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Assessment of Global Sustainable Competitiveness Index, Renewable Energy, and Climate Change Technologies in Realizing Environmental Sustainability: Evidence from Panel Quantile Regression

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Abstract: Environmental sustainability is important for addressing global challenges, as it encourages responsible practices that balance economic, social, and environmental factors. The Global Sustainable Competitiveness Index (GSCI) is a comprehensive measure used to assess the sustainability performance of countries or regions across various dimensions. It typically considers economic, environmental, and social factors to provide a holistic view of sustainability efforts. This study explores the relationship between the GSCI, renewable energy, climate change technologies, and carbon emissions (CO2). Therefore, this study aims to assess the role of sustainability in economic competitiveness and its impact on environmental outcomes. The study utilizes panel quantile regression to analyze the impacts of the GSCI, renewable energy, climate change technologies, and causal determinants on CO2 emissions in OECD countries from 2013 to 2022. We use a comprehensive dataset spanning multiple regions and years to analyze the association between GSCI scores and CO2 emissions levels. This study also employs the long-run estimate using the autoregressive distributed lag (ARDL) approach and panel causality tests. The results based on the panel quantile regression indicate a significant and causal relationship between renewable energy, climate change technologies, CO2 emissions, and causal factors. The GSI scores have a moderating and significant role in reductions in CO2 emissions. Finally, our findings shed light on the extent to which global sustainability initiatives correlate with reductions in carbon emissions and balance economic competitiveness with environmental concerns, providing valuable insights for policymakers, businesses, and researchers striving to address climate change and promote sustainable development on a global scale.

Keywords: Environmental sustainability, Climate change technologies, Renewable energy

Introduction

In the face of escalating environmental challenges such as climate change, resource depletion, and pollution, the imperative for sustainable development has become increasingly crucial. This importance stems from the recognition that unchecked environmental degradation poses profound risks to ecosystems, economies, and societies worldwide. One of the prominent challenges confronting the world today is the rise in carbon emissions stemming from the use of non-renewable energy sources, particularly fossil fuels. The extensive dependence on fossil fuels has led to a significant increase in global energy consumption and a simultaneous surge in carbon dioxide (CO2) emissions, as highlighted by Gershon et al. (2024) and Phadkantha and Tansuchat (2023) and Shah et al. (2023). This escalation presents a pressing threat of global warming, propelled by factors such as industrialization, urbanization, population growth, and shifts in lifestyle habits. Moreover, its impacts extend beyond environmental realms, exerting significant socioeconomic pressures and exacerbating existing inequalities.

The Global Sustainable Competitiveness Index (GSCI) emerges as a comprehensive framework for assessing nations' abilities to generate inclusive wealth while minimizing environmental harm, the GSCI provides a nuanced understanding of the dynamics of sustainable competitiveness. By examining a range of indicators spanning natural capital, resource efficiency, social capital, innovation, governance, and economic sustainability, the index offers insights into the multifaceted dimensions of sustainability and competitiveness. The GSCI stands out as the most comprehensive and precise tool for assessing the competitiveness of nation-states and their prospects. It serves as a valuable gauge for creditors assessing country-specific risks, as well as for other stakeholders seeking to evaluate both risks and opportunities within particular sectors.

However, as the global community strives to address environmental challenges and transition towards a more sustainable future, it is essential to consider the role of renewable energy and climate change technologies in this endeavor. Renewable energy sources, such as solar, wind, hydroelectric, and biomass, offer cleaner and more sustainable alternatives to fossil fuels, with the potential to reduce greenhouse gas emissions, enhance energy security, and foster economic development. Similarly, advancements in climate change technologies, including carbon capture and storage, sustainable transportation solutions, and resilient infrastructure, hold promise in mitigating the impacts of climate change and building adaptive capacity.

In the existing literature of study, several investigations have demonstrated the significant role of renewable energy and green technology in mitigating carbon dioxide (CO2) emissions (Amarante et al., 2021; Bilal et al., 2022; Lin & Ma, 2022; Luo et al., 2021; Nguyen & Le, 2022; Wolde-Rufael & Weldemeskel, 2020). These studies consistently highlight that the use of renewable energy sources tends to decrease CO2 emissions, and also the advancement of green innovation lead to reduction of CO2 emissions. Furthermore, there are several studies has focused on the effects of climate change adaptation and mitigation on CO2 emission levels ((Kahn et al., 2021a, 2021b; Ladenburg et al., 2024; Nyiwul, 2021; Stock, 2020). On the other hand, a few studies indicate that promoting the development of green and low-carbon energy and green technologies holds promise for minimizing environmental harm and achieving carbon neutrality (Hao et al., 2021; Nguyen & Le, 2022; Zhao et al., 2020; Zhu et al., 2023). Additionally, a subset of studies suggests the role of renewable energy consumption, educational level, and economic growth on sustainable goals and decreasing the level of carbon emissions (Erdem et al., 2023; Espoir et al., 2022; Fukase, 2010; Khan, 2020; Magazzino et al., 2023; Naseem & Guang Ji, 2020; Tenaw, 2022; Zhang et al., 2023).

This study aims to investigate the potential impact of climate change technologies, the GSCI, renewable energy, education level, economic growth, and general technology diffusion on CO2 emissions in OECD countries spanning the period from 2013 to 2023 by employing the panel quantile regression approach. To the best of our knowledge, no prior study has comprehensively examined the role of the global sustainable competitiveness index with multiple factors in environmental sustainability within the context of OECD economies. The significance of employing this analytical framework lies in recognizing that environmental sustainability in OECD countries represents a pivotal area of study, given its intricate interplay between economic dynamics and environmental considerations.

The empirical findings of our study underscore the role of climate change technologies, the GSCI, general technology diffusion, and the use of renewable energy in the levels of CO2 emissions in the selected OECD countries. These results highlight the significance of pursuing environmental sustainability, with a particular emphasis on promoting renewable energy utilization and climate change technologies. Overall, our study contributes to advancing knowledge in the field of environmental sustainability by offering insights into the key drivers and mechanisms underlying CO2 emissions reduction efforts. This study proceeds with the data description and methodology is presented. Later, this study reports the empirical results and discussion. Lastly, this study ends with the conclusions and recommendations.

Data Description and Empirical Model

Data

This section provides the data and empirical model for 38 OECD over the period from 2013 to 2023. These countries and periods are chosen based on the data availability. Table 1 presents a compilation of data descriptions. The aim is to examine how the development of climate change technologies, renewable energy, and global sustainable competitiveness index affects carbon dioxide (CO2) emissions, taking into account multiple causal factors such as income level, education index, and general technology diffusion. In the realm of environmental economics, the EKC framework stands out as a pivotal empirical model for investigating renewable energy and environmentally friendly technology, as evidenced by studies conducted by (Chu et al., 2023; Dong et al., 2018; Khoshnevis Yazdi & Shakouri, 2017; Li et al., 2022; Saidi & Omri, 2020; Voumik et al., 2022; Wang et al., 2022; Wolde-Rufael & Weldemeskel, 2020; Hassan et al., 2024).

This study also employs the EKC framework to assess how carbon emissions are affected by climate change, human capital, foreign direct investments, and research and development (R&D) expenditure, as in studies by (Habiba et al., 2022; Jiang et al., 2022; Li et al., 2023; Li & Shao, 2023; Obada et al., 2024; Wang et al., 2023, 2024; Zhang et al., 2022; Zhu et al., 2023).

Table 1. Data descriptions

Variable	**Definition**	**Source**
Carbon dioxide emissions (CO_2)	CO_2 emissions (metric tons per capita)	World Development Indicators (WDI)
Global Sustainable Competitiveness Index (GSCI)	Calculated by 6-dimensional model	World Bank, various UN agencies, the IMF.
Climate Change Technologies (CCT)	The sum of climate change adaptation and mitigation Technologies based on patent applications	Organization for Economic Co operation and Development (OECD) statistics
Economic Growth (GDP)	GDP per capita (current US$)	WDI
Education Index (EDU)	Average of expected years of schooling (of children) and means years of schooling (of adults)	Human Development Report of the UN.
Renewable Energy (GE)	Renewable energy share of renewable energy in total final energy consumption (%)	WDI
General Technology Diffusion (GTD)	The sum of environment-related technologies, climate change adaptation, and sustainable ocean economy, % all technologies (%)	OECD statistics

The GSCI evaluates both the competitiveness and sustainability of nations. Sustainable competitiveness refers to the capacity to create and uphold inclusive prosperity while safeguarding the ability to maintain or enhance current levels of prosperity in the future. Figure 1 shows the sustainable competitiveness model which encompasses natural capital, resource efficiency, social capital, intellectual & innovation capital, economic sustainability, and governance performance. This index relies entirely on quantitative metrics and considers 188 indicators sourced from reputable global data outlets such as the World Bank, various UN agencies, and the IMF.

Figure 1. The sustainable competitiveness model

Figure 2 illustrates a plot of the average global sustainable competitiveness index across 38 OECD countries from 2013 to 2023. The global sustainable competitiveness index reaches a high level in Sweden, Finland, and Iceland in 2023.

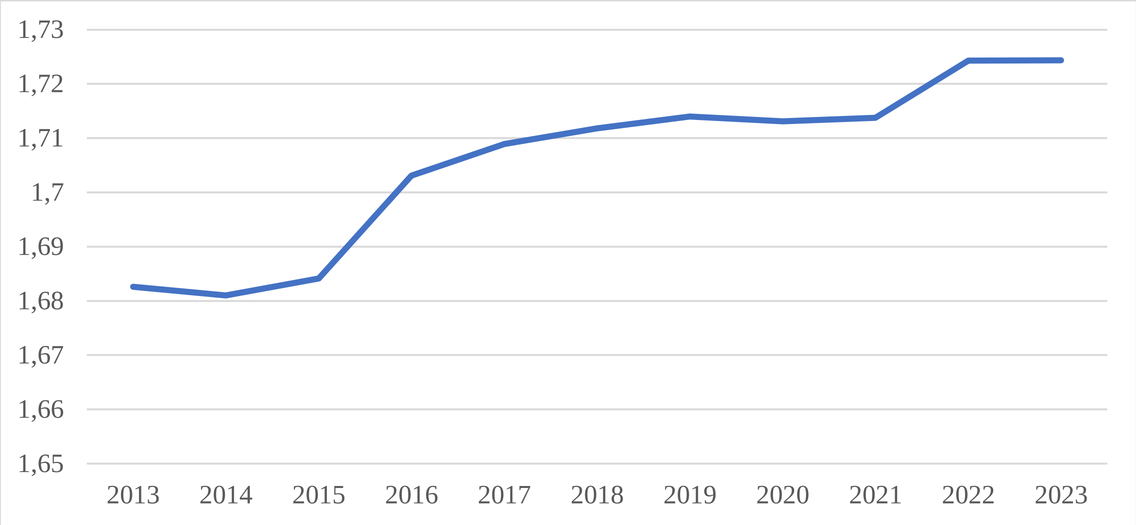

Figure 2. The global sustainable competitiveness ındex, 2013-2023**.**
Source: Author's own calculations.

Empirical Model

Previous literature has predominantly focused on investigating the influence of CO2 emissions on environmental sustainability. Several empirical studies (Chen et al., 2019; Mamkhezri & Khezri, 2023; Mitić et al., 2023; Mongo et al., 2021; Rahman et al., 2022; Sezgin et al., 2021; Shahzad et al., 2020; Tsimisaraka et al., 2023; Yao et al., 2020) aim to investigate the correlation between CO2 emissions and their potential repercussions on sustainable development objectives, encompassing environmental, social, and economic welfare over an extended period. To analyze the determinants affecting carbon emissions, this study employs a dynamic model. Herein, we introduce an empirical model aimed at scrutinizing the impacts of climate change technologies, renewable energy, and global sustainable competitiveness index, economic growth, education level, and general technology diffusion on CO2 emissions in 38 OECD countries.

The model is articulated as follows:

$$LCO_{it} = \beta_{it} + \alpha_{2i}LGSCI_{it} + \alpha_{3i}LGDP_{it} + \alpha_{4i}LCCT_{it} + \alpha_{5i}LEDU_{it} + \alpha_{6i}LRE_{it} + \alpha_{7i}LGD_{it} + \varepsilon_{it}$$

where LCO represents carbon emissions per capita, LGSCI denotes global sustainable competitiveness index, LGDP shows denotes per capita income level, LCCT is the climate change technologies, LEDU denotes education index, LRE represents renewable energy, and also LGD represents general technology diffusion. All variables are taken their natural logarithm level. The error term is denoted as ε_{it}, with *i* and *t* representing countries and time, respectively. This study constructs an empirical model by combining the form of the quantile approach as follows:

$$Q_{\tau}(LCO_{it}) = \beta_{\tau} + \alpha_{2\tau}LGSCI_{it} + \alpha_{3\tau}LGDP_{it} + \alpha_{4\tau}LCCT_{it} + \alpha_{5\tau}LEDU_{it} + \alpha_{6\tau}LRE_{it} + \alpha_{7\tau}LGD_{it} + \varepsilon_{it}$$

where the panel quantile regression is represented as *Q*, with the specific quantile point denoted by *τ*.

Table 2. Descriptive statistics and correlation matrix

Panel A: Descriptive Statistics							
	LCO2	**LGSCI**	**LGDP**	**LCCT**	**LEDU**	**LRE**	**LGD**
Observations (*n*)	418	418	418	418	418	418	418
Mean	0.805	1.705	4.553	0.777	2.032	1.248	3.678
Maximum	1.335	1.784	5.082	4.721	2.214	1.917	5.701
Minimum	0.226	1.594	3.811	0.011	1.802	0.459	2.167
Std. Dev.	0.237	0.037	0.221	0.854	0.063	0.303	0.891
Skewness	-0.259	-0.257	-0.751	1.931	0.615	-0.132	0.301
Kurtosis	3.04	2.610	4.234	6.312	4.277	3.01	2.466
Jarque–Bera	4.849	2.81	5.969	10.474	7.172	2.241	5.751
Probability	0.000	0.002	0.000	0.000	0.000	0.0125	0.000
Panel B: Correlation Matrix							
Probability	**LCO2**	**LGSCI**	**LGDP**	**LCCT**	**LEDU**	**LRE**	**LGD**
LCO2	1.000						
LGSCI	0.186*	1.000					
LGDP	0.591*	0.572*	1.0000				
LCCT	0.133*	-0.338*	-0.0937	1.000			
LEDU	0.238*	0.318*	0.3930*	-0.173*	1.000		
LRE	-0.268*	0.384*	-0.0787	-0.262*	0.2465*	1.000	
LGD	0.435*	0.120*	0.424*	0.215*	0.0430	-0.416*	1.000

Note: *Denote significance levels at 5%.

Table 2 provides a summary of descriptive statistics and the correlation matrix for all indicators. The results suggest that the variables do not follow a normal distribution. Climate change technologies exhibit the lowest mean value, while GDP per capita shows the highest annual mean. In a normal distribution, skewness is typically around zero and kurtosis is close to three or higher than three. However, the distribution of LCCT, LEDU, and LGD is positively skewed, whereas LCO, LGSCI, LGDP, and LRE are negatively skewed. Additionally, the series of LCO, LGDP, LCCT, LEDU, and LRE in the distribution display excess kurtosis, indicating a leptokurtic pattern, while the series of LGSCI and LGD show the low kurtosis, indicating a platykurtic.

Panel B of Table 2 presents the correlation estimates, revealing predominantly positive correlation coefficients among the variables. However, there are negative correlations observed between the variable pairs LCO and LRE, LGSCI and LCCT, LRE and LGDP, LCCT and LEDU, LCCT and LRE, LRE and LGD.

Empirical Results and Discussion

This study delves into the influence of climate change technologies, renewable energy, and global sustainable competitiveness index, economic growth, education level, and general technology diffusion on CO2 emissions. Prior to commencing the model estimation, preliminary analyses of panel data are carried out, including evaluations for cross-sectional dependency and stationarity. The outcomes of the cross-sectional dependency test are presented in Table 3. The results exhibit the findings from three cross-sectional dependence tests: Pesaran's (2021) test, Friedman's test, and Frees' test. The statistical significance of the test statistics for each variable indicates the presence of cross-sectional dependency. After assessing cross-sectional dependency, the analysis proceeds to conduct second-generation unit root tests.

Table 3. Cross-sectional dependence test

	CSD Tests		
Model*	**Pesaran CSD Test**	**Friedman CSD Test**	**Frees CSD Test**
Test statis.	6.849	40.689	4.907
Prob-value	0.000	0.000	0.000

Note: * represents the model of LCO=f (LGSCI, LGDP, LCCT, LEDU, LRE, LGD).

Acknowledging the presence of cross-sectional dependency, the outcomes of the second-generation unit root tests are presented in Table 4. To assess the stationarity of the variables, we conclude this analysis by utilizing multiple panel unit root tests. These tests include Pesaran's (2007) cross-section-enhanced Im-Pesaran-Shin test and Pesaran's Augmented Dickey-Fuller test, denoted by the abbreviations CIPS and CADF, respectively. Remarkably, each test consistently confirms the presence of a unit root under both constant and trend specifications, except for LGDP, and LRE, which exhibit stationarity at the constant and trend level in both tests. Consequently, the results suggest that all series become stationary in their first differences. Based on these findings, we deduce that the variables in this study demonstrate a mixed order of integration.

Table 4. Panel unit root tests

Series	**Model**	**CIPS[a]**	**CIPS[b]**	**CADF [a]**	**CADF [b]**
LCO2	Constant	-2.011	-2.925***	-1.239	-3.001**
	Constant&Trend	-2.517	-2.863**	-2.895***	-3.082***
LGSCI	Constant	-2.283	-3.499***	-1.243	-2.610**
	Constant&Trend	-2.492	-4.012***	-1.383	-3.159***
LGDP	Constant	-3.105***	-2.638***	-2.557***	-2.298***
	Constant&Trend	-2.259	-2.620	-2.687**	-2.233**
LCCT	Constant	-2.039	-3.408***	-1.569	-2.714***
	Constant&Trend	-3.408*	-3.874***	-1.860	-2.085**
LEDU	Constant	-2.053	-2.523***	-2.474**	-2.086**
	Constant&Trend	-2.007	-2.448	-2.375	-2.366**
LRE	Constant	-2.265**	-2.888***	-2.334**	-2.500***
	Constant&Trend	-2.420	-3.074***	-2.566***	-3.360***
LGD	Constant	-2.195**	-3.092***	-2.267	-2.721***
	Constant&Trend	-2.714	-3.039***	-2.760	-2.386**

Note: a refers to unit root test model at level and b refers to unit root test model at first difference. *, ** and *** indicate significance at 10%, 5% and 1% level, respectively.

After stationarity tests, Table 5 presents the results of the bootstrapped version of the Westerlund co-integration test for all panels, based on two sets of statistics. We reject the null hypothesis of no cointegration at a 5% significance level and with the support of 200 bootstrapping repetitions. This rejection suggests the existence of a long-term relationship between CO2 emissions and the determinants analyzed in this study.

Table 5. Panel cointegration tests

Statistic	**Value**	***p*-value**	**Robust *p*-value**
Gt	-2.2144	0.0134**	0.0000***
Ga	-3.0707	0.0011***	0.0000***
Pt	-3.6452	0.0001***	0.0000***
Pa	-2.9017	0.0012***	0.0020***

Note: ** and *** indicate significance at 5% and 1% level, respectively. No lag length is observed across 200 bootstrap repetitions.

In the same vein, this study proceeds to analyze the findings from the fixed-effect panel quantile regression. Table 6 showcases the results derived from panel quantile regression models at various quantiles, specifically at the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th quantiles. By employing nine quantiles, this study conducts the diverse impacts of LGSCI, LCCT, LRE, and other essential factors on CO2 emissions. The results of the panel quantile regression are interpreted by assessing how the coefficients of independent variables vary across different quantiles. Furthermore, this method allows for modeling the entire conditional distribution, offering a nuanced understanding of how independent variables affect the dependent variable across various quantiles. The panel quantile regression model effectively addresses hidden variations within each cross-section and explores distinct slope coefficients across different quantiles. Figure 3 also visually represents panel quantile regression models at the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th quantiles. showcasing specific variations of coefficients across quantiles.

As seen in Table 6, the effect of LGSCI on CO2 emissions is heterogeneous and significantly positive between the 40th and 60th quantiles. After the 70th quantile, its effect turns negative and insignificant. LGDP has a positive and significant impact on CO2 emissions at all quantiles. The positive impact is more robust at the 90th quantile. Similarly, the effect of LCCT is also positive and significant on CO2 emissions at all quantiles. The positive impact of LCCT is more robust at the 60th quantile. Furthermore, the impact of LEDU on CO2 emissions is heterogeneous at all quantiles. LEDU has positive and significant impacts, but its effects turn negative and insignificant at the 40th-60th-70th-80th and 90th quantiles. The effect is also more robust at the 10th quantile of LEDU.

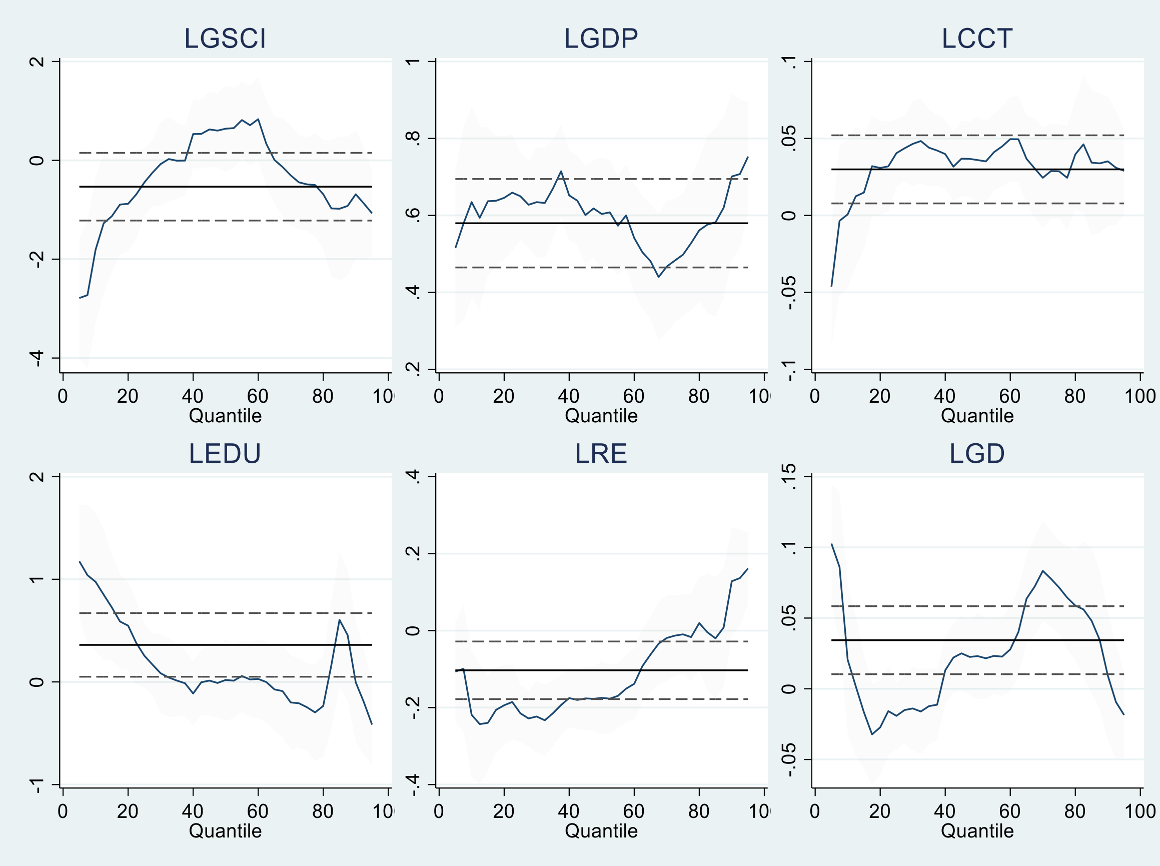

Figure 3. Change in panel quantile regressions coefficients of carbon emissions.
Source: Authors' elaborations

Moreover, the effect of LRE shows negative and significant effects on CO2 emissions from the 10th to the 70th, except for the 70th which is insignificant. Its effect turns positive at the 80th and 90th quantile. Likewise, the effect of LGD on CO2 emissions is negative at the 20th and the 30th quantiles. Its effect turns to positive at 10th and after 40th quantiles, and its significant from 60th to 80th quantile. The positive and significant impact of LGD is more robust at the 70th quantile.

Table 6. Panel quantile regression results

Variable	**Quantile Regression**								
	10th	**20th**	**30th**	**40th**	**50th**	**60th**	**70th**	**80th**	**90th**
C	-0.999**	-1.566**	-1.919**	-2.730***	-2.979***	-3.083***	-0.611	-0.234	-1.188
	(-0.87)	(-2.13)	(-2.92)	(-5.12)	(-4.43)	(-4.72)	(-0.78)	(-0.34)	(-1.19)
LGSCI	-1.808**	-0.879*	-0.075	0.532	0.641	0.833*	-0.304	-0.683	-0.685
	(-2.39)	(-1.82)	(-0.17)	(1.51)	(1.45)	(1.94)	(-0.59)	(-1.23)	(-1.04)
LGDP	0.634***	0.645***	0.634***	0.652***	0.603***	0.541***	0.467***	0.561***	0.701***
	(5.00)	(7.95)	(8.74)	(11.04)	(8.13)	(7.51)	(5.40)	(5.99)	(6.33)
LCCT	0.006	0.031**	0.046***	0.039***	0.035**	0.049***	0.024	0.039**	0.035
	(0.03)	(1.97)	(3.32)	(3.51)	(2.51)	(3.57)	(1.47)	(2.20)	(1.65)
LEDU	0.975***	0.548**	0.084	-0.113	0.019	0.029	-0.201	-0.2344	-0.0042
	(02.85)	(2.50)	(0.43)	(-0.71)	(0.10)	(0.15)	(-0.86)	(-0.93)	(-0.01)
LRE	-0.218***	-0.194***	-0.223***	-0.175***	-0.174***	-0.138***	-0.019	0.019	0.128*
	(-2.65)	(-3.67)	(-4.72)	(-4.55)	(-3.61)	(-2.94)	(-0.34)	(0.32)	(1.78)
LGD	0.021	-0.027	-0.014	0.013	0.023	0.027**	0.083***	0.058***	0.009
	(-0.78)	(-1.61)	(-0.92)	(1.06)	(1.49)	(1.85)	(4.61)	(3.00)	(-1.19)
Pseudo R^2	0.801	0.622	0.587	0.590	0.677	0.682	0.752	0.781	0.698
N	418	418	418	418	418	418	418	418	418

Note: This table shows the results of the panel quantile regression model driving factors on CO2 emissions. *, ** and *** indicate significance at 10%, 5% and 1% level, respectively. The z statistics-values are represented in parentheses.

Following this, we employ the Dumitrescu and Hurlin (2012) Granger non-causality test to investigate the direction of causality, and the results are presented in Table 7.There is a bidirectional causality between LCO and LGSCI at all significance levels. It implies that a change in LGSCI can affect LCO, and similarly, a change in LCO can affect LGSCI. Likewise, there is also bidirectional causality between LCO and LGDP. It shows that a change in LGDP can affect LCO, and similarly, a change in LCO can affect LGDP.

Moreover, there is bidirectional causality between LCCT and LCO. This indicates that a change in LCCT can affect LCO, and similarly, a change in LCO can affect LCCT. Similarly, there is bidirectional causality between LEDU and LCO at all significance levels. This shows that a change in LEDU can affect LCO, and similarly, a change in LCO can affect LEDU. Lastly, there is bidirectional causality between LRE and LCO. It shows that a change in LRE can affect LCO, and similarly, a change in LCO can affect LRE. However, there is no causal relationship between LCO and LGD at any significance level. It implies that a change in LCO can not affect LGD, and similarly, a change in LGD can not affect LGD.

Table 7. Panel causality test results

Null Hypothesis	**W-Stat**	**Zbar-Stat**	**Probability**
LCO → **LGSCI**	1.9985	4.3525	0.0000
LGSCI → LCO	4.9611	7.8400	0.0000
LCO → **LGDP**	1.8574	3.7374	0.0002
LGDP → LCO	2.6848	7.3437	0.0000
LCO → L**CCT**	5.8766	9.8556	0.0000
LCCT → LCO	3.1637	3.8829	0.0001
LCO → **LEDU**	3.5123	4.6503	0.0000
LEDU → LCO	3.1142	3.4037	0.0005
LCO → **LRE**	2.5124	6.5925	0.0014
LRE → LCO	2.1526	5.0241	0.0000
LCO → **LGD**	1.1811	0.7893	0.4299
LGD → LCO	2.6253	7.0844	0.1221

Note: *, ** and *** indicate significance at 10%, 5% and 1% level, respectively.

Conclusion

The dynamic impacts of CO2 emissions have been examined concerning climate change technologies, the GSCI, renewable energy, general technology diffusion, education level, and economic growth. This study encompasses data from 38 OECD countries using panel data analysis. Utilizing the panel quantile regression model, the study findings reveal that the development and creation of climate change technologies exhibit positive effects on CO2 emissions across quantiles ranging from the 10th to the 90th percentile. On the contrary, the effect of renewable energy shows negative and significant on CO2 emissions from the 10th to the 70th quantiles. Additionally, there exists a negative correlation between the GSCI and CO2 emissions, except for the 40th and 60th quantiles. On the other hand, economic growth has a positive and significant impact on CO2 emissions at all quantiles.

The impact of education level on CO2 emissions is also heterogeneous at all quantiles. Education has positive and significant impacts at the 10th-20th and 30th quantiles, but its effects turn negative and insignificant at the 40th-60th-70th-80th and 90th quantiles. Lastly, the effect of general technology diffusion on CO2 emissions is negative at the 20th and the 30th quantiles. Its effect turns positive at the 10th and after the 40th quantiles.

Consequently, the adverse relationship between CO2 emissions and renewable energy use, the GSCI, and general technology diffusion suggests that the integration of environmentally sustainable technologies and the adoption of renewable energy sources are associated with favorable environmental outcomes, contributing to the mitigation of CO2 emissions released into the atmosphere.

On the other hand, we find that a positive relationship between CO2 emission and climate change technologies. This result could potentially indicate various factors at play, including the initial stages of technology deployment requiring significant energy inputs and resources, leading to temporary increases in emissions before the technologies mature and contribute to emissions reductions. Additionally, substitution effects may occur where new technologies displace older, less efficient ones, yet if the new technologies are not yet fully mature or widely adopted, they may not effectively reduce emissions. Indirect effects, such as changes in economic activity or consumer behavior spurred by technology development, could also contribute to increased emissions in the short term. Moreover, feedback mechanisms, such as government policies or market dynamics inadvertently incentivizing carbon-intensive industries alongside technology development, could exacerbate emissions rather than mitigate them.

Moreover, we conclude that there is a long-term cointegration between CO2 emissions and the determinants analyzed in this study. Furthermore, according to Dumitrescu and Hurlin (2012) Granger non-causality test, there is no causal relationship between general technology diffusion and CO2 emissions at all significance levels. Also, there is there is bidirectional causality between all other pairs of variables at all significance levels.

Recommendations

According to the empirical findings of this study, there are several policy recommendations aimed at assisting governments and policymakers in advancing environmental sustainability within nations and aligning with the eco-friendly objectives of sustainable development. Firstly, governments and policymakers should actively foster the development and adoption of technologies and renewable energy sources as a means to mitigate high levels of CO2 emissions.

Secondly, policymakers are urged to explore strategies for diversifying economic growth to reduce reliance on sectors with significant carbon emissions. Encouraging the growth of sustainable and environmentally friendly industries can strike a balance between economic expansion and environmental preservation. Also, governments should improve the technologies and implementations of climate change technologies by decreasing the level of CO2 emissions and providing sustainable development goals.

Moreover, governments should prioritize the integration of sustainability criteria into economic policies and decision-making processes. This can be achieved by expanding the scope and coverage of the GSCI to include additional indicators related to environmental performance, such as carbon footprint, energy efficiency, and natural resource management. Policymakers should leverage the GSCI as a tool for assessing and monitoring progress towards environmental sustainability goals at both national and international levels Similarly, governments should prioritize investments in research, development, and commercialization of climate change technologies. This can be achieved through funding grants, establishing innovation hubs or centers of excellence, and fostering collaboration between academia, industry, and government agencies. Policymakers should also create a supportive regulatory environment that encourages the adoption and diffusion of climate change technologies, such as streamlined permitting processes or technology standards.

Policymakers should prioritize international collaboration and knowledge sharing to accelerate progress towards environmental sustainability. This can involve participation in global initiatives and agreements aimed at addressing climate change, promoting technology transfer and capacity building in developing countries, and sharing best practices and lessons learned from successful sustainability initiatives. Countries can leverage collective expertise and resources to achieve more significant and lasting impacts on environmental sustainability on a global scale.

Furthermore, suggestions for future research could involve conducting sector-specific examinations to discern the diverse effects of climate change technologies and renewable energy on CO2 emissions within distinct industries. This methodology has the potential to provide insights for tailored policies aimed at addressing sectors with the most significant carbon footprint.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the author.

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