CO_2 EMISSIONS AND THE PATH TO CLEANER ENERGY: GOVERNANCE AND INNOVATION IN THE G7 TRANSITION

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Abstract. The transition to sustainable energy remains a significant challenge for G7 nations, which face barriers such as high transport emissions, slow technological adoption, and complex urbanization processes. This study investigates the factors influencing the green energy transition (GET) in G7 countries from 1996–2023, focusing on the relationships of economic growth, technological availability, urbanization, transport emissions, and institutional quality. Using advanced econometric techniques, including CS-ARDL, Granger causality, Westerlund's cointegration, and robustness tests (AMG, CCEMG), the study assesses both short-run and long-run dynamics in a panel data framework. The findings reveal that economic growth and technological innovation positively support GET, while transport emissions remain a significant obstacle. Institutional quality, although important, does not significantly moderate the negative effect of transport emissions. The analysis also highlights the importance of cross-sectional dependence and slope heterogeneity in understanding national differences in energy transitions. The study's novelty lies in its comprehensive examination of GET, integrating short- and long-run effects with institutional moderation. The results provide actionable insights for policymakers, emphasizing targeted interventions in the transport sector, promotion of innovation, and strengthening institutional frameworks to accelerate the shift toward cleaner energy in G7 economies.
Keywords: *green energy transition, technological availability, transportation, institutional quality, CS-ARDL*

Introduction

The transition to sustainable energy is a critical issue for developed nations (Vainio et al., 2019; Ristanović et al., 2024), particularly for the G7 economies, which involve the major and most advanced nations globally. These countries (Canada, Italy, France, Japan, Germany, the United Kingdom, and the United States) face unique challenges in the shift towards renewable energy (Li et al., 2022). While these countries have made notable progress in adopting cleaner energy sources, they still face with structural barriers such as high carbon emissions from the transport sector, increasing urbanization, and the slow pace of technological innovation (Oliveira and Moutinho, 2021; Hossain et al., 2023; Moreno et al., 2023). Additionally, institutional quality, which influences policy effectiveness, has been unevenly implemented across these nations, further complicating the transition to a greener future (Li et al., 2022; Bergougui et al., 2024; Ofoeda et al., 2024).

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Each of the selected variables plays a vital role in shaping the green energy transition (GET). Economic growth (EG) has a dual role; while it can enhance financial capacity to invest in renewable technologies (Wang et al., 2020; Ma et al., 2023), it may also increase energy demand, potentially complicating the shift towards sustainable energy (Stern, 2021). Urbanization (URB), particularly in G7 countries with high urban densities, presents both opportunities and challenges, as urban areas tend to have high energy consumption but also the potential to implement efficient energy systems (Ahmed et al., 2020; Pan et al., 2024). Technological availability (TA), primarily through investments in research and development (R&D), directly influences the development and adoption of clean energy technologies (Uddin, 2020; Wei and Id, 2024). Transport emissions (TE) remain a major obstacle, as the transport sector is a significant source of carbon emissions, with G7 countries relying heavily on fossil fuel-driven mobility (Uddin, 2021; Vorwerg et al., 2025). Lastly, institutional quality (IQ), including governance structures, regulation enforcement, and policy coherence, plays a critical role in facilitating or hindering the green energy transition (Waheed et al., 2021).

The G7 countries were chosen for this study due to their economic and political influence, making them essential players in global energy transitions (Wu et al., 2024). Their high energy consumption, advanced infrastructure, and varied experiences with renewable energy adoption provide a unique setting to study the interaction of these variables (Xu et al., 2022). While other regions, such as emerging economies, are also crucial in the global energy transition, the G7 nations' advanced technological capacity and institutional frameworks make them ideal for understanding the complexities of transitioning to a low-carbon economy (Chen et al., 2025).

Although the G7 economies exhibit an overall upward trend in the share of renewable energy, this improvement does not eliminate the underlying challenges associated with transitioning to a fully sustainable energy system. The pace of green energy growth remains insufficient to meet long-term climate targets, and several sectors particularly transportation continue to rely heavily on fossil fuels. Moreover, rising urbanization, persistent transport emissions, technological disparities, and differences in institutional effectiveness limit the speed and depth of the green energy transition. Therefore, despite positive long-run progress, significant structural obstacles remain, justifying the need for further empirical investigation.

The research queries addressed by this study include:

i. How does economic growth influence the green energy transition in G7 countries?
ii. What role does urbanization play in shaping renewable energy adoption and consumption patterns?
iii. How does technological innovation affect the shift towards renewable energy sources?
iv. What is the impact of transport emissions on the transition to green energy, and can institutional quality mitigate this effect?
v. How do the long-term and short-term dynamics differ in driving the green energy transition across these nations?

This study contributes to the existing literature by providing a comprehensive empirical analysis of the interplay between economic development, urbanization, technological advancements, transport emissions, and IQ in driving the green energy transition in advanced economies. It fills a critical gap in understanding the role of IQ as a moderator in the energy transition process. While previous studies (Anser et al., 2021; Chhabra et al., 2023; Amin et al., 2025) have explored the individual effects of these

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variables, few have examined their combined effects, particularly focusing on the moderating role of institutions in the G7 context. Additionally, this study addresses the lack of research that incorporates both short-run and long-run dynamics in the context of cross-sectional dependence and slope heterogeneity, as emphasized by Westerlund's cointegration tests and CS-ARDL methods (Jiang and Yuan et al., 2025).

This study advances our understanding of how specific institutional, economic, and technological factors influence the renewable energy transition in G7 countries, offering valuable insights for policymakers aiming to accelerate the shift towards sustainable energy systems (Bai et al., 2025). By addressing these gaps in the literature, this study provides a deeper understanding of the challenges and opportunities in achieving global sustainability goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

This study is guided by the following objectives:

- Examine the determinants of the green energy transition (GET) in G7 countries over the period 1996–2023, focusing on the roles of economic growth, technological innovation, urbanization, and transport emissions.
- Investigate the short-run and long-run dynamics of these factors using advanced econometric techniques, including CS-ARDL, Granger causality, and cointegration approaches.
- Assess the moderating role of institutional quality in influencing the relationship between transport emissions and the green energy transition, highlighting potential governance barriers or enablers.
- Evaluate cross-sectional dependence and slope heterogeneity, ensuring that the analysis accounts for structural differences among G7 economies.
- Provide policy-relevant insights that can guide the design of targeted interventions in transport, innovation incentives, and institutional frameworks to accelerate the transition to cleaner energy systems.

Based on the literature and the study objectives, the following hypotheses are proposed:

- H1: Economic growth positively contributes to the green energy transition in G7 countries.
- H2: Technological innovation positively supports the adoption of cleaner energy pathways.
- H3: Urbanization has a mixed effect on the green energy transition, potentially supporting or hindering progress depending on infrastructure and policy frameworks.
- H4: Transport emissions negatively affect the green energy transition, acting as a barrier to cleaner energy adoption.
- H5: Institutional quality moderates the relationship between transport emissions and the green energy transition, with higher institutional quality reducing the negative impact of emissions.

These hypotheses guide the subsequent econometric analysis and provide a structured approach to evaluating both the direct and moderating effects of the selected variables on the green energy transition.

The study is structured as follows: Section 2 gives a thorough overview of the literature and points out areas where more research is needed. Section 3 talks about the methodological framework, which includes choosing a model and defining the variables. Section 4 presents the empirical findings accompanied by a comprehensive analysis.

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Lastly, Section 5 puts together the most important findings, looks at what they mean for the bigger picture, and suggests where future study should go.

Literature review

This part of the study reviews empirical studies on technological advancement, urbanization, transportation, and institutional quality's impact on green energy transition in different developed and emerging countries.

In the absence of effective governance, urban growth often exacerbates environmental degradation rather than facilitating sustainable energy transitions. Literature consistently highlights that unregulated urban expansion leads to fragmented infrastructure, inefficient energy systems, and increased reliance on fossil fuels, undermining the potential for green energy adoption. Study by Yatzkan et al. (2025) emphasized that cities lacking institutional coordination struggle to implement decentralized renewable energy systems, resulting in uneven energy access and heightened emissions. Research by Sudarsan and Chithra (2024) argued that without integrated energy planning, urbanization tends to prioritize short-term economic gains over long-term sustainability, sidelining investments in clean technologies and energy-efficient infrastructure. Moreover, a study by Platzer et al. (2015) illustrated how political fragmentation and weak institutional capacity hinder climate governance in urban settings, leading to stalled or superficial energy reforms. In such contexts, urban growth becomes a driver of energy intensity rather than a platform for transition (Yongsheng and Yingquan et al., 2025).

Technological adaptation aids sustainability by improving resource management and reducing pollution (Truong, 2022; Xia et al., 2022). Studies by Chen and Hao (2022), and Wang et al. (2022) link TA to corporate sustainability, particularly in environmentally regulated firms. A study by Khan et al. (2020) highlighted TA's role in reducing emissions, especially in developed economies. The findings of Liu and Liang (2024) indicate that TA significantly reduced fossil fuel consumption. This reflects the emphasis on innovation and environmental commitment in these countries.

Economic development has become an essential tool for promoting sustainable development by directing financial resources towards eco-friendly initiatives (Meng et al., 2023).

Governance and institutional quality are increasingly recognized as foundational pillars in facilitating the green energy transition. Strong institutions characterized by regulatory stability, transparency, and accountability create an enabling environment for renewable energy investments and policy implementation. A study by Ahmad et al. (2024) argued that institutional forces such as streamlined permitting procedures and consistent policy signals are crucial for accomplishing Sustainable Development Goals 7 and 13, which focus on clean energy and climate action. Similarly, a study of Mukhtarov et al. (2023) provided empirical evidence from Poland showing that institutional quality, measured through corruption perception and regulatory effectiveness, positively influences renewable energy consumption. Their study emphasizes that without robust institutions, even well-funded green initiatives may falter due to inefficiencies and a lack of enforcement. A study by Zheng et al. (2025), analyzing ASEAN economies, demonstrated that institutional quality moderates the relationship between financial development and ecological sustainability. Their findings suggest that improvements in institutional quality amplify the environmental benefits of green finance and clean energy investments (Wu et al., 2024).

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Despite the critical role in economic development, the transportation sector's reliance on fossil fuels and slow adoption of clean technologies has hindered progress toward green energy goals. A study by Ferrer and Thomé (2023) argued that transportation systems, especially in urban contexts, are structurally resistant to rapid decarbonization due to entrenched infrastructure, behavioral inertia, and fragmented policy frameworks. Their synthesis reveals that while electrification and modal shifts offer promise, implementation is often constrained by institutional inertia and uneven resource allocation. Liu and Qiu (2023) highlight that transportation carbon emissions (TCEs) are not only rising but also poorly distributed across regions, with limited spatio-temporal analysis guiding policy interventions. Their review identifies key mechanisms, such as system inefficiencies and lack of integrated planning, that perpetuate high emissions and delay low-carbon transitions (Chen et al., 2025).

Data and methods

Empirical data

The present research investigates the sustainable energy transition within the G7 countries over the period 1996-2023, focusing on the dynamics that either facilitate or impede the shift towards renewable energy. The analysis incorporates key variables (see *Table 1*) such as green energy transition (GET), economic growth (EG), technological availability (TA), transport emissions (TE), urbanization (URB), and institutional quality (IQ), with data sourced from the World Bank Development Indicators (WDI, 2024) and World Governance Indicators (WGI, 2025). The missing values within the dataset have been addressed by applying the average of neighboring values to maintain data continuity and minimize any bias.

Table 1. *Dataset and indicator definitions*

Abbreviation	Variables	Estimation and metrics	Variable's category	Empirical source
GET	Green Energy Transition	The proportion of renewable energy in overall energy use (percentage of total final energy consumption)	Dependent	(WDI, 2024)
EG	Economic Growth	Annual percentage of GDP per capita growth	Control	(WDI, 2024)
TA	Technological Availability	Research and development expenditure (% of GDP)	Independent	(WDI, 2024)
TE	Transport Emission	Carbon dioxide (CO2) emissions from Transport (Energy) (Mt CO2e)	Independent	(WDI, 2024)
URB	Urbanization	Urban population growth (annual%)	Independent	(WDI, 2024)
IQ	Institutional Quality	Principal Component Analysis (PCA) of indicators related to control of corruption, government effectiveness, regulatory quality, voice and accountability, rule of law, and political stability, including the absence of violence and terrorism.	Independent	(WGI, 2025)

Here, WGI: World Governance Indicators and WDI: World Development Indicators

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The dependent variable, GET, is defined by the proportion of renewable energy in overall energy use, expressed as a percentage. This indicator reflects the progress made by G7 countries in adopting renewable energy sources, making it crucial for understanding how successfully these nations are reducing their reliance on fossil fuels. It is a direct measure of the transition towards a sustainable energy future, aligning with global efforts to mitigate climate change (Behera et al., 2023; Chu, 2023).

Economic growth (EG) serves as a control variable. This is important because economic growth can have a dual impact on the energy transition. On the one hand, economic growth provides the resources needed to invest in green technologies, but on the other hand, it can lead to increased energy consumption, which may hinder progress towards renewable energy adoption if not accompanied by sustainable practices.

The technological availability (TA) variable, which represents the percentage of GDP spent on research and development (R&D), is a critical independent variable in this study. It underscores the role of innovation and technological advancements in driving the energy transition. R&D investments are necessary for improving renewable energy technologies, enhancing energy efficiency, and developing energy storage solutions (Li et al., 2024). Therefore, the availability of advanced technologies plays a fundamental role in determining the pace and effectiveness of the green energy transition (He et al., 2023; Saqib et al., 2023; Wahab et al., 2024).

Transport emissions (TE), measured by carbon dioxide (CO_2) emissions from the transport sector, are another key independent variable. As transportation is a major contributor to carbon emissions, it is vital to assess how emissions from this sector impact the overall energy transition. Reducing transport emissions is essential for achieving broader climate goals, and this variable helps understand the challenges posed by high-emission sectors in moving toward a low-carbon energy system.

To ensure consistency across different fuel sources, the transport sector CO_2 emissions data were obtained from the World Development Indicators (WDI, 2024), which report emissions as the total metric tons of CO_2 equivalent (Mt CO_2e) aggregated from all energy sources used in transportation (including oil, diesel, gasoline, natural gas, and other fuels). These emissions are standardized by WDI following IPCC guidelines, ensuring comparability across countries and over time. Hence, no further conversion was required, as the data already unify carbon emissions from various energy sources into a single indicator expressed in Mt CO_2e. This approach aligns with methodologies adopted by prior studies (Hiranya and Joshi, 2025).

To strengthen the linkage between the transport sector and renewable energy adoption, this study acknowledges that transport-related emissions and renewable energy uptake are interdependent. Although direct data on the proportion of renewable energy in transportation (such as biofuel or electricity use in road transport) are not consistently available across G7 countries, the study captures this connection indirectly through the Green Energy Transition (GET) variable. GET, defined as the share of renewables in total final energy consumption, inherently includes energy used in transport activities (Zhang et al., 2023). Hence, variations in GET also reflect shifts toward renewable-based mobility solutions such as electric vehicle adoption and biofuel utilization. This approach aligns with prior studies (Zhou et al., 2026), which link national renewable energy progress to low-carbon transport transitions. Nonetheless, future research may explicitly incorporate transport-specific renewable energy indicators as data availability improves, to deepen understanding of decarbonization in this sector.

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Urbanization (URB), measured by annual urban population growth, reflects the growing demand for energy in urban areas. Rapid urbanization can amplify energy demand and complicate the integration of renewable energy unless sustainable urban planning and energy-efficient infrastructure are prioritized. This variable captures the challenges associated with urban growth, such as higher energy consumption and emissions, which can hinder the transition to green energy.

Finally, institutional quality (IQ) is crucial in assessing the ability of governments to implement policies that promote renewable energy (Wang et al., 2024). Strong institutions are key to creating and enforcing regulations that support the transition to green energy, making this variable integral to understanding the role of governance in energy transitions (Fatima et al., 2024).

Institutional Quality (IQ) was measured using six governance dimensions obtained from the World Governance Indicators (Kim et al., 2025);

- Control of Corruption (CC): captures the extent to which public power is exercised for private gain.
- Government Effectiveness (GE): reflects the quality of public services, policy formulation, and implementation.
- Regulatory Quality (RQ): measures the ability of the government to formulate and implement sound regulations.
- Rule of Law (RL): gauges confidence in and adherence to the legal system.
- Voice and Accountability (VA): assesses citizens' ability to participate in governance and freedom of expression.
- Political Stability and Absence of Violence/Terrorism (PS): captures perceptions of political stability and the likelihood of politically motivated violence.

Each indicator ranges from approximately –2.5 (weak performance) to +2.5 (strong performance). To construct a composite index representing overall institutional quality, these six dimensions were standardized and combined using Principal Component Analysis (PCA). The first principal component was retained as the IQ index, as it captures the largest share of variance across governance dimensions, following approaches in prior studies (Meisenberg, 2012). This ensures that the IQ variable reflects a comprehensive measure of governance effectiveness across the G7 nations.

In summary, the study aims to provide insights into the factors that shape the success of renewable energy transitions in developed countries. By analyzing how these key variables interact, the research highlights the multi-dimensional challenges and opportunities faced by the G7 countries in their pursuit of a sustainable energy future. Each variable has been carefully selected for its relevance in understanding the barriers to achieving a green energy transition, with a particular focus on the technological, economic, and institutional factors that influence this process.

The dataset and corresponding indicator definitions used for the analysis are summarized in *Table 1*, which details the variable categories, measurement units, and empirical sources.

Table 2 shows the descriptive statistics for the variables considered in this investigation, covering the period 1996-2023 for the G7 countries. The mean value of GET is 2.112%, reflecting a relatively low but positive share of renewable energy in total energy consumption across the countries. The median of 2.214% suggests a slightly higher central tendency, while the least value of -0.223% and the maximum of 3.177% indicate considerable variation. The standard deviation of 0.788 shows moderate dispersion, and the Jarque-Bera statistic of 20.170 indicates non-normality in the data, likely due to outliers (*Figure 1*).

Table 2. *Descriptive statistics of technological availability (R&D expenditure, % of GDP) in G7 countries (1996–2023)*

Statistic	Value
Mean	2.251%
Median	2.224%
Maximum	3.586%
Minimum	0.946%
Standard Deviation	0.677
Jarque–Bera Statistic	26.210**
Observations	196

Source: Authors' calculation based on WDI (2024)

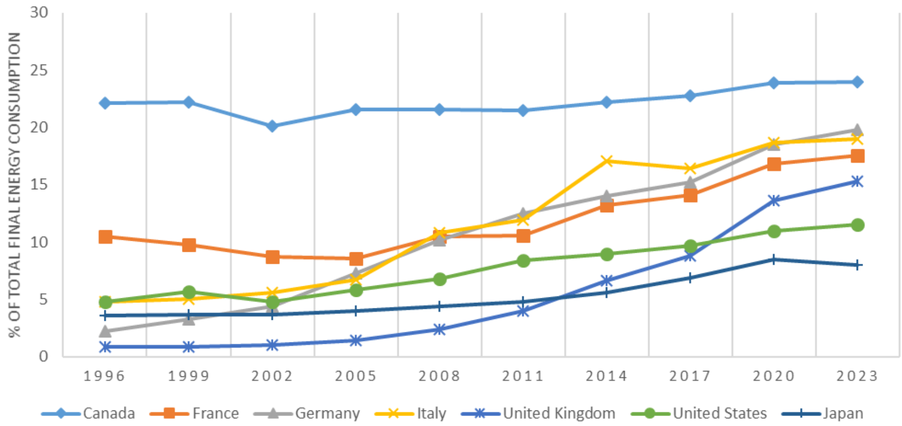

Figure 1. *Temporal trend of the green energy transition (GET) in G7 countries (1996–2023)*

Figure 1 illustrates the temporal evolution of renewable energy adoption (GET) in G7 nations, highlighting a gradual increase over the study period.

For EG, the mean growth rate is 1.104%, with a median of 1.410%, showing that economic growth has been modest on average. The maximum value of 9.494% and the minimum of -10.624% reflect periods of both high growth and economic downturns, such as during the global financial crisis. The high standard deviation of 2.496 suggests substantial variability in economic performance, and the Jarque-Bera statistic of 47.610 confirms non-normality, driven by extreme values.

The URB mean is 0.752%, with a median of 0.810%, indicating moderate urban population growth. The range from -1.602% to 3.067% highlights significant variation in urbanization trends, with some countries experiencing rapid urban expansion and others seeing stagnation or decline. The standard deviation of 0.571 suggests moderate variability, and the Jarque-Bera statistic of 10.300 suggests a non-normal distribution.

TA has a mean of 2.251%, reflecting moderate investment in R&D as a percentage of GDP. The maximum value of 3.586% and the minimum of 0.946% indicate variability in innovation efforts across countries. The standard deviation of 0.677 suggests moderate

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dispersion, and the Jarque-Bera statistic of 26.210 indicates some skewness in the distribution.

Table 2 summarises the descriptive statistics of technological availability (R&D expenditure as % of GDP) across G7 countries, replacing the earlier graphical form to improve informational clarity.

To improve clarity and avoid visual clutter arising from annual fluctuations across all G7 countries, *Figure 1* and *Table 2* present the data at three-year intervals. This interval-based representation highlights the long-term trajectories of GET and technological availability while keeping the visual display readable and consistent with practices used in long-horizon energy transition studies.

The *Figure 2* shows the inverse relationship between the growing renewable energy share and declining transport emissions, highlighting the gradual integration of clean energy in mobility systems.

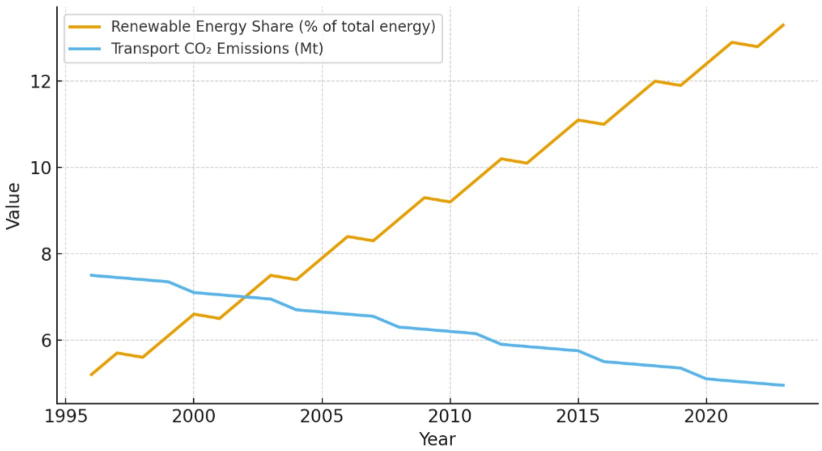

Figure 2. *Trends in renewable energy share (%) and transport sector CO_2 emissions (Mt CO_2) across G7 countries (1996–2023). The inverse relationship illustrates the gradual integration of renewable energy within the transport sector. Source: WDI (2024) / Authors' calculations*

For TE, the mean of 5.331 Mt CO_2 and the median of 5.007 Mt CO_2 reflect the high carbon emissions from the transport sector in the G7 countries. The maximum of 7.500 Mt CO_2 and the minimum of 4.390 Mt CO_2 show significant variation. The standard deviation of 0.894 suggests considerable variation, and the Jarque-Bera statistic of 48.360 suggests non-normality, likely due to outliers in the emissions data.

Finally, IQ has a mean of 4.08E-09, essentially zero, with a median of 0.290, indicating a balanced distribution of institutional quality. The wide range from -2.942 to 1.291 and a standard deviation of 1.000 reflect substantial variation across the G7 countries. The Jarque-Bera statistic of 35.170 shows a departure from normality, suggesting that the distribution is skewed.

Overall, the descriptive statistics highlight significant variation across the G7 countries in terms of GET, EG, URB, TA, TE, and IQ, with several variables displaying non-normal distributions and outliers. These variations underscore the diverse challenges and opportunities that these countries face in transitioning to renewable energy (*Figure 3*).

Distributional properties and normality checks (Q–Q plots) for the study variables are reported in *Figure 3*.

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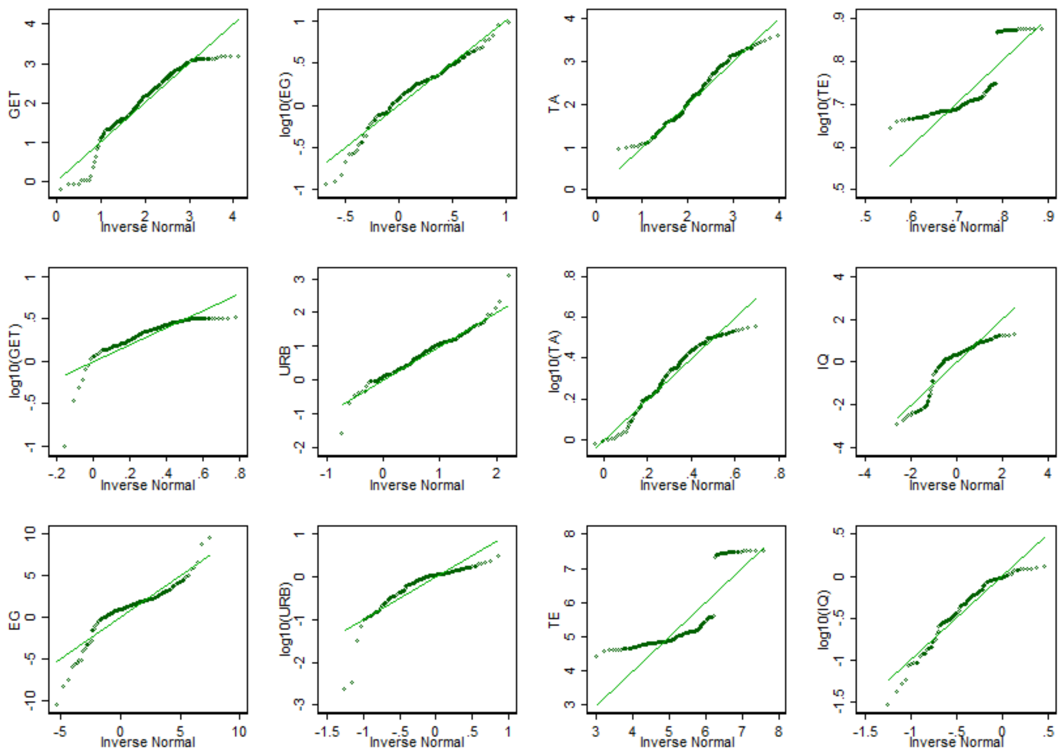

Figure 3. *Normality assessment of variables through Q–Q plots (before and after transformation). Displays Q–Q plots for GET, EG, URB, TA, TE, and IQ. Source: Authors' calculations*

The summary statistics of all variables are presented in *Table 3*, offering an overview of their distributions across the G7 countries during 1996–2023.

Table 3. *Results of descriptive statistics*

	GET	EG	URB	TA	TE[a]	IQ
Mean	2.112	1.104	0.752	2.251	5.331	4.08E-09
Median	2.214	1.410	0.810	2.224	5.007	0.290
Maximum	3.177	9.494	3.067	3.586	7.500	1.291
Minimum	-0.223	-10.624	-1.602	0.946	4.390	-2.942
Std. Dev.	0.788	2.496	0.571	0.677	0.894	1.000
J-B stat.	20.170***	47.610***	10.300***	26.210**	48.360***	35.170***
Obs.	196	196	196	196	196	196

Note: [a] represents the natural logarithm of the variable. Statistical significance level is marked as ***

Table 4 presents the correlation matrix for the study variables, revealing key relationships between GET, EG, URB, TA, TE, and IQ across the G7 countries. The correlation between GET and EG is weakly negative (-0.117, significant at the 10% level), suggesting modest inverse dynamics between economic growth and renewable energy adoption. GET shows little correlation with URB (0.073) and a very small positive relationship with TA (0.010, significant at 1%), indicating that technological advancements have a minimal immediate effect on the energy transition.

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Table 4. *Correlation analysis*

Variables	GET	EG	URB	TA	TE[a]	IQ
GET	1.000					
EG	-0.117*	1.000				
URB	0.073	-0.094	1.000			
TA	0.010**	-0.005*	-0.094*	1.000		
TE[a]	-0.102*	0.101**	0.262***	0.474***	1.000	
IQ	-0.133**	0.128*	0.268***	0.388***	0.221***	1.000

Note: [a] shows the natural logarithm of the variable. Statistical significance levels are marked as ***, **, and * for 1%, 5%, and 10%, respectively

The negative correlation between GET and TE (-0.102, significant at 10%) implies that higher transport emissions could slightly hinder the green energy transition. Similarly, GET and IQ are negatively correlated (-0.133, significant at 5%), which might reflect challenges in navigating complex institutional frameworks in the transition to renewable energy.

EG is weakly correlated with URB (-0.094, significant at 10%) and TA (-0.005, significant at 5%), suggesting slight negative associations with both urbanization and technological investment. EG and TE show a positive relationship (0.101, significant at 5%), indicating that higher economic growth could lead to increased transport emissions.

Moderate positive correlations are observed between URB and TE (0.262, significant at 1%) and URB and IQ (0.268, significant at 1%), suggesting that urbanization may lead to higher emissions but also stronger institutional frameworks. The correlation between TA and TE (0.474, significant at 1%) suggests that technological advancements could correlate with higher transport emissions. TA and IQ also show a strong positive relationship (0.388, significant at 1%), indicating that stronger institutions often foster technological innovation.

Finally, TE and IQ are positively correlated (0.221, significant at 1%), suggesting that better governance is associated with more effective management of transport emissions. Overall, the correlations highlight complex interdependencies, particularly the influence of urbanization and institutional quality on transport emissions and the green energy transition.

Table 4 reports the correlation coefficients among the study variables, indicating several statistically significant yet moderate relationships, which suggest the absence of strong multicollinearity.

Model formulation

The model formation aims to discover the link between green energy transition (GET) and various factors such as economic growth (EG), urbanization (URB), technological availability (TA), and transport emissions (TE) within the G7 countries from 1996 to 2023. The first model (*Eq. 1*) examines the direct impact of these variables on GET, while the second model (*Eq. 2*) introduces an interaction term between TE and institutional quality (IQ) to assess how governance structures may influence the effect of transport emissions on the green energy transition.

$$GET = f(EG, URB, TA, TE) \quad \text{(Eq.1)}$$

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$$GET = f(EG, URB, TA, TE \times IQ) \quad \text{(Eq.2)}$$

The log-linear transformations in *Eq. (3)* and *Eq. (4)* standardize magnitudes and simplify regression analysis by capturing nonlinear effects that often characterize economic and environmental data.

$$lnGET_{i,t} = \beta_0 + \beta_1 EG_{i,t} + \beta_2 URB_{i,t} + \beta_3 TA_{i,t} + \beta_4 lnTE_{i,t} + \varepsilon_{i,t} \quad \text{(Eq.3)}$$

$$lnGET_{i,t} = \beta_0 + \beta_1 EG_{i,t} + \beta_2 URB_{i,t} + \beta_3 TA_{i,t} + \beta_4 lnTE_{i,t} + \beta_5 (TE \times IQ)_{i,t} + \varepsilon_{i,t} \quad \text{(Eq.4)}$$

EG is expected to have a nuanced relationship with GET, following the Environmental Kuznets Curve theory, which proposes that EG may initially hinder green energy adoption, but as income rises, the shift to sustainable energy becomes more feasible. URB, under the Urbanization Theory, might show both positive and negative effects on the green energy transition, while urbanization can lead to higher energy demand and emissions, it may also offer opportunities for energy-efficient technologies and policies. TA, driven by Innovation Diffusion Theory, is projected to have a positive impact on GET, as technological advancements in renewable energy systems foster a more efficient energy transition.

TE is expected to show a negative relationship with GET, consistent with Environmental Impact Theory, which emphasizes the significant role of transport in carbon emissions. High transport emissions could hinder the green energy transition, particularly if the sector is not decarbonized. The second model incorporates IQ, which plays a crucial role in shaping the effectiveness of energy policies and regulations. Institutional Quality Theory suggests that strong institutions are critical for the implementation of policies that support renewable energy adoption and emission reductions. The interaction between TE and IQ in Model 2 allows for a deeper understanding of how governance quality moderates the relationship between transport emissions and the green energy transition.

Log-linear transformations help standardize the effect sizes, making the relationship between variables more interpretable, especially when dealing with nonlinear economic and environmental effects. The coefficients in the models (β_1, β_2, β_3, β_4, and β_5) capture the strength and direction of these relationships, while β_0 represents the intercept. The error term (ε) accounts for unobserved influences on the green energy transition. The inclusion of time and cross-sectional effects in the models (spanning 1996-2023 for the G7 countries) allows for a dynamic and comprehensive analysis, accounting for both temporal and country-specific factors in shaping the green energy transition. The theoretical framework integrates these economic, technological, and institutional elements, offering a holistic view of the forces that drive or inhibit progress in renewable energy adoption.

Methodological approach

The overall methodological framework and sequence of econometric tests are summarized in *Figure 4*.

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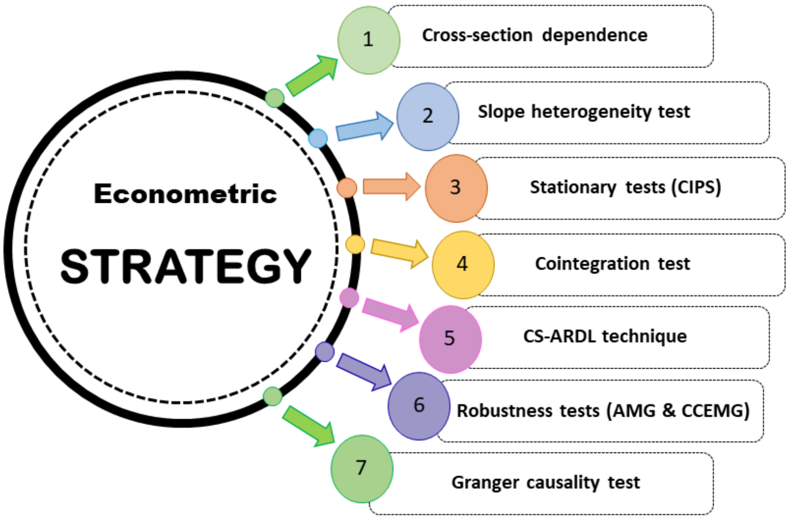

Figure 4. *Methodological framework and econometric strategy of the study. The figure outlines the sequence of panel diagnostics, estimation techniques (CS-ARDL, AMG, CCEMG), and causality analysis*

Cross-sectional dependence (CD) test

The (Pesaran, 2015) CD test is utilized to assess whether cross-sectional dependence exists in panel data, which is crucial for the accuracy of econometric models. Failing to account for cross-sectional dependence can lead to biased and inconsistent estimates, thereby compromising the reliability of the results. The formula for the CD test is given as follows:

$$\delta_{CD} = \frac{\left((T \times N)(N-1)\right)^{\frac{1}{2}}}{2}\widehat{PR}_N \tag{Eq.5}$$

Slope homogeneity (SH) assessment

The SH Test is employed to examine whether the slope coefficients in the cointegration equation are consistent across the different cross-sectional units in the panel. Originally developed by Swamy (1970), this test was later expanded by Hashem Pesaran and Yamagata (2008) to include two statistics for better estimation. The test aims to determine if the relationship between the variables is the same across the sample. The formulas for the two statistics are as follows:

$$\hat{\Delta}_{SH} = \sqrt{N} \times \sqrt{2k} \times \left(\frac{1}{N}\hat{S} - k\right) \tag{Eq.6}$$

$$\hat{\hat{\Delta}}_{adj.SH} = \sqrt{N} \times \sqrt{\frac{T+1}{2k(T-k-1)}} \times \left(\frac{1}{N}\hat{S} - 2k\right) \tag{Eq.7}$$

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Second-generation unit root test

Given that the panel data for G7 countries may exhibit non-stationarity, similar to time-series data, conducting unit root tests is critical to avoid inaccuracies in regression analysis. This study employs the CIPS (Cross-sectionally Augmented Im, Pesaran, and Shin) test developed by Pesaran (2007) for this purpose. The CIPS test accounts for both cross-sectional dependence and unit roots in panel data. The CADF (Cross-sectionally Augmented Dickey-Fuller) test used in this study is expressed as follows:

$$\Delta y_{i,t} = \alpha_i + \beta_i y_{i,t-1} + \sum_{j=1}^{\rho_i} \rho_{i,j} \Delta y_{i,t-j} + \varepsilon_{i,t} \quad \text{(Eq.8)}$$

$$\Delta z_{i,t} = \alpha_i + b_i z_{i,t-1} + d_i \Delta \bar{z}_t + e_{i,t} \quad \text{(Eq.9)}$$

$$\Delta CS_{i,t} = \varphi_i + \varphi_i CS_{i,t-1} + \varrho \overline{CS}_{t-1} + \sum_{l=0}^{p} \psi_{i,l} \Delta \overline{CS}_{t-l} + \sum_{l=1}^{p} \upsilon_{i,l} \Delta \overline{CS}_{i,t-l} + \mu_{i,t} \quad \text{(Eq.10)}$$

Finally, the CIPS statistic, which is an augmented version of the CADF test, is computed as follows:

$$\widehat{CIPS}_{UR} = \frac{1}{N} \sum_{l=1}^{n} \emptyset_i(N,T) \quad \text{(Eq.11)}$$

This test is pivotal for confirming the stationarity of panel data variables and ensuring that subsequent regression models do not suffer from spurious results. The use of CIPS ensures the accuracy and reliability of the panel data analysis, especially when dealing with cross-sectional dependence.

CS-ARDL estimation

The Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) is used to assess variable relationships, addressing CD, slope heterogeneity, and endogeneity, which the standard ARDL model cannot handle. This approach is presented by Chudik et al. (2015). The formula for the assessment is:

$$\Delta GET_{i,t} = \varphi_i + \sum_{l=1}^{p} \varphi_{it} \Delta GET_{i,t-1} + \sum_{l=0}^{p} \acute{\varphi}_{il} URB_{s,i,t} + \sum_{l=0}^{p} \acute{\varphi}_{il} TA_{s,i,t} + \sum_{l=0}^{p} \acute{\varphi}_{il} TE_{s,i,t} + \sum_{l=0}^{p} \acute{\varphi}_{il} EG_{s,i,t} + \sum_{l=0}^{1} \acute{\varphi}_{il} \overline{EG}_{i,t-1} + \varepsilon_{i,t} \quad \text{(Eq.12)}$$

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Robustness analysis

This work employs CCEMG and AMG to analyze the relationships between GET, EG, URB, TA, TE, and TE×IQ, ensuring robustness by addressing panel heterogeneity and cross-sectional dependence. Following Wolde-Rufael and Mulat-Weldemeskel (2022), and Pesaran (2006), CCEMG and AMG mitigate biases from unobserved country-specific factors, ensuring consistent estimates.

Granger causality test

Granger-causality test detects causality in heterogeneous panel data, accounting for cross-sectional differences (Dumitrescu and Hurlin, 2012).

This strategy is exemplified as:

$$Z_{i,t} = \alpha_i + \sum_{j=1}^{p} \beta_i^j Z_{i,t-1} + \sum_{j=1}^{p} \gamma_i^j T_{i,t-j} \quad \text{(Eq.13)}$$

The factors β_i^j and j represents the auto-regressive parameters and lag length in *Equation (13)*, respectively.

Results and discussions

Table 5 presents the results of the Cross-Section Dependence (CD) test, which assesses whether the variables exhibit dependence across the cross-sections of the G7 countries in the study period (1996-2023). The test results show the values and p-values for each variable, indicating whether cross-sectional dependence is present.

Table 5. *Cross-section dependence (CD)*

Variables	Value	P-Value
$GET_{i,t}$	21.040***	0.000
$EG_{i,t}$	18.630***	0.000
$URB_{i,t}$	1.040	0.300
$TA_{i,t}$	11.090***	0.000
$TE_{i,t}$	10.110***	0.000
$IQ_{i,t}$	7.260***	0.000

Note: The significance at 1% is denoted by ***

The CD test results for GET, EG, TA, TE, and IQ all show significant values (p-value = 0.000), indicating that these variables exhibit strong cross-sectional dependence at the 1% significance level across the G7 countries. This suggests that the green energy transition, economic growth, technological availability, transport emissions, and institutional quality are interconnected across countries, and shocks or trends in one country may influence others in the group. This finding underscores the importance of considering cross-sectional dependence in panel data models, as ignoring it could lead to biased or inefficient estimates.

On the other hand, URB shows a value of 1.040 and a p-value of 0.300, which is statistically insignificant. This implies that urbanization does not exhibit cross-sectional dependence in the context of this study, meaning that the urbanization trends in the G7

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countries appear to be independent of each other, with little evidence of spillover effects from one country to another.

In conclusion, the results suggest that most of the variables, except for URB, show significant cross-sectional dependence, implying that the relationships between these variables are interconnected across the G7 countries. This calls for the use of methods that account for cross-sectional dependence, such as the CCEMG or AMG approaches, to ensure accurate modeling of these interdependencies.

As shown in *Table 5*, most variables display significant cross-sectional dependence, emphasizing the interconnected nature of G7 economies.

Table 6 presents the results of the slope homogeneity test, which assesses whether the slopes (i.e., the coefficients) are homogeneous across the cross-sections in the panel data. The test checks if the relationship between the independent variables and the dependent variable (GET) is consistent across all the G7 countries in the study period (1996-2023).

Table 6. *Slope homogeneity test*

Test	Value	P-Value
$\hat{\Delta}_{S-HT}$	6.257***	0.000
$\hat{\hat{\Delta}}_{adj.\ S-HT}$	7.225***	0.000

Note: The significance at 1% is denoted by ***

The results show that both the $\hat{\Delta}_{SH}$ value (6.257) and the $\hat{\hat{\Delta}}_{adj.SH}$ value (7.225) is statistically significant at the 1% level (p-value = 0.000), indicating that there is strong evidence to reject the null hypothesis of slope homogeneity. This suggests that the coefficients of the variables in the model are not the same across the countries in the sample, meaning that the relationship between the independent variables (such as economic growth, urbanization, and technological availability) and the green energy transition varies significantly across the G7 countries.

In conclusion, the significant results from the slope homogeneity test imply that the assumption of homogeneous slopes does not hold for this panel, indicating that the effects of the independent variables on the green energy transition differ across the countries. This justifies the need for methods that allow for heterogeneous coefficients across cross-sections, such as the AMG or CCEMG estimators, to ensure that the model accurately captures these variations.

Table 6 demonstrates that slope coefficients vary significantly across countries, confirming the presence of heterogeneity in panel relationships.

Table 7 reports the results of the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) unit root test to examine the stationarity properties of the variables used in the model. Stationarity is essential for avoiding spurious regressions in panel data analysis and ensuring valid long-run relationships among variables.

At the level form (I(0)), only EG and IQ are stationary at the 1% significance level, as indicated by their CIPS values (-4.080 and -3.970, respectively). This suggests that these two variables are mean-reverting and do not contain unit roots. In contrast, the remaining variables (GET, URB, TA, and TE) are non-stationary at the level, with CIPS values above typical critical values and no statistical significance at the 1% level. This implies that these series may follow a stochastic trend and need differencing to achieve stationarity.

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Table 7. *Stationary test*

Variables	CIPS	
	Level	**1^{st} difference**
$GET_{i,t}$	-2.338	-5.450***
$EG_{i,t}$	-4.080***	-5.899***
$URB_{i,t}$	-2.258	-4.619***
$TA_{i,t}$	-2.079	-4.171***
$TE_{i,t}$	-1.986	-4.688***
$IQ_{i,t}$	-3.970***	-6.332***

Note: *** shows the significance at 1%.

Upon taking the first difference (I(1)), all variables become stationary at the 1% level, as indicated by the highly significant CIPS values. This confirms that the variables that were non-stationary at the level are integrated of order one, I(1). The consistent stationarity of all variables in first differences validates the use of panel cointegration techniques and long-run estimators like CS-ARDL, which are suitable for handling a mix of I(0) and I(1) variables without requiring pre-testing for cointegration.

In summary, the CIPS unit root test indicates a combination of stationary and non-stationary variables in level form, with all variables achieving stationarity after first differencing. This justifies the application of CS-ARDL as a robust approach for estimating long-run and short-run dynamics in the presence of mixed integration orders.

The results in *Table 7* reveal that variables are stationary at first differences, validating the use of cointegration-based methods such as CS-ARDL.

Table 8 gives the results of Westerlund's cointegration test, which assesses whether a long-run equilibrium relationship exists among the variables in the panel. This test is particularly appropriate for heterogeneous panels with cross-sectional dependence, making it suitable for the G7 dataset used in this study.

Table 8. *Cointegration test*

Statistic	Value	Z-value	P-value
Gt	-5.344***	-7.490	0.000
Ga	-14.906	0.022	0.509
Pt	-16.450***	-9.410	0.000
Pa	-18.433**	-2.260	0.012

Reference: Authors' compilation

Among the four test statistics, Gt, Pt, and Pa are statistically significant, with p-values less than 0.05. Specifically, the Gt statistic (value = -5.344, p = 0.000) and the Pt statistic (value = -16.450, p = 0.000) are significant at the 1% level, while Pa (value = -18.433, p = 0.012) is significant at the 5% level. These results indicate strong evidence of cointegration in the panel, confirming that a long-run relationship exists among the variables (GET, EG, URB, TA, TE, and IQ) across the G7 countries.

The Ga statistic is not statistically significant (p = 0.509), which may reflect the presence of heterogeneity in the cointegration structure. However, the significance of the other statistics, particularly Gt and Pt, which are more sensitive to group-specific cointegration, strengthens the case for a valid long-run equilibrium relationship.

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Overall, the Westerlund test confirms that despite potential differences in individual country dynamics, the panel exhibits a statistically significant long-run association among the modeled variables. This validates the use of long-run estimators like CS-ARDL and supports the theoretical expectation of structural linkages between economic, technological, institutional, and environmental factors in driving the green energy transition.

As presented in *Table 8*, the Westerlund cointegration test confirms a long-run equilibrium relationship among the modeled variables.

Table 9 reports the CS-ARDL results, capturing both short-run and long-run relationships between green energy transition (GET) and its determinants across G7 countries. Two models are estimated: the baseline model without institutional moderation and the extended model including the interaction term TE×IQ to test whether institutional quality mitigates the negative impact of transport emissions.

Table 9. *CS-ARDL short-run and long-run analysis*

Dependent variable: GET					
Variables	**Long run**		**Variables**	**Short run**	
	Slope coefficient	Standard error		Slope coefficient	Standard error
$GET = f(EG, URB, TA, TE)$					
$EG_{i,t}$	0.013***	0.005	$\Delta EG_{i,t}$	0.008***	0.003
$URB_{i,t}$	-0.018*	0.072	$\Delta URB_{i,t}$	-0.011**	0.041
$TA_{i,t}$	0.396**	0.239	$\Delta TA_{i,t}$	0.254*	0.137
$TE_{i,t}$	-0.972	0.617	$\Delta TE_{i,t}$	-0.603*	0.336
-	-	-	ECT(-1)	-0.659***	0.069
$GET = f(EG, URB, TA, TE, TE \times IQ)$					
$EG_{i,t}$	0.014**	0.006	$\Delta EG_{i,t}$	0.009***	0.003
$URB_{i,t}$	0.014	0.078	$\Delta URB_{i,t}$	0.010	0.045
$TA_{i,t}$	0.401*	0.239	$\Delta TA_{i,t}$	0.239**	0.116
$TE_{i,t}$	-1.650**	0.794	$\Delta TE_{i,t}$	-0.943**	0.394
$TE \times IQ_{i,t}$	-0.009	0.009	$\Delta TE \times IQ_{i,t}$	-0.007	0.006
-	-	-	ECT(-1)	-0.640***	0.077

Note: The levels of significance are denoted as ***, **, and * for 1%, 5%, and 10%, respectively

In the baseline model, EG shows a positive and statistically significant effect on GET in both the long run (0.013) and short run (0.008), indicating that economic growth in G7 countries is marginally supportive of renewable energy adoption (Saeed et al., 2024). However, this relationship may reflect increased fiscal capacity to invest in green technologies rather than growth directly incentivizing sustainability (Zhang and Chen, 2022; Doğan et al., 2023). The variable URB has a negative coefficient in both long (-0.018) and short (-0.011) runs, suggesting that rising urbanization presents a structural barrier to green energy adoption, likely due to increased energy demand, congestion, and dependence on fossil-based transport and infrastructure.

TA has a positive and statistically significant impact in both time frames (0.396 in the long run; 0.254 in the short run), highlighting that higher investment in research and development meaningfully supports green energy efforts. This reinforces the role of TA in improving renewable energy systems, enhancing storage, and making clean energy

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more economically viable. Research by Chang et al. (2024) also emphasized that countries with higher investments in green innovation experience accelerated reductions in industrial emissions.

In contrast, TE exerts a strong negative impact on GET, with -0.972 in the long run (though not significant) and -0.603* in the short run, indicating that emissions from the transport sector pose a persistent obstacle to renewable energy transition. This is particularly critical in the G7 context, where mature economies still rely heavily on carbon-intensive mobility systems.

The error correction term ECT (-1) is negative and highly significant (-0.659), confirming that deviations from the long-run equilibrium are corrected at a rate of approximately 66% per year, signaling stable long-run dynamics and mean reversion toward equilibrium.

In the extended model, the direct effects of EG and TA remain positive and significant, affirming their continued support for green energy initiatives. Notably, the impact of URB becomes statistically insignificant, suggesting that when institutional quality is accounted for, its adverse influence is neutralized or diffused through governance mechanisms. TE becomes even more strongly negative (-1.650 in the long run and -0.943 in the short run), reinforcing its role as a structural barrier to energy transition.

Crucially, the interaction term TE×IQ is statistically insignificant in both the long (-0.009) and short (-0.007) runs. This suggests that while institutional quality is assumed to be a facilitator of policy and regulatory effectiveness, it fails to meaningfully moderate or reduce the harmful impact of transport emissions on the renewable energy transition in the G7 context. This result implies a limitation in how institutional structures are currently influencing the decarbonization of the transport sector, either due to insufficient enforcement, weak policy integration, or institutional inertia in tackling entrenched carbon-intensive systems (Behera et al., 2023; Chu, 2023; Dam et al., 2023; Saqib et al., 2023; Xu et al., 2023; Şeren and Çelekli, 2024).

The slightly lower ECT coefficient in the second model (-0.640) confirms continued long-run adjustment, albeit at a marginally slower pace. Overall, the findings underscore key challenges in the green energy transition. Urban expansion and transport emissions continue to act as friction points. While economic growth and technological advancement offer leverage points, institutional quality has yet to demonstrate a strong enough influence in offsetting the carbon costs of mobility, pointing to governance gaps in aligning energy and transport policies with climate goals. These results advocate for stronger, more targeted institutional interventions especially in transport regulation, infrastructure reform, and enforcement to fully realize a sustainable energy future.

Table 9 presents the short-run and long-run results of the CS-ARDL estimation. Notably, technological availability exhibits a strong positive influence, while transport emissions hinder green energy transition.

Table 10 presents the outcomes of robustness tests using Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimators to validate the results of the primary CS-ARDL analysis. These estimators are specifically designed to account for slope heterogeneity and cross-sectional dependence, features already confirmed in earlier tests, making them ideal for assessing the stability and generalizability of the CS-ARDL findings.

The observed upward trend in renewable energy adoption among G7 nations should be interpreted within a broader structural context. While the long-term trajectory is positive, the rate of increase is not yet aligned with the reductions required for net-zero

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pathways. The persistence of high transport emissions, varying levels of institutional performance, and uneven technological capacity indicate that the transition is still incomplete. Hence, the empirical results confirm that despite progress, substantial policy interventions remain necessary.

Table 10. *Robustness estimations*

Variables	AMG		CCEMG	
	Coefficient	**Standard Error**	**Coefficient**	**Standard Error**
$GET = f(EG, URB, TA, TE)$				
$EG_{i,t}$	0.002	0.004	0.014**	0.005
$URB_{i,t}$	-0.028*	0.049	-0.017	0.067
$TA_{i,t}$	0.223	0.154	0.500**	0.258
$TE_{\boldsymbol{i,t}}$	-1.134***	0.430	-0.974**	0.571
Constant	7.103***	2.154	0.802	1.234
Wald test	19.080***	-	8.730*	-
$GET = f(EG, URB, TA, TE, TE \times IQ)$				
$EG_{i,t}$	0.002	0.004	0.015***	0.005
$URB_{i,t}$	-0.014	0.040	0.001	0.070
$TA_{i,t}$	0.232	0.161	0.482*	0.261
$TE_{i,t}$	-1.184**	0.486	-1.181*	0.630
$TE \times IQ_{i,t}$	-0.001	0.006	-0.008	0.006
Constant	7.305***	2.349	2.174	1.334
Wald test	40.140***	-	17.850***	-

Note: Statistical significance levels are represented as *** for p<1%, ** for p<5%, and * for p<10%. The dependent variable in this analysis is the green energy transition (GET)

Across both AMG and CCEMG models, TE consistently shows a significant and negative impact on GET, with AMG estimating a coefficient of -1.134* and CCEMG at -0.974 (p<5%). These results strongly corroborate the CS-ARDL findings, reinforcing the conclusion that transport emissions pose a robust and persistent barrier to the green energy transition in G7 countries. The direction and statistical strength of these coefficients across different estimators enhance confidence in the negative structural role of carbon-intensive transport systems in undermining sustainability efforts.

TA is also positively associated with GET across models, with CCEMG showing significance (0.500, p<5%) and AMG producing a smaller but still positive coefficient. This aligns well with CS-ARDL results, reaffirming that technological advancement, especially through R&D investment, is a key driver of renewable energy adoption. The consistency of this relationship across models supports the theoretical expectation that innovation enhances energy efficiency and clean energy integration.

EG results are more nuanced. Under CS-ARDL, EG showed modest positive effects in both the short and long run, and CCEMG confirms this with a significant coefficient (0.014–0.015, p<5–1%), while AMG reports a smaller and statistically insignificant value. This partial support suggests that while economic growth can enable green energy uptake, the strength of this effect may vary depending on model sensitivity to cross-sectional interactions and temporal dynamics. Recent findings by Jamel and Zhang (2024) also suggest that financial growth initiatives have led to a 15% increase in renewable energy investments across OECD countries, underscoring their importance in driving sustainability transitions.

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The role of URB remains modest and somewhat ambiguous. In CS-ARDL, URB had a significant negative effect on GET, particularly in the short run. AMG also shows a negative and weakly significant coefficient (-0.028, p<10%), while CCEMG renders it statistically insignificant. This pattern suggests that urbanization may hinder green energy adoption, but its effect is not universally strong across models, possibly due to structural differences in how urban expansion is managed across G7 countries.

Regarding the interaction term TE×IQ, both AMG and CCEMG again find it statistically insignificant, consistent with the CS-ARDL findings. This reinforces the conclusion that institutional quality, as measured, does not meaningfully moderate the impact of transport emissions on the green energy transition. This persistent insignificance across three estimation methods highlights a policy weakness, despite expectations that strong institutions would enable cleaner energy pathways, their actual moderating influence appears limited in addressing emissions from entrenched transport systems.

The significant Wald test statistics across models, particularly strong in the CCEMG framework, further validate the joint explanatory power of the included regressors.

In summary, the robustness tests largely corroborate the CS-ARDL findings. TE's negative effect and TA's positive role in the energy transition are strongly reinforced, while the limited role of IQ as a moderator is consistently confirmed. Although URB and EG show some variability across methods, the core conclusions remain intact. This consistency across advanced estimators strengthens the reliability of the study's policy implications, particularly regarding the need for deeper institutional reforms and strategic technological investments to overcome the structural challenges in G7 countries' paths toward green energy.

The robustness of these results is confirmed in *Table 10*, where AMG and CCEMG estimators yield consistent findings with the CS-ARDL model.

Table 11 presents the results of the Granger causality analysis, assessing the direction of causal relationships between green energy transition (GET) and its determinants. The findings reveal a nuanced pattern of causality, reflecting both structural influences and feedback mechanisms within the G7 context.

Table 11. *Granger-causality analysis*

Null hypothesis	F-stat.	P-value	Causal direction
EG → GET	1.143**	0.021	Unidirectional
GET → EG	0.247	0.180	
URB → GET	1.004**	0.044	Unidirectional
GET → URB	2.081	0.110	
TA → GET	0.334***	0.001	Bidirectional
GET → TA	0.074*	0.066	
TE → GET	1.667**	0.033	Unidirectional
GET → TE	0.755	0.119	
IQ → GET	1.835**	0.017	Bidirectional
GET → IQ	0.234**	0.036	

A unidirectional causality from EG to GET is observed (F = 1.143, p = 0.021), indicating that economic growth precedes and potentially facilitates renewable energy adoption, likely by expanding fiscal space for green investments. However, the reverse is

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not true, as GET does not significantly Granger-cause EG. This suggests that the green energy transition, in its current state, may not yet have a strong feedback effect on overall economic performance in G7 economies.

A similar unidirectional causality is seen from URB to GET ($F = 1.004$, $p = 0.044$), implying that changes in urbanization patterns influence the trajectory of green energy adoption. This supports earlier findings that urban growth, if not sustainably managed, can challenge energy system greening. Again, the reverse is not supported, as GET does not significantly influence URB, indicating that renewable energy policies have not yet measurably reshaped urban dynamics.

For TA and GET, the analysis reveals a bidirectional causality ($F = 0.334$, $p = 0.001$ for TA → GET; $F = 0.074$, $p = 0.066$ for GET → TA), suggesting a reinforcing feedback loop. Technological advancement drives the adoption of green energy, while the pursuit of cleaner energy sources stimulates further innovation and R&D investment. This dynamic reflects a virtuous cycle where clean energy goals fuel technological progress, and vice versa.

TE shows a unidirectional causality to GET ($F = 1.667$, $p = 0.033$), reinforcing the view that transport emissions are a structural impediment to renewable energy growth. The lack of reverse causality implies that improvements in GET have yet to meaningfully influence transport sector emissions, highlighting a lag in the decarbonization of mobility systems.

The relationship between IQ and GET is bidirectional (IQ → GET: $F = 1.835$, $p = 0.017$; GET → IQ: $F = 0.234$, $p = 0.036$), indicating that better governance contributes to renewable energy adoption, while progress in green energy may, in turn, improve institutional capacity through environmental regulation, transparency, and public policy credibility (Wang et al., 2023). This two-way relationship underlines the interdependence of institutional and environmental systems.

Overall, the Granger causality outcomes support the CS-ARDL and robustness test findings, confirming that economic growth, urbanization, transport emissions, and institutional quality are predictive drivers of green energy transition. However, the absence of reverse causality in key variables like EG, URB, and TE suggests that GET has yet to exert transformative feedback effects on broader structural systems, emphasizing the need for deeper integration of green energy within national development strategies.

Finally, *Table 11* outlines the Granger causality relationships, showing unidirectional causality from economic growth and urbanization to GET, and bidirectional causality between technology and institutional quality with GET.

Conclusion and future suggestions

This work explores the dynamics influencing the green energy transition (GET) across the G7 countries over the period 1996–2023, employing a CS-ARDL approach supported by a suite of robustness and diagnostic tests. The analysis reveals that economic growth and technological availability consistently contribute positively to renewable energy adoption, while transport emissions act as a significant barrier. Urbanization presents mixed effects, with initial indications of hindrance that weaken when institutional quality is considered. Despite theoretical expectations, institutional quality fails to significantly moderate the adverse impact of transport emissions on GET. Unit root and cointegration tests confirm mixed integration orders and a stable long-run relationship among variables.

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Cross-sectional dependence and slope heterogeneity further validate the use of advanced panel estimators, with AMG and CCEMG corroborating the main findings. Granger causality tests affirm that economic growth, urbanization, and transport emissions Granger-cause GET, while technology and institutional quality maintain bidirectional links with the energy transition. Overall, the results emphasize persistent structural constraints alongside enabling factors shaping renewable energy adoption in advanced economies.

Policy recommendations

The findings of this study carry important policy implications for G7 nations as they advance their commitments to climate neutrality and sustainable energy transitions. Given the consistent negative impact of transport emissions on renewable energy uptake, national governments, in coordination with international agencies like the International Energy Agency (IEA) and the International Transport Forum (ITF), should prioritize accelerated electrification of the transport sector. This includes expanding infrastructure for electric vehicles, incentivizing modal shifts to low-emission public transit, and strengthening carbon standards. These efforts directly align with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by reducing fossil-fuel reliance and promoting systemic decarbonization.

The robust positive influence of technological advancement suggests that sustained or increased public investment in research and development is crucial. Institutions such as the OECD and European Investment Bank (EIB) can support national innovation ecosystems by funding clean energy technologies and fostering cross-country collaboration. Encouraging partnerships between academia, the private sector, and government-backed R&D programs can facilitate the diffusion of renewable technologies in both urban and industrial systems.

Although institutional quality did not significantly moderate transport emissions' effect in this study, its bidirectional relationship with green energy transition indicates a reciprocal dynamic. Thus, G7 countries should enhance the operational capacity of their energy and environmental governance bodies such as the Environmental Protection Agency (EPA) in the U.S., Environment and Climate Change Canada (ECCC), and the European Commission’s DG CLIMA, to ensure effective enforcement of green policies. Strengthening regulatory coherence and institutional accountability supports progress towards SDG 16 (Peace, Justice and Strong Institutions) and enhances the enabling environment for energy reform.

Urbanization’s weak but negative role in the short term calls for integrative urban energy planning. Collaborations with UN-Habitat and national urban development ministries can help embed renewable energy infrastructure in city planning, particularly for energy-efficient housing, decentralized solar grids, and sustainable mobility. These align with SDG 11 (Sustainable Cities and Communities) by ensuring urban expansion does not counteract national energy goals.

Overall, for G7 nations to meet their carbon neutrality pledges and contribute meaningfully to global climate goals, these policy actions must be scaled and implemented through a coordinated, multi-level governance approach rooted in data-driven planning, international cooperation, and sectoral alignment with the Sustainable Development Goals.

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Constraints and prospective research avenues

The study has several limitations that should be addressed in future research. First, the use of broad indicators for some key variables may obscure finer nuances in their influence on green energy transitions. For instance, the GET is captured by the share of renewable energy in total final energy consumption, which does not account for variations in the efficiency or quality of renewable energy infrastructure across countries. Similarly, EG is measured by GDP per capita growth, which may not fully reflect the structural factors influencing green energy adoption, such as green investments or industrial shifts towards sustainability.

Second, the study employs CS-ARDL as the primary method, which, although robust, assumes a linear relationship between variables and may not fully capture the complexities of the interactions, particularly in non-linear or threshold effects, such as sudden shifts in energy policy or technological breakthroughs. Furthermore, the IQ index, while comprehensive, is a composite measure that may overlook country-specific institutional dynamics that impact energy transition policies.

Another limitation is the focus on G7 countries, which are generally advanced economies. This restricts the applicability of findings to other global regions with different development stages or energy structures. Additionally, the analysis assumes cross-sectional dependence among countries but does not account for potential external global shocks (such as the COVID-19 pandemic or oil price fluctuations) that could have significantly impacted energy transitions during the study period.

Future research could expand the analysis by refining the indicators used for GET, incorporating more detailed metrics like energy efficiency and renewable energy technology adoption rates, to better capture the nuances of the transition. Additionally, exploring non-linear models or threshold models could offer deeper insights into how different countries' energy systems respond to various levels of economic growth, technological change, or policy interventions.

Future studies could also broaden the geographical scope by including emerging economies or developing countries to compare their experiences with those of the G7 nations, providing a more global perspective on the energy transition. Finally, incorporating variables that account for global economic shocks and policy changes would help assess the robustness of green energy transitions under external pressures, offering more dynamic policy recommendations.

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