamental transformation of economic structures, encompassing energy systems, production technologies, innovation dynamics, and governance frameworks. Understanding whether this transformation leads to convergence toward common development pathways or, conversely, reinforces structural divergence across countries has become a critical question for both scholars and policymakers.

Existing research has made substantial progress in identifying the drivers and outcomes of the green transition. A growing body of literature examines decarbonization trajectories, renewable energy deployment, green innovation, and climate-related financial instruments (Wojciechowski et al., 2025; Tomczyk et al, 2025). Studies rooted in evolutionary economics and political economy emphasize that green transition processes are inherently path-dependent, non-linear, and institutionally embedded, suggesting that countries may follow heterogeneous trajectories rather than converge toward a single equilibrium (Kemp & Never, 2017; Lamperti et al., 2020; Besley & Persson, 2023). In contrast, neoclassical and systems-based perspectives often imply that technological diffusion, policy harmonization, and market integration, particularly within regions such as the European Union, may foster gradual convergence in energy efficiency, emissions intensity, and innovation performance (Gea-Bermúdez et al., 2021; Naqvi et al., 2023; Veckalne & Tambovceva, 2023).

This tension between convergence and divergence hypotheses remains a central controversy in the field. On the one hand, advancements in renewable energy technologies, digitalization, and green finance are expected to lower transition costs and enable lagging economies to catch up. On the other hand, empirical evidence increasingly points to persistent asymmetries driven by energy poverty, institutional quality, fiscal capacity, and exposure to economic and geopolitical shocks (Asim et al., 2023; Joiţa et al., 2023; De Haas et al., 2025). Recent crises, including the COVID-19 pandemic and disruptions in global energy markets, have further intensified these asymmetries, raising concerns that the green transition may exacerbate rather than reduce structural inequalities across countries.

A core limitation of the existing literature lies in the insufficient operationalisation of the green transition as a multidimensional structural process. Although widely recognised as involving energy restructuring, technological upgrading, and institutional adaptation, empirical convergence analyses rarely compare adjustment dynamics across these pillars within a unified framework. Most studies focus on environmental performance indicators alone, implicitly treating them as proxies for broader transition progress. As a result, it remains unclear whether different dimensions of the transition adjust at comparable speeds or whether structural asymmetries persist across economic, technological, and institutional domains. Addressing this gap requires a systematic comparison of convergence patterns across core transition dimensions in order to identify whether the green transition unfolds symmetrically or through uneven structural adjustment.

Against this background, the central unresolved question concerns whether the green transition exhibits comparable convergence dynamics across its key structural dimensions or whether adjustment remains uneven across economic, technological, and institutional domains. The existing literature provides substantial evidence on dimension-specific convergence, yet lacks a systematic comparative analysis of how different transition pillars evolve relative to one another. Accordingly, the main aim of this study is to examine and compare convergence patterns across multiple structural components of the green transition in European countries over the period 2004–2023. Rather than assuming that progress in one domain reflects overall transformation, the analysis evaluates whether convergence occurs symmetrically or whether structural asymmetries persist across dimensions. By providing comparative evidence on multidimensional convergence dynamics, this study contributes to the theoretical understanding of the green transition as a structural transformation process. It refines the theoretical discussion by demonstrating that convergence may occur unevenly across transition pillars, thereby challenging implicit assumptions of uniform adjustment. The findings also offer policy-relevant insights into whether harmonized EU frameworks foster balanced structural alignment or whether differentiated instruments remain necessary to address persistent asymmetries.

The paper has the following structure: the literature review outlines the theoretical foundations of the green transition as a structural transformation and synthesizes prior evidence on convergence dynamics. The methodological approach describes the dataset, variable construction, and the σ- and β-convergence framework applied in the analysis. The section conducting research and results presents the empirical findings and evaluates convergence patterns across the examined transition dimensions. The discussion interprets the results in light of existing theoretical debates and policy frameworks. The conclusion summarises the main findings, theoretical implications, policy relevance, and avenues for future research.

2. LITERATURE REVIEW

The results of analysis showed that most studies increasingly conceptualise the green transition not as a narrow environmental or sectoral policy, but as a deep structural transformation of economic systems, involving coordinated changes in production structures, technological regimes, institutional arrangements, and governance architectures. Kemp and Never (2017) and Kemp-Benedict (2018) frame the green transition as an outcome of industrial policy, long-term investment reallocation, and systemic innovation dynamics, emphasising the necessity of active state involvement and cross-sectoral coordination. From this perspective, the green transition represents a reconfiguration of growth models rather than an incremental adjustment within existing structures. Lamperti et al. (2020) employ agent-based integrated assessment models to demonstrate that green transitions are inherently non-linear, path-dependent, and heterogeneous across countries. Their findings suggest that transition dynamics are shaped by feedback loops between technology, policy, and economic behaviour, leading to divergent development trajectories. This theoretical foundation directly motivates empirical investigations into whether countries exhibit convergence toward common green development pathways or whether structural asymmetries persist over time.

Besides, the vast range of research focuses on the energy and emissions dimensions of the green transition, highlighting their central role in shaping structural convergence or divergence. Asim et al. (2023) emphasise that energy poverty and energy crises significantly constrain the capacity of economies to pursue decarbonization, particularly in the early stages of transition. Such constraints generate asymmetric adjustment paths, thereby limiting the likelihood of uniform convergence in energy and emissions indicators.

Joiţa et al. (2023) and Kim et al. (2025) identify a persistent trade-off between ensuring reliable energy supply and accelerating the green transition, particularly under conditions of geopolitical instability. Crnčec et al. (2023) further demonstrate that the COVID-19 pandemic marked a turning point in the European Union's policy priorities, temporarily shifting the focus from long-term sustainable energy transition toward a broader green transition framework integrating recovery, resilience, and security concerns.

From a systems perspective, Gea-Bermúdez et al. (2021) show that sector coupling across electricity, heating, transport, and industry can significantly reduce transition costs and facilitate convergence of national energy systems in Europe. In contrast, case-based evidence from Dallavalle et al. (2021) illustrates how geographic isolation and infrastructural constraints, such as those faced by island economies, may lock regions into divergent transition trajectories, reinforcing structural heterogeneity.

Technological innovation constitutes a core driver of green transition as structural transformation. Empirical studies by Uche et al. (2024) and Li and Li (2019) reveal that the relationship between green innovation and environmental performance is characterized by threshold effects and non-linearities, indicating that innovation contributes to transition outcomes only after certain institutional or regulatory conditions are met. These findings underscore the importance of moving beyond average effects and assessing heterogeneous convergence patterns.

Recent research (Gobniece & Titko, 2024; Trofymenko et al., 2023; Piwowarski, 2024) highlights the growing role of digitalization in shaping green transition dynamics. Ma et al. (2023) and Huang et al. (2025) provide evidence that digital infrastructure, industrial intelligence, and e-commerce can enhance energy efficiency and reduce emissions. However, these studies also caution that digital transformation may amplify structural polarization, as countries with weaker innovation ecosystems and institutional capacity may fail to capture its green dividends. Xing and Ye (2022) complement this line of inquiry by demonstrating that consumption upgrading and industrial structural change interact with low-carbon constraints, generating differentiated transition pathways across economies.

The financial dimension of the green transition plays a decisive role in shaping structural outcomes. Studies focusing on advanced economies, such as Naqvi et al. (2023) and Zhang et al. (2025), show that well-developed financial markets, green finance instruments, and environmental taxation policies significantly accelerate progress toward carbon neutrality. At the firm level, Wang et al. (2021) and Chi and Yang (2023) demonstrate that access to green finance and market-oriented governance mechanisms supports enterprise-level green transformation.

Nevertheless, financial development alone does not guarantee convergence. De Haas et al. (2025) identify managerial capabilities and internal financial constraints as critical barriers that may slow green transition even in financially mature economies. In developing regions, Onuoha et al. (2023) reveal that governance quality and public debt dynamics condition the effectiveness of renewable energy financing, further entrenching cross-country disparities in transition performance.

At the same time, the reseachers proved that the political economy of the green transition has emerged as a central theme in recent scholarship. Thus, Besley and Persson (2023) provide a theoretical framework linking green transition outcomes to political institutions, redistribution mechanisms, and investment incentives. From a distributive perspective, Baute (2025) and Crespy and Munta (2023) highlight how social justice concerns and distributional conflicts shape public support for climate policies, particularly within the European Union.

Labor market institutions and social actors further influence transition trajectories. Clarke and Sahin-Dikmen (2020), Kalt (2022), and Pulignano et al. (2023) analyze the role of trade unions, showing that they can function either as agents of transformation or as defenders of incumbent structures, depending on national institutional settings. Øjvind Nielsen et al. (2024) emphasize the importance of collaborative governance, arguing that inclusive coordination among public, private, and societal actors can mitigate transition asymmetries and support more balanced structural adjustment.

The literature converges on the view that the green transition constitutes a multidimensional, institutionally embedded process of structural transformation. However, most empirical studies examine individual dimensions, energy, emissions, innovation, finance, or governance, in isolation. Systematic evidence on whether these dimensions evolve coherently toward common trajectories remains limited.

Against this background, the present study contributes to the theoretical background by empirically testing convergence and divergence patterns across energy systems, carbon emissions, innovation capacity, and governance quality, thereby offering an integrated assessment of green transition as a structural transformation.

3. METHODOLOGICAL APPROACH

The empirical analysis is based on a balanced panel dataset covering 27 European Union member states and Ukraine over the period 2004–2023. The inclusion of all EU member states ensures full coverage of the European integration framework and allows capturing structural heterogeneity across advanced, cohesion, and transition economies operating under a common regulatory and climate policy architecture. Ukraine is incorporated as a structurally relevant comparator economy. First, Ukraine represents a transition economy undergoing institutional transformation and energy restructuring under conditions of external shocks and geopolitical instability. Second, the country has progressively aligned its environmental, energy, and governance frameworks with EU standards, particularly following the Association Agreement and deepening integration processes. Including Ukraine therefore enables assessment of whether convergence dynamics extend beyond the formal EU institutional boundary and provides analytical insight into the broader European green transition space. The period 2004–2023 is selected for several methodological and structural reasons. The year 2004 marks the largest EU enlargement wave, which significantly reshaped institutional and economic heterogeneity within Europe. Starting the panel in 2004 ensures comparability under a relatively stable integration regime. The endpoint 2023 allows capturing the most recent structural adjustments, including post-financial crisis recovery, acceleration of renewable energy deployment under the European Green Deal framework, and institutional responses to recent systemic shocks.

The study focuses on four structural indicators that represent key dimensions of the managed green transition: renewable energy penetration (RE), carbon emissions (CO_2), research and development intensity (RD), and institutional governance quality (WGI).

Renewable energy penetration (RE) captures the share of renewable sources in the national energy mix and reflects the degree of decarbonisation of production systems. The literature identifies renewable deployment as a primary structural driver of long-run green growth and energy transition dynamics (Apergis & Payne, 2010; Inglesi-Lotz, 2016; Saqib et al., 2022; Addai et al., 2024). Countries with higher renewable penetration tend to exhibit stronger alignment between economic expansion and environmental sustainability, particularly within managed transition frameworks.

Carbon emissions (CO_2) represent total emissions associated with economic activity and proxy the environmental pressure dimension of growth. CO_2 remains the most widely used macro-level environmental performance indicator in empirical green growth and convergence studies, as it captures both scale effects and structural intensity of industrial activity (Payne, 2020; Tariq et al., 2024). Its inclusion allows assessment of whether decarbonisation accompanies structural economic upgrading.

Research and development intensity (RD), measured as R&D expenditure relative to GDP, reflects technological capacity and innovation-driven structural upgrading. Endogenous growth theory and ecological modernisation frameworks consistently emphasise innovation as a fundamental mechanism enabling decoupling between economic growth and environmental degradation (Huang & He, 2023; Nie et al., 2024). Empirical evidence demonstrates that R&D investment accelerates cthetdiffusiondiffof clean technologies strengthens green productivity performance (Huang et al., 2020; Fang et al., 2022).

Institutional governance quality (WGI), derived from the Worldwide Governance Indicators framework (Kaufmann & Kraay, 2024), captures regulatory quality, rule of law, and institutional effectiveness. Institutional quality is increasingly recognised as a structural determinant of green transition success, as effective governance reduces policy uncertainty, improves environmental regulation enforcement, and facilitates coordinated energy reforms (Lyytimäki et al., 2018; Li, & Tong, 2024). Convergence studies further indicate that institutional asymmetries contribute to persistent divergence in environmental and innovation outcomes across countries.

Table 1 presents the definition and data sources for four core indicators that represent key dimensions of the managed green transition

Table 1

Definition and data sources of structural determinants of the managed green transition

Abbreviation	**Indicator**	**Definition / Measurement**	**Data Source**
RE	Renewable Energy Penetration	Share of renewable energy sources in gross final energy consumption (%)	Eurostat (2024)
CO_2	Carbon Emissions	Total CO_2 emissions (million tonnes) associated with economic activity	World Bank (2024)
RD	Research and Development Intensity	Gross domestic expenditure on R&D as a percentage of GDP (%)	World Bank (2024)
WGI	Worldwide Governance Indicators	Composite governance quality index (regulatory quality, rule of law, government effectiveness, control of corruption, political stability, voice & accountability)	World Bank (2024)

Source: developed by the author.

To evaluate whether the dispersion of core determinants has weakened over time or remained persistent, two complementary frameworks for convergence were applied. First, σ-convergence is examined through the time dynamics of dispersion measures (Mouhamed, 2025; Savas, 2025), which captures whether cross-country inequality in RE, CO2, RD, and WGI decreases over time:

$$\sigma_t(Z) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Z_{i,t}-\bar{Z}_t\right)^2} \tag{1}$$

where $Z_{i,t}$ denotes the value of the indicator Z for the country i at time t, and $\bar{Z}_t$ represents the cross-country mean at time t.

and its scale-adjusted form, the coefficient of variation:

$$CV_t(Z) = \frac{\sigma_t(Z)}{\bar{Z}_t} \tag{2}$$

A declining trend in either $\sigma_t(Z)$ or $CV_t(Z)$ over time indicates σ-convergence, implying a reduction in cross-country inequality.

Second, β-convergence is assessed using standard convergence regressions (Zhang et al., 2024; Aulia & Sari, 2025; Xie et al., 2023), which test whether countries with lower initial levels of a given indicator exhibit faster improvement relative to initially high-performing economies. β-convergence is evaluated using the standard convergence regression:

$$\Delta\ln(Z_{i,t}) = \alpha + \beta\ln(Z_{i,t-1}) + \varepsilon_{i,t} \tag{3}$$

where $\Delta\ln(Z_{i,t})$ denotes the growth rate of indicator Z, α is a constant term, and $\varepsilon_{i,t}$ is the error term.

A statistically significant negative coefficient β indicates convergence, meaning that initially lagging countries improve faster than advanced economies. A non-significant or positive β result suggests divergence or persistence of structural gaps.

The first stage of the β-convergence procedure uses a pooled regression model that relates each structural indicator's growth rate to its lagged level. This specification assumes homogeneous dynamics across countries and does not control for unobserved cross-country heterogeneity. However, this approach suffers from omitted variable bias if structural differences across countries are correlated with the explanatory variable.

To address unobserved time-invariant country-specific characteristics, the second stage introduces country fixed effects. This specification isolates within-country dynamics and removes bias stemming from structural heterogeneity that does not change over time. If the convergence coefficient remains negative and statistically significant after controlling for country effects, this indicates that convergence is not merely driven by structural cross-sectional differences but reflects genuine adjustment dynamics.

In the third stage, the model incorporates year dummies to control for common macroeconomic and policy shocks affecting all countries simultaneously. By introducing time effects, the model separates structural convergence from synchronised external shocks.

3. CONDUCTING RESEARCH AND RESULTS

Table 2 presents descriptive statistics for four core indicators that represent key dimensions of the managed green transition. For each country, the table reports the mean level (M), standard deviation (SD), and coefficient of variation (CV), which capture both a country's structural position and the degree of volatility or instability in the respective dimension over time. In this framework, the mean values reflect long-run structural characteristics, whereas the CV provides a standardised measure of dispersion, enabling comparison of variability across indicators with different units and magnitudes (Mills & Markellos, 2008).

Table 2

Cross-country descriptive statistics of key structural determinants of green economic growth.

Country	Stat	RE	$CO2$	RD	WGI	Country	Stat	RE	$CO2$	RD	WGI
	M	31.833	69.868	2.868	1.490		M	14.929	388.228	1.291	0.559
Austria	SD	4.186	5.893	0.356	0.112	Italy	SD	4.343	66.112	0.148	0.061
	CV	0.131	0.084	0.124	0.075		CV	0.291	0.170	0.115	0.109
	M	7.674	104.140	2.483	1.260		M	36.549	7.826	0.612	0.728
Belgium	SD	3.938	10.033	0.590	0.085	Latvia	SD	4.642	0.626	0.106	0.094
	CV	0.513	0.096	0.238	0.068		CV	0.127	0.080	0.174	0.129
	M	16.117	48.744	0.658	0.162		M	22.816	13.976	0.918	0.837
Bulgaria	SD	4.816	4.758	0.172	0.060	Lithuania	SD	4.638	0.754	0.126	0.122
	CV	0.299	0.098	0.261	0.368		CV	0.203	0.054	0.137	0.146
	M	26.504	19.751	0.919	0.396		M	5.680	9.979	1.311	1.684
Croatia	SD	2.824	2.422	0.197	0.048	Luxembourg	SD	4.275	1.537	0.217	0.034
	CV	0.107	0.123	0.214	0.122		CV	0.753	0.154	0.165	0.020
	M	9.753	7.434	0.533	0.911		M	6.783	165.842	2.006	1.633
Cyprus	SD	5.659	0.577	0.157	0.175	Netherlands	SD	4.541	17.533	0.251	0.053
	CV	0.580	0.078	0.294	0.192		CV	0.669	0.106	0.125	0.033
	M	12.943	113.199	1.656	0.925		M	11.353	317.214	0.949	0.669
Czechia	SD	3.962	12.603	0.341	0.062	Poland	SD	3.489	12.063	0.331	0.145
	CV	0.306	0.111	0.206	0.067		CV	0.307	0.038	0.349	0.217
	M	27.981	40.144	2.847	1.760		M	27.396	51.895	1.341	1.006
Denmark	SD	9.332	10.123	0.230	0.082	Portugal	SD	5.210	8.893	0.278	0.076
	CV	0.334	0.252	0.081	0.047		CV	0.190	0.171	0.207	0.076
	M	26.720	18.568	1.495	1.131		M	22.448	87.304	0.463	0.171
Estonia	SD	7.138	3.903	0.380	0.108	Romania	SD	2.884	12.244	0.043	0.088
	CV	0.267	0.210	0.254	0.095		CV	0.128	0.140	0.094	0.515
	M	37.111	52.120	3.161	1.801		M	11.517	37.474	0.746	0.690
Finland	SD	6.556	11.242	0.341	0.071	Slovakia	SD	3.880	2.979	0.217	0.073
	CV	0.177	0.216	0.108	0.040		CV	0.337	0.079	0.291	0.106
	M	14.307	350.578	2.183	1.153		M	21.741	15.610	1.996	0.929
France	SD	3.968	37.356	0.080	0.094	Slovenia	SD	2.163	1.852	0.371	0.048
	CV	0.277	0.107	0.037	0.082		CV	0.099	0.119	0.186	0.052
	M	13.929	767.328	2.858	1.450		M	15.261	288.229	1.275	0.852
Germany	SD	4.391	76.876	0.267	0.057	Spain	SD	4.664	49.249	0.104	0.091
	CV	0.315	0.100	0.094	0.040		CV	0.306	0.171	0.082	0.106
	M	12.422	51.584	1.259	0.627		M	51.100	45.411	3.321	1.695
Hungary	SD	3.444	5.512	0.243	0.190	Sweden	SD	8.137	6.820	0.110	0.076
	CV	0.277	0.107	0.193	0.303		CV	0.159	0.150	0.033	0.045
	M	8.280	39.321	1.292	1.455		M	4.655	274.751	0.644	-0.621
Ireland	SD	4.211	4.825	0.201	0.078	Ukraine	SD	2.698	68.885	0.228	0.125
	CV	0.509	0.123	0.156	0.054		CV	0.580	0.251	0.354	-0.201

Note: M – mean; SD – standard deviation; CV – coefficient of variation.
Source: developed by the author.

The descriptive evidence confirms that European economies differ substantially not only in their average transition profiles but also in the stability of their trajectories. Countries such as Sweden and Finland exhibit structurally high renewable energy shares combined with relatively stable dynamics, which reflect early and consistent integration of renewables into the national energy system. In contrast, several economies with historically fossil-intensive structures display lower renewable penetration and higher volatility, suggesting that the energy transition process remains uneven and dependent on country-specific constraints. Similarly, the CO2 indicator demonstrates extreme cross-country differences in scale, reflecting structural contrasts between large industrial economies and smaller service-oriented states. The RD dimension also reveals substantial variation in innovation intensity, indicating that technological capacity remains highly asymmetric across Europe. Governance quality measured through WGI exhibits pronounced disparities, with advanced institutional systems maintaining persistently higher levels, while transition economies display lower governance scores and higher instability, which is consistent with institutional path dependence and long-run divergence dynamics.

Figure 1 reports the dynamics of cross-country dispersion measured through the coefficient of variation for four structural pillars of the green transition. The results reveal asymmetric convergence patterns.

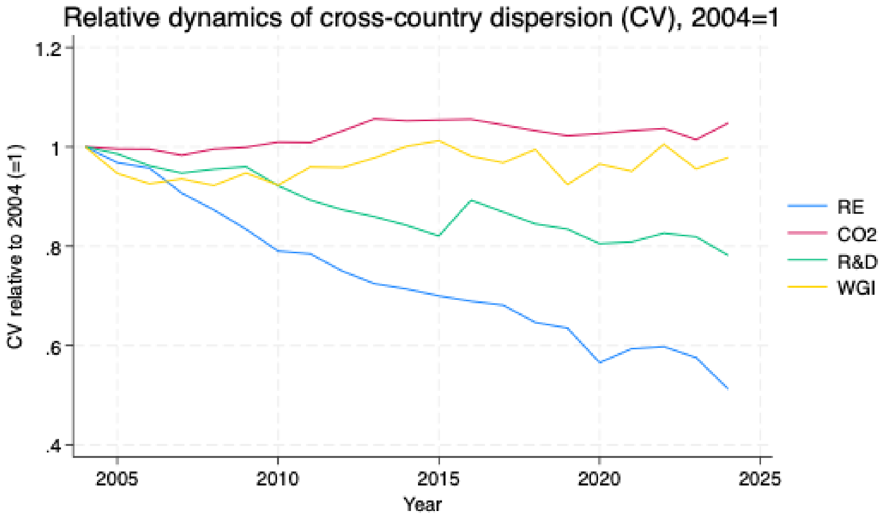

Figure 1. Dynamics of cross-country dispersion (CV) in key green transition pillars
Source: developed by the author.

The dispersion of renewable energy adoption declines substantially over time, indicating gradual convergence in energy transition trajectories across European economies. A similar, although weaker, convergence trend is observed for R&D intensity. In contrast, the dispersion of CO_2-related indicators remain persistently high throughout the period, suggesting that structural differences in emission intensity and industrial composition continue to generate heterogeneous environmental pressure. Governance-related dispersion remains relatively stable, implying that institutional quality differences are not eliminated by EU-level harmonisation.

The results of baseline pooled β-convergence regressions (Table 3) indicate statistically significant convergence in RE and RD, but no convergence in CO2. In contrast, WGI exhibits a positive, statistically significant coefficient, suggesting divergence in governance quality across countries. These findings suggest that while technological and investment-related sustainability indicators converge due to harmonised EU policy frameworks, institutional quality remains characterised by persistent cross-country divergence and path dependence.

Table 3

The baseline pooled β-convergence regressions.

Variables	*RE*	*CO2*	*RD*	*WGI*
L.lnRE	-0.0596*** (0.0047)			
L.lnCO2		-0.0021 (0.0021)		
L.lnRD			-0.0140** (0.0059)	
L.lnWGI				0.0161** (0.0076)
Constant	0.2199*** (0.0131)	-0.0125 (0.0087)	0.0217*** (0.0039)	-0.0377** (0.0166)
Observations	532	532	532	532
R-squared	0.2302	0.0020	0.0105	0.0093

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1
Source: developed by the author.

Table 4 presents fixed-effects β-convergence estimates controlling for unobserved time-invariant country characteristics. The results demonstrate statistically significant convergence across all four indicators.

Table 4. The results of fixed-effects β-convergence estimates.

Variables	***RE***	***CO2***	***RD***	***WGI***
L.lnRE	-0.0614*** (0.0067)			
L.lnCO2		-0.0590*** (0.0139)		
L.lnRD			-0.0968*** (0.0290)	
L.lnWGI				-0.2705** (0.1293)
Constant	0.2247*** (0.0175)	0.2154*** (0.0557)	0.0407*** (0.0067)	0.5741** (0.2761)
Observations	532	532	532	532
R-squared	0.0887	0.0168	0.0562	0.0951
Number of id	28	28	28	28
Individual FE	YES	YES	YES	YES

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1
Source: developed by the author.

Compared to pooled specifications, the convergence effect becomes substantially stronger for CO2 and RD, highlighting that structural heterogeneity masks within-country adjustment dynamics. The sign reversal for WGI suggests that governance divergence dominates at the cross-sectional level, whereas within-country dynamics display partial mean reversion and convergence over time.

Table 5 extends the fixed-effects model by including year dummies that capture common structural shocks. The convergence coefficients remain negative and statistically significant, confirming the robustness of β-convergence patterns.

Table 5

The results of fixed-effects β-convergence estimates by incorporating year dummies.

Variables	RE	$CO2$	RD	WGI
L.lnRE	-0.0842*** (0.0153)			
2006.year	-0.0265 (0.0221)	0.0157 (0.0160)	0.0159 (0.0120)	-0.0032 (0.0140)
2007.year	0.0328* (0.0190)	0.0110 (0.0110)	-0.0178 (0.0201)	0.0225 (0.0304)
2008.year	0.0074 (0.0260)	-0.0201** (0.0076)	0.0373* (0.0187)	-0.0262 (0.0294)
2009.year	0.0692*** (0.0217)	-0.0904*** (0.0135)	0.0200 (0.0248)	-0.0061 (0.0111)
2010.year	0.0425 (0.0498)	0.0230 (0.0179)	0.0185 (0.0176)	0.0023 (0.0108)
2011.year	0.0135 (0.0265)	-0.0375*** (0.0099)	0.0427* (0.0216)	-0.0099 (0.0106)
2012.year	0.0578** (0.0227)	-0.0510*** (0.0089)	0.0252 (0.0221)	-0.0053 (0.0109)
2013.year	0.0427* (0.0220)	-0.0558*** (0.0158)	0.0088 (0.0206)	0.0000 (0.0142)
2014.year	0.0342 (0.0222)	-0.0664*** (0.0086)	0.0044 (0.0217)	-0.0052 (0.0135)
2015.year	0.0226 (0.0221)	-0.0430** (0.0161)	0.0174 (0.0284)	-0.0195* (0.0112)
2016.year	0.0084 (0.0227)	-0.0383** (0.0161)	-0.0671** (0.0298)	-0.0145 (0.0137)
2017.year	0.0250 (0.0222)	-0.0220** (0.0086)	0.0242 (0.0170)	-0.0141 (0.0101)
2018.year	0.0457 (0.0280)	-0.0431*** (0.0124)	0.0384** (0.0186)	-0.0191 (0.0121)
2019.year	0.0400 (0.0297)	-0.0810*** (0.0164)	0.0344 (0.0232)	0.0012 (0.0140)
2020.year	0.1224*** (0.0257)	-0.1357*** (0.0161)	0.0659** (0.0244)	-0.0312* (0.0171)
2021.year	0.0200 (0.0283)	-0.0142 (0.0131)	0.0009 (0.0210)	-0.0063 (0.0143)
2022.year	0.0482** (0.0205)	-0.0842*** (0.0115)	-0.0073 (0.0284)	-0.0260 (0.0166)
2023.year	0.0744*** (0.0216)	-0.1255*** (0.0152)	0.0373 (0.0267)	-0.0060 (0.0160)
L.lnCO2		-0.1896*** (0.0247)		
L.lnRD			-0.0977** (0.0403)	
L.lnWGI				-0.2760** (0.1286)
Constant	0.2481*** (0.0445)	0.7832*** (0.1017)	0.0252* (0.0133)	0.5947** (0.2757)
Observations	532	532	532	532

Variables	RE	$CO2$	RD	WGI
R-squared	0.1736	0.3905	0.1722	0.1312
Number of id	28	28	28	28
Individual FE	YES	YES	YES	YES

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1
Source: developed by the author.

The time effects reveal pronounced crisis-driven dynamics, particularly for CO2 and RE, with significant negative shocks in 2009 and 2020 for emissions, and positive shifts in renewable energy deployment during the post-crisis and pandemic recovery phases. This indicates that the convergence process is not purely gradual but is also shaped by major structural disturbances and coordinated EU policy responses.

The results presented in Tables 3–5 confirm that ensuring green economic growth cannot be interpreted as a purely technological process or a purely market-driven phenomenon. Instead, it requires a governance architecture capable of coordinating multiple subsystems of transformation. In this context, governance is understood not as an abstract "institutional background" but as a structured set of policy instruments, regulatory commitments, and implementation capacities that determine whether the transition trajectory becomes stable, scalable, and productivity-enhancing.

4. DISCUSSION

The empirical results deepen the understanding of the green transition as a multidimensional structural transformation, confirming and extending insights from previous research while also revealing important deviations from dominant assumptions in the literature. The observed convergence patterns across energy systems, innovation capacity, carbon emissions, and governance quality indicate that transition dynamics are neither uniform nor synchronized across structural dimensions.

The convergence detected in renewable energy penetration is broadly consistent with earlier studies emphasizing the effectiveness of coordinated policy frameworks and technological diffusion within integrated economic spaces. Prior research highlights that common targets, regulatory harmonisation, and financial instruments facilitate alignment of energy transition trajectories, particularly within the European Union (Gea-Bermúdez et al., 2021; Naqvi et al., 2023). The present findings reinforce this view by demonstrating not only declining dispersion over time but also statistically significant β-convergence, suggesting that countries with initially lower renewable shares have been catching up. At the same time, the persistence of heterogeneous volatility across countries complements case-based evidence showing that national resource endowments, infrastructural constraints, and historical energy legacies continue to shape the speed and stability of transition paths (Dallavalle et al., 2021).

In contrast, the results for carbon emissions diverge from optimistic convergence expectations implied in parts of the neoclassical literature. While some studies report evidence of emissions convergence driven by technological upgrading and regulatory pressure (Payne, 2020; Tariq et al., 2024), the absence of σ-convergence and pooled β-convergence in the present analysis indicates that cross-country emission disparities remain structurally entrenched. This finding aligns more closely with evolutionary and political economy perspectives, which argue that decarbonisation is constrained by industrial composition, scale effects, and energy dependence (Lamperti et al., 2020; Asim et al., 2023). The emergence of convergence only in fixed-effects specifications suggests that countries are reducing emissions relative to their own baselines, rather than converging toward a common emissions trajectory. This distinction helps reconcile mixed evidence in the literature by highlighting the importance of separating within-country adjustment from cross-country structural convergence.

Innovation capacity, proxied by R&D intensity, exhibits convergence patterns that partially corroborate endogenous growth and ecological modernisation theories. Previous studies emphasize innovation as a key mechanism enabling decoupling between economic growth and environmental pressure (Huang et al., 2020; Fang et al., 2022). The observed convergence supports these arguments, indicating increasing alignment in innovation investment across countries. However, the relatively slow pace of σ-convergence and persistent dispersion confirm earlier findings that innovation effectiveness is subject to threshold effects and institutional complementarities (Li & Li, 2019; Uche et al., 2024). Compared with studies focusing on single-country or sector-level innovation dynamics, the present cross-country evidence demonstrates that innovation convergence is conditional and does not automatically eliminate structural asymmetries.

Governance quality displays the most pronounced divergence relative to prior convergence expectations. While some studies suggest that regulatory harmonisation and policy diffusion within the EU may foster institutional convergence over time (Øjvind Nielsen et al., 2024), the pooled estimations in this study reveal persistent divergence across countries. This outcome is consistent with political economy analyses emphasizing institutional path dependence, uneven administrative capacity, and enforcement credibility as long-term constraints on convergence (Besley & Persson, 2023; Onuoha et al., 2023). The fixed-effects results, however, indicate partial convergence within countries, suggesting incremental institutional improvement rather than cross-country alignment. This dual finding extends earlier work by empirically demonstrating that governance convergence is conditional, slow, and asymmetric, reinforcing arguments that governance should be treated as an endogenous driver of transition outcomes rather than as an exogenous background condition.

The role of systemic shocks further differentiates this study from much of the existing convergence literature. The significant time effects associated with the global financial crisis and the COVID-19 pandemic corroborate recent studies showing that crises can temporarily accelerate decarbonisation through demand contraction, while also reshaping policy priorities (Crnčec et al., 2023; Joiţa et al., 2023). The acceleration of renewable energy deployment during recovery phases aligns with evidence that counter-cyclical green investment strategies can support structural adjustment. At the same time, the heterogeneous impact of shocks across countries supports arguments that fiscal capacity and institutional resilience condition the long-term convergence effects of crisis-driven interventions.

The findings confirm and extend prior research by demonstrating that convergence within the green transition is dimension-specific and institutionally conditioned. While earlier studies often focus on individual pillars, such as energy, emissions, or innovation, the integrated framework employed here shows that progress in one dimension does not necessarily translate into convergence across others. This integrated evidence supports calls in the literature to move beyond sector-specific analyses and to conceptualise the green transition as an interconnected system of technological, economic, and institutional transformations.

By explicitly distinguishing between cross-country structural divergence and within-country adjustment dynamics, this study contributes to resolving longstanding ambiguities in the convergence debate. The results suggest that technological and innovation-related dimensions are more responsive to coordinated policy intervention, whereas emissions and governance outcomes remain strongly shaped by structural and institutional legacies. This interpretation reinforces the view that achieving balanced and resilient green transition pathways requires not only technological diffusion and financial support, but also sustained institutional development tailored to country-specific conditions.

5. CONCLUSION

This study set out to examine the green transition as a managed structural transformation by testing convergence dynamics across four core dimensions: renewable energy penetration, carbon emissions, innovation capacity, and institutional governance quality. Using a balanced panel of 27 EU member states and Ukraine over the period 2004–2023, the analysis combined σ-convergence and β-convergence approaches to assess whether structural disparities across European economies have narrowed or persisted during the transition process.

The σ-convergence analysis reveals a clear reduction in cross-country dispersion for renewable energy penetration and, to a lesser extent, for research and development intensity, indicating gradual structural alignment in technology adoption and innovation investment. In contrast, dispersion in carbon emissions remains persistently high, reflecting enduring differences in industrial composition, scale effects, and energy dependency. Governance quality shows limited σ-convergence, suggesting that institutional disparities are highly persistent despite long-term EU-level harmonisation efforts. The β-convergence estimations further refine these insights. Pooled regressions indicate convergence in renewable energy and innovation indicators, no convergence in carbon emissions, and divergence in governance quality at the cross-sectional level. However, once unobserved country-specific effects and common time shocks are controlled for, fixed-effects models reveal statistically significant convergence across all four dimensions. These finding highlights that within-country adjustment dynamics differ fundamentally from cross-country structural gaps, and that governance convergence operates slowly and conditionally rather than uniformly. The inclusion of time dummies confirms that major shocks, particularly the global financial crisis and the COVID-19 pandemic, have played a significant role in shaping convergence trajectories, accelerating renewable deployment while generating sharp but temporary emission adjustments.

These results confirm that the green transition in EU cannot be interpreted as a purely technological or market-driven process. Instead, it unfolds as an institutionally mediated structural transformation, in which energy systems and innovation capacity display higher convergence potential than carbon intensity and governance quality. Institutional path dependence remains a critical source of long-run heterogeneity.

The findings yield several important policy implications. Thus, the observed convergence in renewable energy and innovation suggests that coordinated supranational policy frameworks, such as the European Green Deal, can effectively reduce technological disparities. Continued support for cross-border energy integration, sector coupling, and innovation diffusion is therefore essential.

Besides, the persistence of carbon emission disparities indicates that decarbonisation requires targeted, country-specific policy instruments rather than uniform regulatory approaches. Economies with fossil-intensive structures may require differentiated transition pathways, combining investment support, industrial restructuring, and social compensation mechanisms.

Furthermore, the slow and conditional convergence in governance quality highlights that institutional reforms cannot be assumed to follow automatically from regulatory harmonisation. Strengthening administrative capacity, regulatory enforcement, and policy credibility, particularly in transition economies, remains a prerequisite for sustaining green transition outcomes. From this perspective, governance should be treated as a core pillar of green transition policy, rather than as a background condition.

The crisis-sensitive nature of convergence dynamics underscores the importance of counter-cyclical green policy design. Coordinated investment programmes during economic downturns can accelerate renewable deployment and innovation while preventing long-term divergence.

Despite its contributions, this study is subject to several limitations. First, the analysis relies on aggregate national-level indicators, which may mask important sectoral and regional heterogeneity within countries. Second, the convergence framework focuses on long-run adjustment dynamics and does not explicitly model causal mechanisms or feedback effects between dimensions. Third, while the inclusion of Ukraine enriches the comparative perspective, the results should not be interpreted as fully representative of non-EU transition economies with substantially different institutional contexts.

Future research could extend this framework in several directions. First, integrating spatial and club-convergence approaches would allow identification of convergence clusters and spillover effects across neighbouring economies. Second, sector-level analyses could uncover heterogeneous transition dynamics within energy-intensive industries, transport, and manufacturing. Third, incorporating additional dimensions, such as green finance, labour market adjustment, or social acceptance, would further enrich the structural perspective. Such extensions would contribute to a deeper understanding of how green transition pathways can be designed to support both environmental sustainability and balanced economic development.

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