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Energy Transition and Carbon Emissions in G7 Economies: New Insights from MMQR Estimation

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Abstract

This study investigates the effects of energy intensity, renewable energy consumption, economic growth, technological innovation, and urbanization on carbon emissions in G7 countries from 2000 to 2024. The Method of Moments Quantile Regression (MMQR) is employed to capture heterogeneous effects across different emission quantiles, with robustness checks using FGLS and PCSE to confirm the model's reliability and stability. The findings indicate that energy intensity and economic growth increase carbon emissions across all quantiles, whereas REC significantly reduces environmental pressure. Technological innovation exhibits a rebound effect at higher emission levels, while urbanization contributes to emissions reduction in advanced quantiles, highlighting the nuanced role of sustainable urban planning. Further, findings emphasize the critical importance of integrating energy efficiency, renewable energy adoption, and targeted technological strategies to achieve carbon neutrality in G7 economies. The findings suggest that G7 countries should support renewable energy adoption, enhance energy efficiency, increase green technological innovation, and implement sustainable urban planning to get long-term carbon neutrality.

Keywords: Carbon emissions, Energy intensity, Renewable energy, Economic growth, Technological innovation, Urbanization, MMQR, G7 economies

JEL Codes: Q43, Q48, O33, Q56 and C21

Introduction

The rise in Carbon emissions (CO2) remains one of the most significant environmental issues facing in the world economy. The Intergovernmental Panel on Climate Change (IPCC) states that global warming and environmental instability are further exacerbated by increasing greenhouse gas emissions. Climate risks and environmental degradation have ramped up across the globe, driven by rapid industrialization, high fossil fuel consumption, URB, and high-impact energy production [55]. Despite a number of countries having implemented climate policy and transitioning to cleaner energy systems, the carbon emissions in several advanced nations have continued to rise due to their reliance on traditional energy systems and unsustainable production processes [52]. The consequence of this has been that the concept of EINT, REC, economic growth, technological innovation and urbanization have become important drivers of environmental sustainability. Past research indicates that low efficiency in energy utilization and economic growth has resulted in high environmental pressure, while the implementation of renewable energy and green technology has been found to lessen emissions [4] [11] [29].

Among these factors, energy intensity has become a key determinant as it indicates the efficiency of economies in energy consumption (EC) during production. Increased EINT tends to be correlated with fossil fuel reliance and emissions increases [52] [39]. While on the other hand, the use of renewable energy is playing a vital role in global decarbonization initiatives because of its potential to reduce carbon emissions and advance environmental quality [11] [29]. Technology can also have a complicated place in environmental sustainability. Technological advancement can help to enhance the energy efficiency and aid the transition towards cleaner energy production systems, but it can also lead to an increase in the EINT and energy demand resulting in rebound effects (Shu & Tan, 2023). Meanwhile, environmental pressures are still being exerted by GDP growth and URB, particularly in advanced countries where industrial and urban population are large [55]. Recent research also indicates that the environmental impacts of these factors vary across countries and emission levels, increasingly requiring advanced econometric techniques to account for heterogeneous relationships, as in [9] [8].

The G7 economies are the heart of the global economy and leading in climate governance. However, despite the progresses made towards the transition to REC and carbon neutrality goals, these countries still rank among the world's biggest emitters of carbon emissions, due to their high industrialization levels, energy consumption and urbanization. Furthermore, there is significant economic and technological interdependence between the G7 countries, so that environmental and economic shocks in one country are likely to rapidly impact others. Therefore, it is crucial to understand the relationship between EINT, REC, TI, economic growth and carbon emissions in the G7 economies to formulate effective environmental policies that are sustainable to the environment.

Although previous studies have extensively examined the determinants of carbon emissions, several important research gaps remain. First, the existing studies on G7 economies investigate average effects using the traditional panel approaches, which may mask heterogeneous association among different emission levels. Second, the specific factors such as technological innovation, economic growth, energy intensity, renewable energy consumption, and urbanization have been generally investigated, these factors are mostly examined separately rather than within a unified empirical framework. Third, the environmental effects of technological innovation and urbanization remain inadequate, mainly among economies with different levels of carbon emissions. To address gaps, this study used the MMQR, which holds heterogeneous affects among the conditional distribution of the input variables at different quantiles of the carbon emissions.

The primary purpose of this study is analyzing the heterogeneous effects of energy intensity, REC, economic growth, TI, and urbanization on carbon emissions across G7 countries. This goal is pursued by using panel data for G7 countries from 2000 to 2024. To estimate the MMQR model, it is required to perform several preliminary econometric tests, such as cross sectional dependence, slope heterogeneity, unit root and cointegration tests. Further, FGLS and PCSE estimators are used to check the robustness of the results. The rest of the study is structured as follows. Section 2 reports literature. Section 3 presents data and methodology. Section 4 presents results and interpretation. Finally, Section 5 reports conclusion and policy recommendation.

Literature Review

With the growing concerns about climate change and environmental degradation, there are growing interest in finding out the primary sources of carbon dioxide (CO_2) emissions. Environmental sustainability is a big policy issue that environmentalists are grappling with due to rapid industrialization, urbanization and over-reliance on fossil fuels, which has led to a significant rise in greenhouse gas emissions. Consequently, the impact of energy intensity, renewable energy use, economic development, technological innovation and urbanization on environmental quality have been examined. But the results are inconclusive so far due to the diversity of countries in terms of their economic structure, energy consumption, and policy context.

Energy intensity is considered as one of the main factors causing environmental degradation due to its role in energy efficiency in production. High energy-intensive economies use more energy for a given output, resulting in higher fossil fuel consumption and carbon emissions. The study conducted by Shokoohi et al. (2022) revealed that increasing energy intensity has a negative impact on environmental quality in Middle Eastern countries. Likewise, Wang and Zhang (2023) demonstrated that inefficient energy utilization is still a significant contributor of emissions in industrialized economies. Similarly, Muhammad et al. (2025) found that intensive systems of production exacerbate environmental degradation particularly in the fast-developing economies. These studies have together served to underscore the need of making energy use more efficient for sustainable development.

Renewable energy consumption on the other hand is generally linked with low carbon emission and high environmental quality. Renewable energy consumption sources like solar, wind, hydro and biomass power decreases reliance on fossil fuels and promotes 'cleaner' production systems.[11] demonstrated that carbon emissions in G7 countries can be substantially lowered with the use of renewable energy. Similarly, [29] noted that the use of renewable energies enhances energy efficiency and reduces reliance on fossil fuels. Similarly, Destek and Aslan (2020) also found that the role of renewable energy in reducing environmental degradation in developed economies is very critical. The results show the importance of scale-up of renewable energy systems to reach long-term sustainability and carbon neutrality targets.

The economic growth-environmental quality nexus is controversial. According to the traditional theories, economic growth leads to environmental pressure since industrial production, transport and infrastructure development require big energy consumption.[54] discovered that economic growth plays a significant role in carbon emissions in E7 countries because of the increases in industrial activities and energy consumption. Similarly, [8] noted that technological development and climate policies are not making the environment any cleaner without the improvement of the economy. Some researchers, however, suggest that in the future, advanced economies could be able to enhance environmental quality with more stringent environmental laws and cleaner technologies, in line with the Environmental Kuznets Curve (EKC) hypothesis. As a case study, Balsalobre-Lorente et al. (2022) proposed that green investment and sustainable growth policies can mitigate some of the environmental costs of economic growth.

Technological innovation is another important consideration of environmental sustainability, but the impact is not yet clear. Green innovation can help to improve energy efficiency, reduce production costs, and facilitate cleaner industrial processes. Meanwhile, technological advances could boost production and energy use in industry, resulting in rebound effects that drive up carbon emissions. Technological innovation positively affects energy consumption and industry in developed nations, leading to higher emissions, as per Shu and Tan (2023). As in the former, [9] suggested that innovations are not enough to enhance environmental quality if there are no good climate policies and institutional support. [19] have found that, on the contrary, an environmentally oriented technological innovation positively affects the ecological sustainability of OECD countries. The mixed results highlight the importance of the design of policy, the quality of institutions and the structure of energy use on the environmental consequences of technological innovation.

The urbanization process is also a decisive factor in determining the environmental outcomes, particularly in advanced countries where the industrial and urban sector is strong. The energy consumption of urbanization is rising because of transport requirements, housing and infrastructure development, which can make the strain on the environment even more intense. In more developed countries, however, sustainable urban planning, smart infrastructure and efficient transportation systems could help to limit emissions.[43] established that ecological pressure rises in economies of industrialization, and sustainable urban policies can enhance environmental quality in the developed world.[40] also noted that the deployment of environmentally friendly urban infrastructure, and the use of renewables, are crucial for emissions abatement in contemporary economies. The overall picture from the literature is mixed, as the effects of energy intensity, REC, economic growth, TI and URB on the environment are not unambiguously positive or negative, especially in the cases of the advanced economies. The inconsistencies found indicate that there is a need for further empirical research in relation to G7 countries.

Methodology

This study examines the environmental impacts of EINT, economic growth, technological innovation, REC, and urbanization on carbon emissions in G7 countries (USA, UK, Japan, Italy, Germany, France, Canada) over the period 2000-2024. The study used on balanced panel data consisting of 175 observations. The variables were taken from the World Development Indicators (WDI) database.

Table 1: Variables Descriptions

Variable	Symbol	Measurement	Data Sources
Carbon dioxide emissions	lnCO2	per capita (tCO_2e/capita)	WDI
Energy intensity	lnEINT	Energy intensity level of primary energy use	
Renewable energy consumption	lnREC	% of total final energy consumption	
Economic growth	lnGDP	constant 2015 US$	

Technological innovation	lnTI	Research and development expenditure (% of GDP)	
Urbanization	lnURB	Urban population (% of total population)	

The general model is:

lnCO2 = f (lnEINT, lnREC, lnGDP, lnTI, lnURB)

Now the econometric or empirical models of this study is specified as follows:

$$lnCO2_{it} = \beta_0 + \delta_1 lnEINT_{it} + \gamma_2 REC_{it} + \vartheta_3 lnGDP_{it} + \sigma_4 lnTI_{it} + \varphi_5 lnURB_{it} + \varepsilon_{it}$$

Where:

$lnCO2_{it}$ = Carbond Dioxide Emissions
$lnEINT_{it}$ = Energy Intesity
REC_{it} = Renewable energy consumption
$lnGDP_{it}$ = Economic Growth
$lnTI_{it}$ = Tecnolgoical innovations
$lnURB_{it}$= Urbanziation

δ_1, γ_2, ϑ_3, σ_4, and φ_5 are the coefficient of the indepenent variables. Besdies, the ε_{it}shows the error terms. As well, the i and t indicates the country and time dimensions repsectively.

Empirical Strategy

This study used a comprehesive panel econometric framework to ensure reliable and robust estimation. First, the dscription statistics (it measures th main aspects of the a dataset, such as mean, variability, and frequency distrubition, to provides a clear overview before analysis) [29] [27]. Therefore, correlation (To describe the direction between inputs variables, and variance Inflation factor (VIF) test are used to examine the direct and multicollinearity issues [27]. Secondly, the slope of homogeneity and CSD test conducted to examine the suitable econometric approach. Third, unit root test Pesaran CIPS and Westerlund cointegration test are used to examine the stationary properties and long run relationships among the variables. Finally, the Method of Moments Quantile Regression (MMQR) estimator is used to examine heterogeneous effect among different emissions quantiles. FGLS and PCSE approach are further used for robustness analysis. Figure 1 displays step by step methodological procedures.

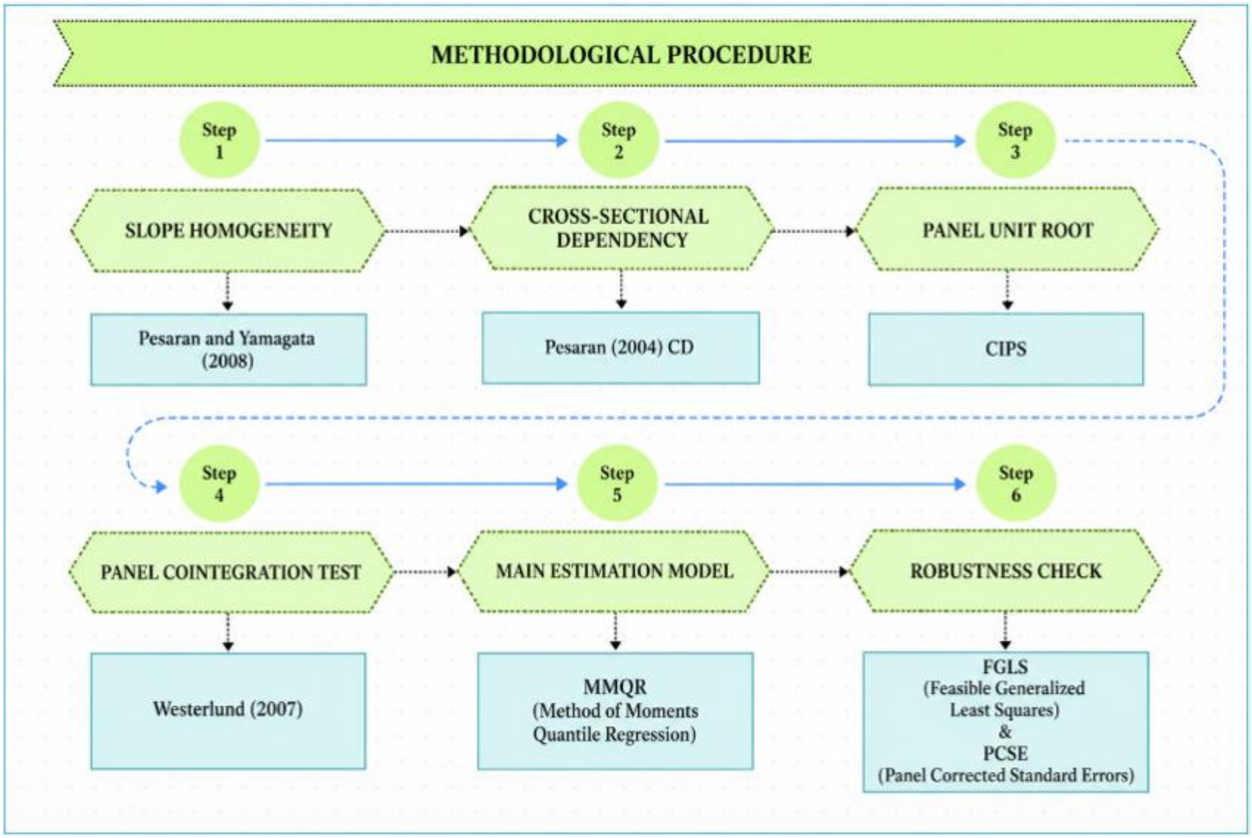

Fig 1: Methodological Procedure

Slope Heterogeneity Test

To examine whether the slope coefficient are homogeneous among panel countries, this study used the Pesaran and Yamagata (2008) slope homogeneity test. The test statistics are described as follows:

$$\Delta = \sqrt{\mathrm{N}}\left(\frac{\mathrm{N}^{-1}\quad \hat{\mathrm{S}} - \mathrm{K}}{\sqrt{2\mathrm{k}}}\right)$$

Thus asjusted sttstics is:

$$\Delta_{adj} = \sqrt{\mathrm{N}}\left(\frac{\mathrm{N}^{-1}\hat{\mathrm{S}} \quad -\mathrm{E}(z_{jt})}{\sqrt{\mathrm{Var}(z_{it})}}\right)$$

Where, N, k and S are represents number of cross-sections, number of regressors, and Swamy test statistics. H_0 Examine the homogenous slope coefficients, while the Ha suggests heterogeneous slopes. The outcomes are shows significant Δ and Δ_{adj} statistics indicating the present of slope heterogeneity among G7 countries.

Cross-Sectional Dependence Test (CSD-Test)

The high economic integration among the G7 economies, CSD may arise due to common shocks and spillover effects. Therefore, the Pesaran (2004) CSD test is used:

$$CS = \sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}}$$

Where, T, N and $\hat{\rho}_{ij}$ indicates the time dimension, number of CSD units, and pairwise correlation of residuals. The empirical outcomes show significant CSD among all variables, applying that shocks in one G7 countries influence others.

Unit Root Test:
In this study used the Pesaran (2007) CIPS unit root test to measure for CSD. The CIPS statistics is expressed is:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i$$

Where $CADF_i$ indicate the cross-sectionally augmented Dickey-Fuller statistics. The otuocmes shows that most variables are non-stationary at I(0), but become statiionary after the I(1).

Cointegration test
This study used the Westerlund cointegration (2007) test to investiage the long run associton among the projected variables. The Westerlund error-correlation model is specified as follow:

$$\Delta y_{it} = a_i + \delta_{it} + \emptyset_i(y_{it-1} - \partial_i x_{it-1}) + \sum \gamma_{ij}\, \Delta y_{it-j} + \sum \emptyset_{ij}\, \Delta x_{it-j} + \epsilon_{it}$$

The H_0 examines no cointegration among the specific variables, while $H_a$shows the presence of cointegration. The empirical outcomes rejectH_0, confirming the existence of a long-run relationship among the specific variables.

Method of Moments Quantile Regression (MMQR)
The hold heterogenous effects among the different CO2 distributions, this study uses the Machado and Silva (2019) MMQR estimator. Unlike convertional panel esitmators, MMQR allows sloe coefficent to vary among quantiles and effectively captures distributional hetergeneity. The MMQR speciffication is given as:

$$Q_y(\tau|X_{it}) = \left(a_i + \delta_i q(\tau)\right) + X'_{it}\beta_i + Z'_{it}\gamma q(\tau)$$

Thus, $Q_y(\tau|X_{it})$ shows the conditiona quntitles functio, $q(\tau)$ is the quantile distribution and X'_{it} shows the input variables and (τ) the differences quantiles. So, the MMQR approach is mainly suitale because the study confims both the CSD and slope heterogenetiy.

Robustness Analysis
To exmaine the reliablity of the MMQR outocmes, this study further used the FGLS and PCSE approaches. The FGLS estiamtor address heterokeasticity and serial correlaiton , while the PCSE estiamtor contorls for panel-specific contermporaneious correlation and autocorrealtion.

Results and discussions

The descriptive statistics for the variables used in the analysis of G7 countries 2000 to 2024 are shown in Table 2. The results reveal that, on average, carbon emissions are at 2.232 and have a standard deviation of 0.440, displaying moderate variation in carbon emissions of the sample economies. The largest variability among the explanatory variables is represented by REC, with evidence of significant variations in pattern of REC among the G7 countries. In contrast, the standard deviation of the URB is the smallest, indicating relatively stable urbanization rates over time. In general, the descriptive statistics indicate that the data are appropriate for an empirical study. The study variables were correlated as shown in Table 3. The results show strong positive association between EINT and CO2 indicating that increase in energy intensity is correlated with increase in carbon emissions. Likewise, the level of carbon emissions is positively associated with GDP, suggesting that economic growth still puts strain on environmental quality in G7 economies. The REC, on the other hand, has a poor negative correlation with CO2 emissions, which indicates that a greater share of renewable energy can contribute to a decrease in environmental degradation. Notably, all the correlations are under the normal accepted value of 0.8, which means that there is no serious multicollinearity problem in the model. Figure 2 display correlation through Heatmap.

Table 2: Summary Statistics

Variable	Obs	Mean	SD	Min	Max
lnCO2	175	2.232	0.44	1.387	3.045
lnEINT	175	1.353	0.358	0.595	2.113
lnREC	175	2.224	0.717	-0.223	3.264
lnGDP	175	10.598	0.181	10.291	11.103
lnTI	175	0.784	0.325	0.001	1.249
lnURB	175	4.376	0.074	4.208	4.524

Table 3: Correlation Matrix

Variable	(1)	(2)	(3)	(4)	(5)	(6)
(1) lnCO2	1.000					
(2) lnEINT	0.846	1.000				
(3) lnREC	-0.014	0.102	1.000			
(4) lnGDP	0.504	0.281	0.045	1.000		
(5) lnTI	0.184	0.091	-0.029	0.374	1.000	
(6) lnURB	0.269	0.241	-0.175	0.281	0.791	1.000

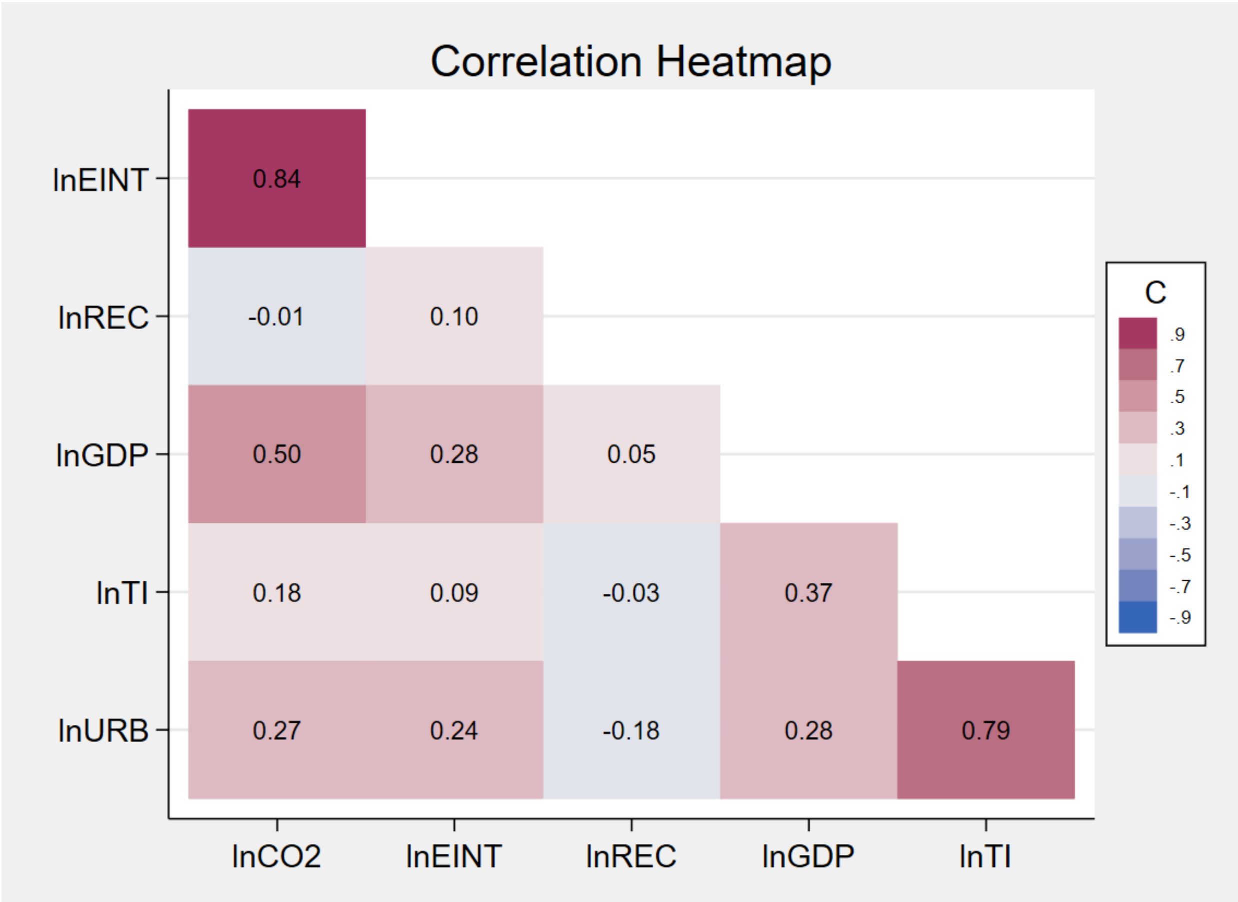

Fig: 2 Correlation Heatmap

Table 4 shows the Variance Inflation Factor (VIF) values that are all under the standard VIF limit of 10 with an Average VIF of 1.993. This indicates that there is no multicollinearity problem in the model and shows that there is no reason why the explanatory variables should not be simultaneously included in the model without the loss of the quality of the regression estimates. Based on this, the results of the test for the slope homogeneity can be seen in Table 5. The Delta, as well as the adjusted Delta are statistically significant at 1% level and the Null Hypothesis of Homogeneous slopes is rejected. The result shows that slopes vary between countries in the G7, suggesting the presence of heteroscedasticity slopes. Therefore, it is appropriate and necessary to use heterogeneous estimators like MMQR. Table 6 further investigates the presence of cross sectional dependence among panel units, based on the evidence of heterogeneity. The findings demonstrate the validity of the CD statistics at the 1% level for all variables, thus confirming the existence of high level cross-sectional dependence of the G7 countries. As a practical matter, this means that the economic or environmental impact of a shock in one country is likely to reverberate throughout other countries, given the high level of economic integration of these economies.

Table 4: Variance Inflation Factor

Variable	VIF	1/VIF
lnURB	3.195	0.313
lnTI	3.167	0.316
lnGDP	1.267	0.789

lnEINT	1.229	0.813
lnREC	1.106	0.904
Mean VIF	1.993	.

Table 5: Slope Homogeneity Test

Test	Statistic	p-value
Delta	9.134***	0.000
Adj. Delta	11.077***	0.000

Table 6: Cross-sectional dependency

Variable	statistic	p-value	Decision
lnCO2	20.526***	0.000	Exist
lnEINT	21.871***	0.000	
lnREC	20.828***	0.000	
lnGDP	15.118***	0.000	
lnTI	8.292***	0.000	
lnURB	15.829***	0.000	

**** p<.01, ** p<.05, * p<.1*

Table 7 presents the results of the Pesaran CIPS unit root test to check the stationarity properties of variables taking into account the presence of heterogeneity and cross-sectional dependence. The results show that most variables are non-stationary at level and they are integrated of order one, I (1), after first differencing. The results confirm and justify the next step of the analysis, which is the panel cointegration analysis to investigate the presence of long-run interplay between the variables. The outcomes of the Westerlund (2007) cointegration test are thus shown in Table 8. The significant group statistics of the test of the null hypothesis of no cointegration reject the null hypothesis and therefore validate the presence of a stable long run equilibrium interplay between CO_2 emissions, EINT, REC, economic growth, TI and urbanization in the G7 countries.

Table 7: Unit Root Test Results

Variable	At-Level	At-First Diff	Decision
lnCO2	-2.644	-5.311***	Exist
lnEINT	-3.452***	-4.724***	
lnREC	-2.105	-5.662***	
lnGDP	-1.593	-4.137***	
lnTI	-2.351	-6.024***	
lnURB	-2.693	-5.041***	

**** p<.01, ** p<.05, * p<.1*

Table 8: Westerlund (2007) Cointegration Test

Statistic	value	p-value
$\boldsymbol{Gt}$	-1.751	0.007***
$\boldsymbol{Ga}$	-5.318	0.994
$\boldsymbol{Pt}$	-3.900	0.027**
$\boldsymbol{Pa}$	-5.396	0.865

**** p<.01, ** p<.05, * p<.1*

The estimation results from the MMQR are shown in Table 9, which exhibits several interesting trends on the impacts of the explanatory variables on carbon emissions across various carbon emission quantiles. The results indicate that the energy intensity is a significant and positive determinant of carbon emissions at all quantiles, indicating that inefficiency in using energy continues to be a significant sources of environmental degradation in G7 countries. This is similar to the findings of Ibad et al. (2025) who also found that the higher the EINT, the higher the CO_2 emissions in developed economies. In contrast, the use of REC has positive influence on carbon emissions at all quantiles, reflecting the positive impact of renewable energy on environmental quality in terms of fossil fuels. This discovery is consistent with the study by [11] which highlighted the critical importance of renewable energy adoption for environmental protection. The same applies to the impact of GDP on carbon emissions over the different emission distributions: GDP is still shown to be positive and significant in spite of continuously improving technology, indicating a sustained increase of environmental pressure from economic growth in G7 countries. This result aligns with the findings of [8] who drew the conclusion that GDP is still strongly linked with carbon emission. Technological innovation shows heterogeneous effects across quantiles, on the other hand. Its effect is not statistically significant at lower quantiles, but is positive and statistically significant at higher quantiles, thus pointing to the existence of rebound effects in higher emission economies. In other words, TI can trigger the industrialization process and the demand for energy which can lead to higher emissions in advanced countries. This interpretation is in line with Shu and Tan (2023) who discovered that TI can cause an increase in EC and industrial production at the outset, only to provide environmental advantages later. Urbanization too is heterogeneous. Its impact is negligible at low quantiles and negative and significant at high quantiles, suggesting that sustainable URB positively affects the environment in advanced economies. This finding is in line with [29], who highlighted the role of smart urban infrastructure and efficient transportation systems in reducing environmental degradation. For robustness check of these results, the results from the FGLS and PCSE estimators are reported in Table 10. The robustness estimates have been fairly stable overall compared to the MMQR estimates. Carbon emissions are still on the rise with the rising consumption of energy and GDP, while the REC consistently lowers environmental degradation. Technological innovation has a relatively small emission-reducing impact, and URB continues to have a negative but less stable association with carbon emissions. The robustness analysis increases the robustness of the main empirical results.

Table 9: Method of Moments Quantile Regression (MMQR) Results

Variable	$\boldsymbol{Quantile_{0.1}}$	$\boldsymbol{Quantile_{0.25}}$	$\boldsymbol{Quantile_{0.50}}$	$\boldsymbol{Quantile_{0.75}}$	$\boldsymbol{Quantile_{0.90}}$
lnEINT	1.142***	1.010***	0.913***	0.868***	0.844***
lnREC	-0.101**	-0.080***	-0.064***	-0.057***	-0.053***
lnGDP	1.169***	0.846***	0.609***	0.497***	0.439***
lnTI	-0.201	-0.018	0.116**	0.179***	0.212***
lnURB	0.659	-0.026	-0.529**	-0.766***	-0.889***
Constant	-14.539***	-7.894***	-3.023**	-0.723	0.465

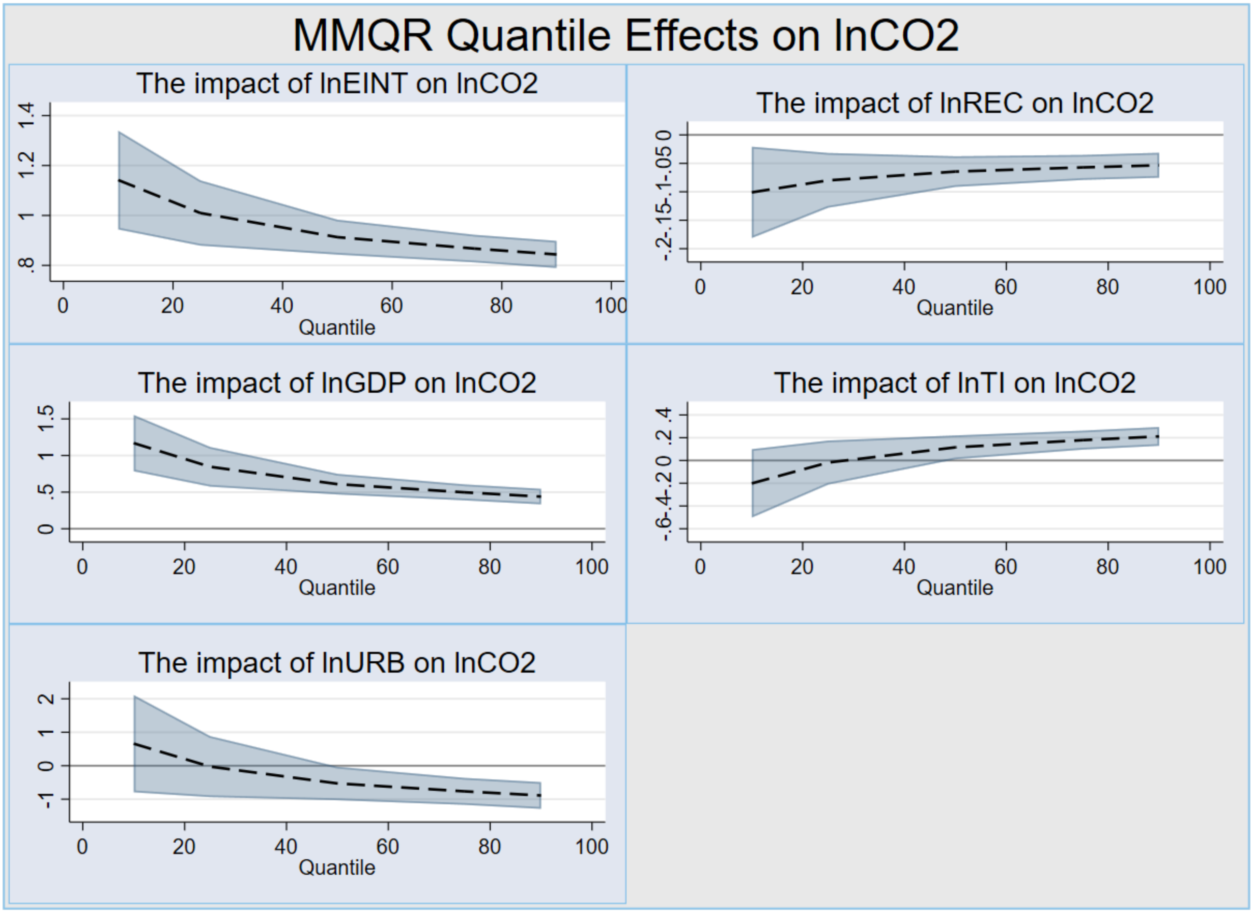

Table 10: Robustness Results (FGLS and PCSE)

Variable	FGLS	PCSE
	Coef.	Coef.
lnEINT	0.885***	0.884***
lnREC	-0.069***	-0.070***
lnGDP	1.014***	0.998***
lnTI	-0.099***	-0.092*
lnURB	-0.716**	-0.100
Constant	-6.322***	-8.894***

Conclusion and Policy Recommendations

This study investigates the effects of energy intensity, renewable energy consumption, economic growth, technological innovation, and urbanization on carbon emissions in G7 countries from 2000 to 2024. The results indicate that energy intensity and economic growth have a significant upward effect on carbon emissions in all quantiles, reinforcing the findings by the Method of Moments Quantile Regression (MMQR) that inefficient EC and expansion of economic activity continue to be important factors causing environmental degradation. However, renewable energy use is always linked to carbon emission reduction and environmental sustainability. Another finding is technological innovation has mixed impacts. It has a smaller effect at lower emission quantiles and more effect at higher quantiles due to rebound effects related to higher levels of industrial activity and energy consumption. Consider the emissions at higher quantiles: urbanization reduces emissions, indicating that sustainable urban planning and efficient infrastructure can help to improve environmental quality in an advanced economy. The findings are also consistent with the FGLS and PCSE results. Policy-wise, G7 countries should increase investments in renewable energy and energy efficient technologies to decrease fossil fuel reliance and help achieve carbon neutrality. It is also important that green innovation is encouraged through environmental policies, research support and clean production policies so that technology development works in favor of long-term environmental sustainability.

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