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Do the digital economy and institutional quality help reduce consumption-based CO_2 emissions in OECD countries? Evidence from the MMQR analysis

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Abstract

Global warming poses an increasing threat due to rapid economic expansion and human activities. The digital economy emerges as a promising strategy for countries aiming to achieve carbon neutrality while sustaining economic performance. However, the relationship between the digital economy and institutional quality concerning consumption-based carbon emissions remains underexplored. This study investigates the impact of the digital economy and institutional quality on CBE in OECD countries from 2003 to 2024. The findings obtained from the Moments Quantile Regression technique indicate that both factors can significantly contribute to environmental sustainability by reducing CBE. Additionally, industrial upgrading can aid in emissions reduction. Factors such as the GDP, urbanization, and FDI are obstructing progress toward environmental sustainability. The study recommends strengthening digital infrastructure and providing institutional support for environmental sustainability.

Keywords: Digital economy, institutional quality, consumption-based CO_2 emissions, OECD economies, advanced panel estimation

JEL Classification: Q56, O33, C21, P48

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1. Introduction

The highest recorded daily concentration of carbon dioxide emissions in May 2023 serves as a warning sign of global warming. The UN Conference on Climate Change (COP27) calls on nations to meet their Paris Agreement commitments by reducing greenhouse gas (GHG) emissions and limiting global warming to 1.5 °C above pre-industrial levels. The challenge is to balance emissions reduction with economic prosperity. Scholars in environmental economics are exploring strategies to foster growth without compromising environmental quality. Governments around the world are adopting sustainable development practices (Saia 2023).

The digital economy (DGE) has emerged as a prominent area of research, with a particular emphasis on its impact on energy infrastructure and emissions reduction, which has garnered significant academic interest. The DGE offers a potential means to attain carbon peak and neutrality objectives without compromising economic progress (Du, Xu and Lin, 2024). We have yet to determine an exact definition of the DGE. However, it is generally accepted that the information and communication (ICT) industrial sectors, along with the service and internet industries, shape the concept of digitalization. It can also encompass economic activities that rely on ICTs, such as online services and ICT services (Tao *et al*., 2023). The DGE, as a novel economic model, has consistently enhanced social digitization, networking, and intelligence through the progressive processes of digital industrialization and industrial digitization. This has resulted in notable environmental improvements while effectively driving high-quality economic growth and enhancing innovation capabilities (Dong *et al*., 2022). It is a type of technology that alters methods and procedures to improve resource efficiency. Although DGE is widely recognized as an effective strategy to reduce emissions, its implementation faces certain hurdles.

The environmental outcome of DGE depends significantly on the quality of institutions both within and across countries. Advancing the DGE necessitates considerable government support, with the effectiveness of public sector institutions being crucial to achieving the social and environmental objectives of DGE initiatives. The effectiveness of these indirect techniques depends on the ability of corporations to respond to government regulations and incentives, taking into account environmental quality as a public benefit. IQ is a way to rate how reliable, effective, and efficient a region's legal, regulatory, and policy framework is, as well as how well it works in real life. It is crucial for putting DGE policies into action and getting businesses involved. An effective institutional framework offers explicit guidance for developing the DGE, enhancing environmental rules, and establishing a business regulatory environment that guarantees market fairness and transparency. Furthermore, the level of IQ has a substantial influence on investor confidence. It is crucial to have a solid and trans-

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parent institutional environment to enhance public awareness of the DGE and encourage organizations and businesses to participate in the digitalized economy (Hassan *et al*., 2020).

The increasing significance of DGE and its considerable impact on environmental quality have attracted growing academic interest in the relationship between DGE and emissions. Despite current research suggesting a potential link between DGE and environmental degradation, the evidence remains fragmented and unclear. Previous research typically focuses on isolated elements – such as DGE or IQ – without providing a comprehensive analysis of how DGE and institutional factors collectively shape the sustainability trajectory. This underscores the urgent need to further investigate the impact of the DGE and IQ on environmental outcomes, both to enrich academic discourse and to inform the development and implementation of sustainable policies. First, the impact of DGE on environmental deterioration via IQ channels is absent for the esteemed group of nations known as OECD countries. It is essential to investigate the relationship among DGE, IQ, and environmental deterioration to develop a comprehensive policy framework for the OECD bloc. Additionally, research on DGE and environmental sustainability has primarily concentrated on production-based CO_2 emissions, while empirical evidence regarding consumption-based CO_2 emissions (CBE) as a measure of environmental decline is lacking. The assertion that national (or production-based) emissions are affected by the consumption patterns or levels of different consumers is often misinterpreted. A significant portion of locally consumed goods may be imported, while domestically produced items are exported. This study addresses a significant gap by employing CBE to investigate the relationship between DGE, IQ, and environmental sustainability. Using CBE as a measure of environmental degradation is essential, as it can aid in formulating a comprehensive policy to tackle environmental issues. Thus, to implement effective measures for minimizing environmental harm, countries should take into account the emissions resulting from consumption (Baloch and Danish, 2022).

Second, the majority of research attempting to understand DGE and environmental degradation is based on time series analysis or a panel of emerging economists. However, the literature on developed economies, such as those of the Organization for Economic Co-operation and Development (OECD) countries, is largely absent, a situation that demands immediate attention given their significant economic standing and contribution to global emissions. The causal mechanisms outlined in this study suggest that the DGE has the potential to reduce pollution by improving efficiency, promoting advanced technologies, and encouraging innovation in the energy sector. Conversely, it may also lead to increased emissions through high digital consumption, the growth of e-commerce, and the energy demands of data-intensive infrastructures.

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OECD economies have experienced an increase in per capita income, alongside a focus on minimizing environmental damage. However, pollution levels continue to rise in these countries, indicating that progress is insufficient. Particularly, these nations demonstrate a significant and growing CBE, primarily driven by imported emissions that are part of global supply chains. Climate change is impacting human lives, economies, biodiversity, and ecosystems. Various factors, including income levels, strict environmental regulations, and the quality of institutions, affect the trajectory of emissions. The digital technology ecosystem is driving economic and societal transformations, with the ICT sector demonstrating adaptability and resilience despite economic challenges. In OECD countries, the ICT sectors have reported higher growth rates than the overall economy (Metin *et al*., 2024). This study, motivated by an auspicious gap in the literature and the urgent need to address climate change, intends to examine the DGE and environmental pollution nexus in OECD countries by incorporating an important factor of IQ.

Finally, the study used the most recent method of moment-quantile regression (MMQR) because of its ability to generate robust estimates, increasing the findings' reliability. This study's use of thorough diagnostic tests and meticulous methodology ensures the results' robustness and dependability.

The study organizes the subsequent sections as follows: Section 2 provides an overview of the literature review; Section 3 gives the detailed methodology used to analyze the data; Section 4 describes and discusses the empirical results; and Section 5 concludes the study and recommends policy implications.

2. Literature Review

2.1 Digital economy and emissions nexus

Chang *et al*. (2023) investigate the mechanism of the DGE's impact on CO_2 emissions intensity by analyzing provincial panel data from China. The findings indicate that the DGE has a substantial impact on reducing the intensity of CO_2 emissions. Dong *et al*. (2022) conducted an empirical analysis to investigate the influence of DGE development on environmental pollution in 60 countries around the world. The empirical findings indicate that while the DGE's advancement significantly reduces the intensity of CO_2 emissions, it also increases per capita CO_2 emissions. Saia (2023) examines the relationship between digitalization and CO_2 emissions in 55 high- and middle-income economies.

The study finds that economies with lower investment in research and development (R&D) tend to show significantly higher indicators of digitalization. Sun *et al*. (2024) studied

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the complex and non-linear relationship between DGE and CO_2 emissions in the Qinghai region of China, revealing an inverted "U"-shaped correlation that intensifies with the growth of DGE. Hong *et al*. (2024) conducted a study to investigate the impact of the DGE on CO_2 emissions at the provincial level. The findings indicate that the DGE's growth led to a rise in CO_2 emissions at the collective level between 2012 and 2017. Ullah *et al*. (2024) indicates that digitalization in OECD countries contributes to an increase in CO_2 emissions, based on a three-stage panel data econometric analysis.

2.2 Institutional quality and emission nexus

Numerous studies have examined the essential role of IQ in the ongoing discussions surrounding economic growth and CO_2 emissions. For instance, Ahmad *et al*. (2021) conducted a study that explores the IQ-emissions nexus in developing nations. The study reveals that higher IQ contributes to environmental sustainability by decreasing ecological impact. Stef *et al*. (2023) utilize data from 136 nations to present convincing evidence that implementing strong institutional mechanisms aimed at promoting environmentally friendly economic growth can successfully decrease CO_2 emissions. Wahab *et al*. (2024) investigated how IQ affects CO_2 emissions in OECD countries. The quality of institutions had a significant impact on emissions, emphasizing the critical role of robust regulatory frameworks and efficient environmental governance in reducing emissions. Metin *et al*. (2024) examine the influence of IQ on CO_2 emissions and ecological footprints in OECD nations. The analytical findings suggest that there is a positive and strong long-term relationship between IQ and environmental deterioration. Jianguo *et al*. (2022) examine the impact of IQ on environmental quality in 37 OECD nations. The findings indicate that the quality of institutions is a critical factor in managing environmental degradation. Le and Ozturk (2020) analyze the IQ impact on environmental pollution in 47 emerging nations. The research finding reveals that IQ contributes to the growth in CO_2 emissions.

Research Gap

The review of the relevant empirical literature reveals several significant gaps in understanding environmental determinants. In particular, there is a lack of comprehensive research on the effects of DGE in combination with IQ on CBE, especially in OECD countries. This study seeks to fill this gap by examining the influence of DGE and IQ on CBE. Furthermore, it employs the latest econometric method, MMQR, which is robust against cross-sectional dependence (CSD) and heterogeneity to present reliable estimates.

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3. Methodological approach and data sources

3.1 Theoretical underpinnings and model formulation

This section explains the theoretical framework that underlies the link between the variables of interest in the present investigation. It is argued that *DGE* may influence CO_2 emissions in various ways. The advancement of digitalized technology, such as AI, big data, and the Internet, is beneficial for improving green technologies, increasing clean energy utilization efficiency, and decreasing fossil fuel consumption, leading us toward achieving carbon neutrality. Moreover, the advancement of the *DGE* enables the dissemination of information and environmentally friendly technologies across different locations, thereby aiding in improving environmental quality (J. Wang, Luo, and Zhu, 2022). Digitalization allows companies to audit, optimize, and manage energy consumption in real time, facilitating efficient resource utilization and reducing operational losses associated with low-carbon transitions (Shen *et al*., 2025). The *DGE* promotes the digital industry, which is eco-friendly and has few negative environmental impacts. Information firms, including information services and internet enterprises, have a greater presence in the *DGE* compared to traditional manufacturing industries. These information enterprises typically operate with a higher degree of environmental sustainability. The *DGE*, which includes electronic governance and production, presents a novel management system for society. It enhances public engagement with environmental issues and facilitates access to information. Additionally, digital technology enables thorough monitoring of pollution levels, thereby bolstering the government's ability to govern effectively in the modern era (Dong *et al*., 2022).

Ozturk *et al*. (2023) highlight that the efficacy of the government, encompassing the established regulations, customs, and systems that influence and oversee a nation's social, economic, and political engagements, plays a crucial role in guaranteeing environmental sustainability. *IQ* is essential to ensuring compliance with environmental laws and regulations by imposing penalties and fines and encouraging voluntary efforts to address the primary sources of degradation. Bhattacharya *et al*. (2017) contend that institutions that safeguard property rights foster voluntary transactions, support governments in achieving sustainable development, and improve environmental and energy policies, thereby ensuring the effectiveness of government programs. Omri (2014) argues that strong institutions improve energy efficiency and facilitate the adoption of renewable energy, while also enforcing strict energy and environmental regulations.

Urbanization and economic growth have resulted in higher energy consumption and increased CO_2 emissions, adversely affecting environmental quality. The connection be-

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tween *FDI* and CO_2 emissions is a subject of debate. Supporters contend that *FDI* can reduce pollution by transferring environmentally friendly technologies to developing countries. In contrast, critics argue that corporations move polluting industries to countries with less stringent regulations, causing environmental harm in those regions. To achieve environmental sustainability and effectively address environmental challenges, industrial upgrading is essential.

This study develops three distinct models based on the methodological framework established by Wang *et al*. (2023), detailed as follows:

Model-I

$$\ln CBE_{it} = \alpha_0 + \alpha_1 \ln DGE_{it} + \alpha_2 \ln Y_{it} + \alpha_3 \ln URB_{it} + \alpha_4 \ln FDI_{it} + \alpha_5 \ln INU_{it} + v_i + \sigma_t + \varepsilon_{it} \quad (1)$$

Model-II

$$'BE_{it} = \alpha_0 + \alpha_1 \ln IQ_{it} + \alpha_2 \ln Y_{it} + \alpha_3 \ln URB_{it} + \alpha_4 \ln FDI_{it} + \alpha_5 \ln INU_{it} + v_i + \sigma_t + \varepsilon_{it} \quad (2)$$

Model-III

$$\ln CBE_{it} = \alpha_0 + \alpha_1 \ln DGE_{it} + \alpha_2 \ln Y_{it} + \alpha_3 \ln IQ_{it} + \alpha_4 \ln URB_{it} + \alpha_5 \ln FDI_{it} + \alpha_6 \ln INU_{it} + v_i + \sigma_t + \varepsilon_{it} \quad (3)$$

The rationale for employing these three models is to comprehensively analyze the relationship between the independent variables (*i.e.*, *DGE* and *IQ*) and their connection to *CBE*. Additionally, Model-III assesses the overall impact of these specific variables on *CBE*.

Where *CBE* refers to consumption-based CO_2 emissions and is further defined as the digital economy (*DGE*), economic growth (*Y*), institutional quality (*IQ*), urbanization (*URB*), foreign domestic investment (*FDI*), and industrial upgrading (*INU*). We take a natural logarithmic conversion of Equation 1 to create a model that reduces data variability and facilitates analysis.

In this context, the variable i = countries, t = time, α_0 = content term, v_i = fixed effect, σ_t = fixed effect of the time, and ε_{it} = random disturbance term. The calculated coefficients are α_1, …, and α_6; specifically, α_1 represents the elasticity of the *DGE* on carbon emissions, whereas α_3 represents the elasticity of the *IQ* on *CBE*.

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3.2 Variable descriptions and sources of data

This study analyzes a subset of 21 OECD[1] countries using data from 2003 to 2024. The selection of the sample's time and geographic dimensions is based on limitations in data availability during the investigation. One advantage of panel data is its ability to facilitate more efficient and flexible modeling of differences in group behavior. The paper focuses on *DGE* and *IQ* as the primary independent variables. There is limited literature on measuring *DGE* indices. The digital economy index was developed based on the work of Shahbaz *et al*. (2022) by examining four key factors: digital infrastructure, social effects, digital trade, and social support. There are four subindexes that measure digital infrastructure: fixed broadband subscriptions, fixed landline subscriptions, mobile subscriptions, and the Telecommunication Infrastructure Index. Social effects are evaluated by the number of individuals using the Internet, the Online Service Index, and the E-Participation Index, as well as medium and high-tech manufacturing value added.

Exports and imports of ICT goods represent digital trade, while the service industry's per capita value-added measures social support. All indexes were normalized, and the composite index was calculated employing the entropy approach. This method allocates weights based on the variability of each indicator to reduce information loss and guarantee objective weighting. Elevated index values indicate more robust development of the *DGE*. The International Country Risk Guide (ICRG), which includes twelve sub-indices, provides the data for *IQ*. These include law and order, corruption, government stability, bureaucratic quality, and democratic accountability, all of which are used for analysis. The study identifies *CBE* as the primary dependent variable, which serves as a measure of environmental quality. *CBE* is influenced by both direct and indirect emissions linked to manufacturing processes that fulfill the needs of domestic final consumers and net imports. Data for *CBE* has been obtained from the Global Carbon Atlas. To evaluate economic growth and urbanization, the study incorporates GDP per capita (in 2010 US dollars) and the percentage of the total population living in urban areas as control variables. The contribution of the service industry to *GDP*, expressed as a percentage, reflects the level of industrial upgrading. Foreign direct investment (*FDI*) is determined by dividing net investment inflows by GDP and expressing it as a percentage. All control variable data is sourced from the World Development Indicators WB (2022).

1 Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America.

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3.3 Econometric strategy

In panel data sets, there is often a significant likelihood of cross-sectional dependence (CSD) and issues related to heterogeneity. Therefore, before proceeding to estimates in the long-run analysis, we first conducted a cross-sectional dependency test (CDT) using the Pesaran (2004) CSD test. Additionally, we employed the Hashem Pesaran and Yamagata (2008) slope heterogeneity (SH) method for this purpose. Next, to assess the stationarity of the variables, our study utilized (Pesaran, 2007) cross-sectionally augmented IPS tests, commonly referred to as CIPS. Following this, we applied the (Westerlund and Edgerton, 2007) cointegration test to verify the long-term viability of the study's variables, given its capacity to address the potential challenges posed by heterogeneity and CSD in the dataset.

For the long-term analysis, we employed the latest "Method of Moments Quantile Regression" (MMQR) proposed by Machado and Santos Silva (2019), which incorporates fixed effects. The MMQR approach examines "conditional heterogeneous covariance effects" by extracting the criteria variable and taking into account the entire data distribution. This methodology is adept at analyzing distinct impacts on individuals, thereby influencing subsequent outcomes. In contrast, traditional quantile regressions, such as those developed by Koenker (2004) and Canay (2011), do not possess this capability, as they only adjust the means. Furthermore, the endogeneity characteristics of MMQR, along with its organization of the dataset based on individual impacts, enhance its reliability. This approach effectively addresses issues of endogeneity and heterogeneity and is applicable in cases where the data display asymmetric features.

4. Empirical results and discussion

This section presents empirical findings, explains their significance, and explores the relationship between *CBE* and the study's independent variables.

We begin by applying Pesaran's (2007) SH test to assess the uniformity of coefficient slopes across various cross-sections. The statistical analysis presented in Table 1 indicates that the expected test statistics do not support the null hypothesis of slope homogeneity at a significance level of 1%. This finding confirms the presence of the SH issue.

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Table 1: Slope heterogeneity test

	Statistics
Model-I	
$\tilde{\Delta}$	15.037*
$\tilde{\Delta}_{Adjusted}$	18.287*
Model-II	
$\tilde{\Delta}$	13.443
$\tilde{\Delta}_{Adjusted}$	16.280
Model-III	
$\tilde{\Delta}$	12.337
$\tilde{\Delta}_{Adjusted}$	15.544

Note: * denotes statistical significance at the 1% level of significance.
Source: Authors' own calculations

Next, we employ Pesaran's (2004) CDT to assess the independence of the cross-sections. Table 2 illustrates the rejection of the null hypothesis, as indicated by statistically significant test statistics, which underscores the interdependence of the cross-sections.

Table 2: Results for cross-sectional

	ln *DGE*	ln *IQ*	ln *GDP*	ln *FDI*	ln *INU*	ln *URB*	ln *CBE*
CDT-Test	40.44* [0.000]	50.45 [0.000]	35.99* [0.000]	7.50* [0.000]	38.24* [0.000]	50.56* [0.000]	28.95 * [0.000]

Note: * denotes statistical significance at the 1% level of significance.
Source: Authors' own calculations

To address the issues of CDT and SH, this study employs the second-generation CIPS unit root test to tackle the challenges associated with cross-sectional dependence and slope homogeneity. The outcomes of the CIPS unit root test are presented in Table 1. At the 1% significance level, the test results yield a statistically significant finding, leading to the rejection of the null hypothesis of non-stationarity. The result indicates that the integration of all variables occurs at the first difference, denoted as I(1).

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Table 3: CIPS unit root test

Variables	Intercept and Trend	
	CIPS (level)	CIPS (Δ)
ln *DGE*	–2.083	–3.747*
ln *IQ*	–1.227	–1.779**
ln *GDP*	–1.505	–2.570**
ln *FDI*	–3.43	–5.378*
ln *INU*	–2.042	–3.516*
ln *URB*	–1.068	1.732**
ln *CBE*	–2.468	–3.903*

Note: * and ** denote statistical significance at the 1% and 5% levels, respectively.

Source: Authors' own calculations

This paper utilizes three models to investigate the relationship between *DGE*, *IQ*, and *CBE* in depth. The study applies the Westerlund and Edgerton (2007) cointegration test to meet the specific requirements of each model. The results, presented in Table 4, indicate that the group and panel data are statistically significant at the 1% level, suggesting stable long-term correlations among the variables in the model.

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Table 4: Cointegration results

Statistics	Value	*Z*-Value
Model-I		
G_t	−2.589**	−1.758
G_a	−2.223	5.670
P_t	−5.275*	2.738
P_a	−1.686	3.657
Model-II		
G_t	−3.334*	−5.114
G_a	−3.864	4.691
P_t	−10.084*	−1.196
P_a	−3.476	2.625
Model-III		
G_t	−3.075*	−2.913
G_a	−2.909	6.014
P_t	−9.095*	0.541
P_a	−2.409	3.977

Note: * and ** denote statistical significance at the 1% and 5% levels, respectively.
Source: Authors' own calculations

After confirming the long-term viability of the study's variables, this study employs MMQR regression analysis for Model-I, and Table 5 presents the estimated findings.

The coefficient of *DGE* indicates a negative and statistically significant effect on *CBE* across all quantiles. This finding implies that digitalization helps reduce *CBE*, likely by enhancing efficiency, promoting dematerialization, and facilitating the implementation of smart infrastructure. Urbanization and *FDI* have a positive and significant influence in every quantile, suggesting that increased urban development elevates *CBE*, possibly due to energy-intensive lifestyles and infrastructure typical of urban areas. Additionally, *FDI* often flows to regions with less stringent environmental regulations. *GDP* consistently and sig-

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nificantly boosts *CBE*, reinforcing the conventional perspective that economic growth leads to environmental degradation unless sustainable practices are implemented. The effects of industrial degradation show variability; it initially seems negligible in lower quantiles but becomes significantly negative in higher quantiles (Q_{70}–Q_{90}). This evidence indicates that in more industrialized economies, indicators of degradation may signify a reduction in emission intensity due to the adoption of cleaner production methods.

The positive and negative impacts of explanatory factors at all quantiles are visually depicted by their corresponding coefficient values in Figure 1.

Table 5: Method of moment regression results (Model-I)

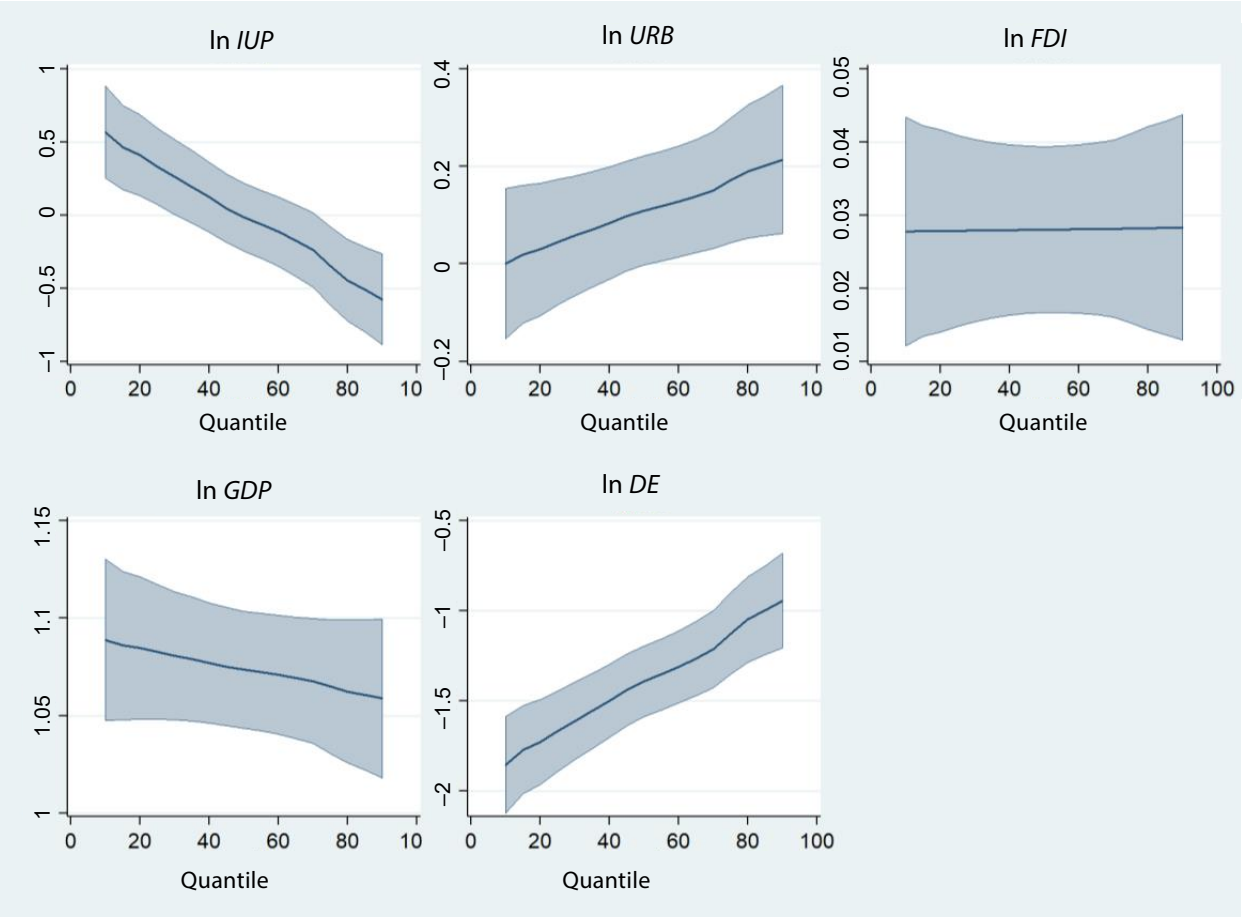
Variables	ln *DGE*	ln *URB*	ln *FDI*	ln *GDP*	ln *INU*	Constant
Location	–1.3875* [0.000]	0.1098*** [0.054]	0.0280* [0.000]	1.0734* [0.000]	–0.0185 [0.874]	–10.334* [0.000]
Scale	–0.2855* [0.000]	0.0671** [0.044]	0.0001 [0.959]	–0.0093 [0.295]	–0.3589* [0.000]	–1.3151* [0.000]
Q10	–1.8542* [0.000]	0.0019 [0.999]	0.0277* [0.001]	1.0888* [0.000]	–0.5681* [0.000]	–12.4844* [0.000]
Q30	–1.6097* [0.000]	0.0576 [0.358]	0.0278* [0.000]	1.0807* [0.000]	–0.2606** [0.046]	–11.358* [0.000]
Q50	–1.3896* [0.000]	0.1093*** [0.056]	0.0280* [0.000]	1.0735* [0.000]	–0.0159 [0.893]	–10.344* [0.000]
Q70	–1.2122* [0.000]	0.1510** [0.013]	0.0281* [0.000]	1.0676* [0.000]	–0.2390*** [0.065]	–9.527* [0.000]
Q90	–0.9435* [0.000]	0.2142* [0.006]	0.0283* [0.000]	1.0588* [0.000]	–0.5767* [0.000]	–8.290* [0.000]
Observations	454	454	454	454	454	454
Countries	21	21	21	21	21	21

Note: *, **, and *** denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' own calculations

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Figure 1: Visual depiction of MMQR estimations (Model-I)



Source: Authors' own elaboration

As for Model II, Table 6 presents the MMQR estimation, indicating that *IQ* has a negative and statistically significant relationship with *CBE* across all quantiles. One possible explanation for the relationship is that robust institutions facilitate the enforcement of environmental legislation, promote green investment, and foster sustainable habits. Importantly, the magnitude of this effect remains consistently stable, suggesting that institutional strength is a reliable predictor of reduced emissions. Regarding other variables, such as *GDP*, it continues to significantly contribute to emissions. Urbanization also exerts a positive influence, particularly at lower quantiles, where *FDI* shows negligible effects, suggesting that institutional robustness, rather than capital inflows, drives emission outcomes. Finally, industrial upgrading continues to enhance environmental quality, potentially due to a shift toward cleaner production methods or the outsourcing of pollution-intensive sectors.

The positive and negative effects of each variable, along with their coefficient estimates, can be illustrated graphically, as shown in Figure 2.

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Table 6: Method of moment regression results (Model-II)

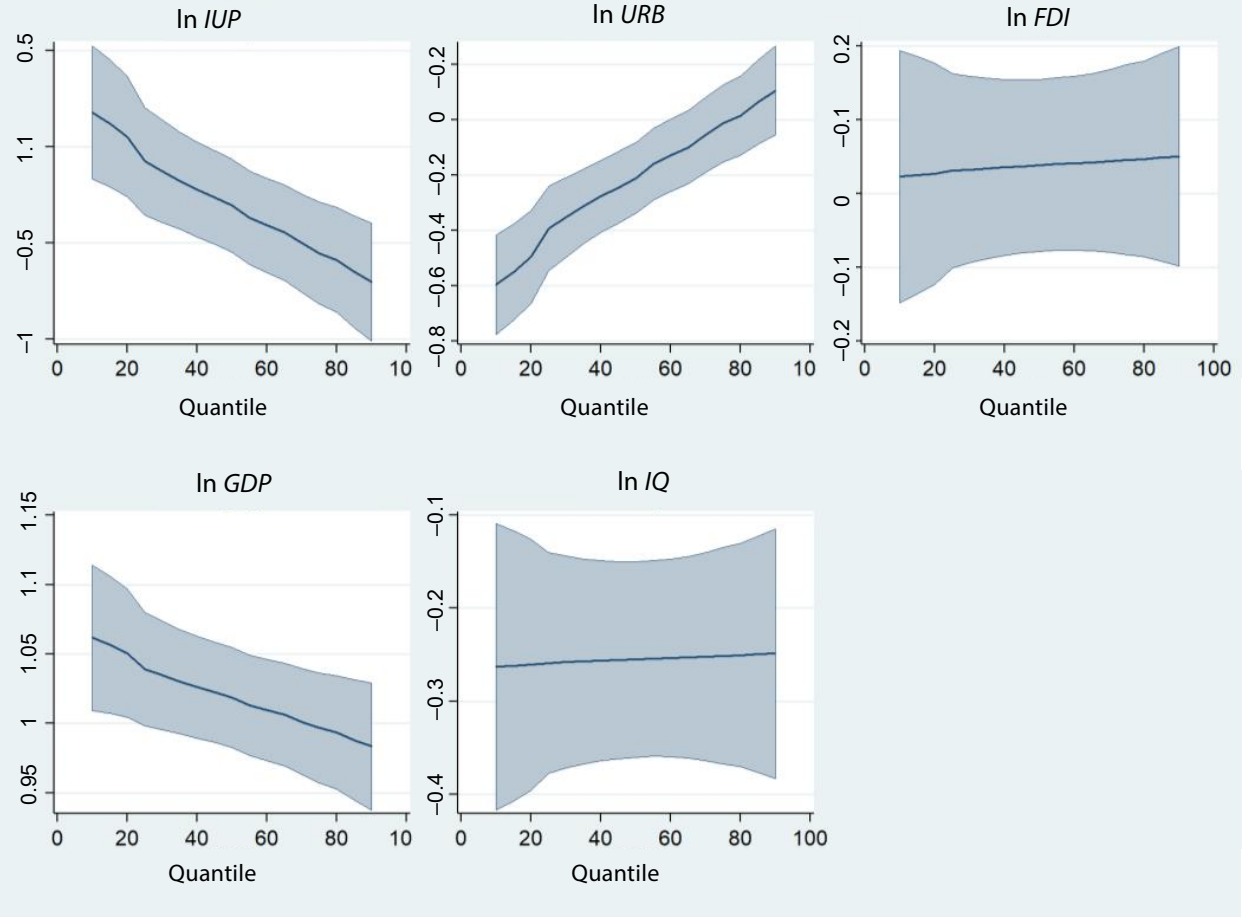
Variables	ln *IQ*	ln *URB*	ln *FDI*	ln *GDP*	ln *INU*	Constant
Location	−0.2551* [0.000]	0.2129* [0.001]	0.0037 [0.525]	1.0189* [0.000]	−0.3027* [0.013]	−7.023* [0.000]
Scale	−0.0043* [0.007]	0.2149* [0.000]	0.0008 [0.805]	0.0239** [0.022]	−0.26921* [0.000]	0.5898** [0.023]
Q_{10}	−0.2629* [0.001]	0.5966* [0.000]	0.0022 [0.794]	1.0616* [0.000]	0.1778 [0.313]	−8.0768* [0.000]
Q_{30}	−0.2579* [0.000]	0.3535* [0.000]	0.0032 [0.617]	1.034* [0.000]	−0.1266 [0.352]	−7.4098* [0.000]
Q_{50}	−0.2550* [0.000]	0.2108* [0.001]	0.0037 [0.524]	1.0187* [0.000]	−0.3053** [0.013]	−7.0182* [0.000]
Q_{70}	−0.2519* [0.000]	0.0544 [0.430]	0.0043 [0.488]	1.0013* [0.000]	−0.5013* [0.000]	−6.5887* [0.000]
Q_{90}	−0.2486* [0.000]	0.1064 [0.196]	0.0050 [0.509]	0.9834* [0.000]	−0.7028* [0.000]	−6.1473* [0.000]
Observations	462	462	462	462	462	462
Countries	21	21	21	21	21	21

Note: *, **, and *** denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' own calculations

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Figure 2: Visual depiction of MMQR estimations (Model-II)



Source: Authors' own elaboration

The MMQR for Model 3 offers a thorough regression analysis of all explanatory variables affecting *CBE*. Each explanatory variable shows a similar effect on *CBE* emissions, aligning with the results from the first two models. This research suggests that, within OECD economies, *DGE* contributes to a reduction in *CBE*. These findings align with those of Dong *et al*. (2022), Tao *et al*. (2023), and Yu *et al*. (2023). However, they contradict the results reported by Xie *et al*. (2024) and Ullah *et al*. (2024). Hong *et al*. (2024) found that the relationship between *DGE* and emissions is not linear. We attribute the discrepancies between our study and previous research to our specific focus on OECD data collection and our use of advanced analytical methodologies to draw our conclusions.

Additionally, *IQ* within OECD economies plays a significant role in reducing ongoing *CBE*, as it is negatively and significantly correlated with *CBE* across all quantiles. These findings support the expected role of OECD countries and are consistent with the outcomes reported by Wang *et al*. (2022a), Danish and Ulucak (2020), and Hassan *et al*. (2020a).

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However, Le and Ozturk (2020) found that institutions can contribute to environmental degradation. The factors of location and scale continue to have negative impacts, although these effects lessen when considering institutional and digital variables.

In contrast, economic growth, urbanization, and *FDI* are identified as major contributors to increasing *CBE*. Both *DGE* and *IQ* have negative and statistically significant effects on *CBE*, highlighting the influence of digitization and governance in its reduction. Urbanization is significant only at higher quantiles (Q_{70}–Q_{90}), suggesting that it exacerbates emissions in more carbon-intensive environments. *FDI* shows statistical significance across all quantiles; however, its positive coefficients indicate that foreign investments could increase emissions if not properly regulated. *GDP* consistently acts as a strong positive driver of emissions across all quantiles. Industrial degradation may signal a shift toward cleaner industrial practices in nations with high emissions, as evidenced by its negative relationship with *CBE*.

Figure 3 illustrates the impact of each explanatory variable on *CBE* based on the latest model.

Table 7: Method of moment regression results (Model-III)

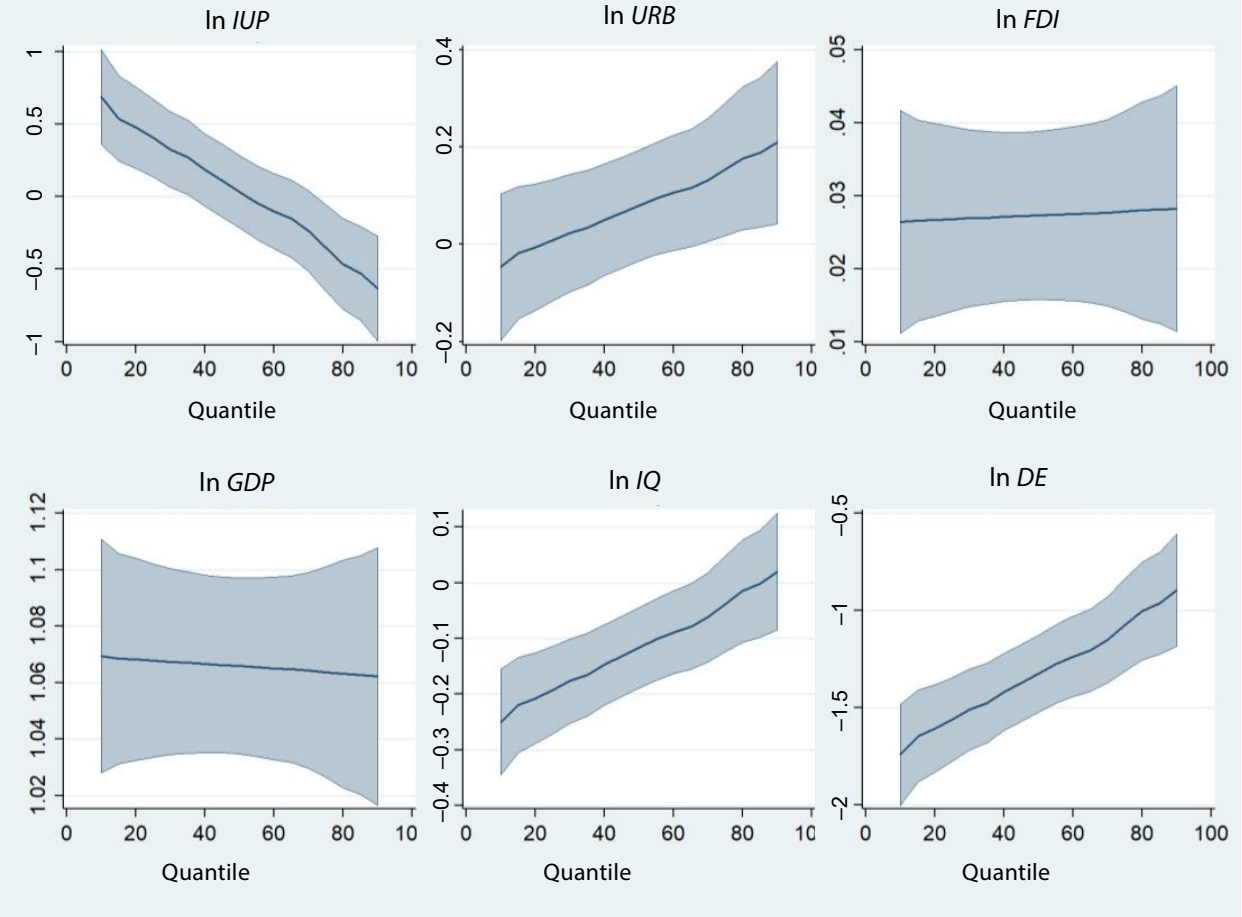
Variables	ln *DGE*	ln *IQ*	ln *URB*	ln *FDI*	ln *GDP*	ln *INU*	Constant
Location	−1.3134* [0.000]	−0.1135* [0.002]	0.0828 [0.154]	0.0273* [0.000]	1.0657* [0.000]	0.0178 [0.887]	−10.047* [0.000]
Scale	−0.2582* [0.000]	−0.0823* [0.000]	0.0780** [0.024]	0.0005 [0.874]	−0.0021 [0.817]	−0.4031* [0.000]	1.1889* [0.000]
Q10	−1.742* [0.000]	−0.2503* [0.000]	−0.0467 [0.544]	0.0264* [0.001]	1.0693* [0.000]	0.6875* [0.000]	−12.022* [0.000]
Q30	−1.5103* [0.000]	−0.1763* [0.000]	0.0233 [0.703]	0.0269* [0.000]	1.0674* [0.000]	0.3252** [0.015]	−10.953* [0.000]
Q50	−1.3239* [0.000]	−0.1168* [0.001]	0.0796 [0.171]	0.0273* [0.000]	1.0658* [0.000]	0.0341 [0.788]	−10.095* [0.000]
Q70	−1.1499* [0.000]	−0.0613 [0.135]	0 .1322** [0.041]	0.0276* [0.000]	1.0643* [0.000]	−0.2374 [0.096]	−9.294* [0.000]
Q90	−0.8953* [0.000]	0.0199 [0.710]	0.2091** [0.041]	0.0282* [0.001]	1.0621* [0.000]	−0.6349* [0.001]	−8.122* [0.000]
Observations	454	454	454	454	454	454	454
Countries	21	21	21	21	21	21	21

Note: *, **, and *** denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Source: Authors' own calculations

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Figure 3: Visual depiction of MMQR estimations (Model-III)



Source: Authors' own elaboration

Robustness Analysis: An alternative estimation method

This study utilized quantile regression as a robustness test to validate the empirical findings obtained from the MMQR estimations. The results are presented in Table 8. The quantile regression analysis further confirms the reliability of the MMQR regression results.

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Table 8: Robustness test (Quantile Regression)

Variables	ln *DGE*	ln *IQ*	ln *URB*	ln *FDI*	ln *GDP*	ln *INU*	Constant
Q_{10}	−1.2936* [0.000]	−0.2109* [0.003]	0.3281* [0.001]	0.0007** [0.022]	1.0516* [0.000]	−0.4813* [0.000]	−9.9554* [0.000]
Q_{30}	−1.3969* [0.000]	−0.1272** [0.016]	0.0995** [0.026]	0.0209* [0.000]	1.0496* [0.000]	−0.0543*** [0.068]	−10.0844* [0.000]
Q_{50}	−1.3074* [0.000]	−0.1279*** [0.068]	0.1883** [0.018]	0.0157** [0.026]	1.0832* [0.000]	−0.1056** [0.037]	−10.1567* [0.000]
Q_{70}	−1.1866* [0.000]	−0.0506*** [0.050]	0.3111* [0.000]	0.0106 [0.167]	1.0556* [0.000]	−0.1152** [0.037]	−10.4764* [0.000]
Q_{90}	−0.8661* [0.000]	−0.1025** [0.034]	0.2265*** [0.065]	0.0255** [0.019]	1.0547* [0.000]	−0.4364** [0.019]	−9.1450* [0.000]
Observations	454	454	454	454	454	454	454
Countries	21	21	21	21	21	21	21

Note: *, **, and *** denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own calculations

5. Conclusion

The thriving DGE presents significant opportunities for global and OECD nations to reduce CBE. This study aims to investigate the impact of DGE and IQ on CBE while controlling for factors such as income growth, FDI, urbanization, and industrial upgradation. The research specifically examines a panel dataset comprising 21 OECD nations using the latest panel data analysis methods. The findings indicate that DGE and IQ positively influence environmental quality. In contrast, urbanization and FDI contribute to the ongoing CBE. Additionally, industrial upgrading plays a crucial role in mitigating CBE within OECD economies. These results are essential for informing long-term policymaking.

5.1 Policy implications

Drawing from this study's findings, we propose the following policy recommendations for policymakers in OECD countries: The finding that the advancement of the DGE reduces CBE suggests that OECD nations can further leverage modern technologies – such as AI, block-

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chain, smart grids, and IoT – to mitigate both local and imported emissions. The integration of digital technology into traditional production methods is essential. To achieve this, government institutions must develop and implement policies that promote environmentally friendly and low-emission technologies. Additionally, the governments of the countries examined should advocate for DGE initiatives to create opportunities for industries and businesses to transition from conventional to intelligent, low-emission practices. The energy sector, a significant contributor to emissions, must align with the digital and energy revolutions to enhance the energy framework. To boost energy efficiency, it is crucial for governments to fully leverage digital technologies within the energy sector. These advancements will aid in reducing reliance on traditional energy sources, optimizing the energy structure, and supporting efforts to cut emissions. While DGE plays a vital role in driving substantial economic growth, it also demands considerable electrical and energy consumption, which can lead to adverse environmental impacts. Consequently, we must be cautious about the potential negative effects of DGE on environmental quality. Therefore, OECD nations should prioritize the thorough integration of DGE and clean energy initiatives while investing in carbon capture and storage infrastructure. This approach would not only stimulate the digital economy's growth but also help achieve carbon neutrality, resulting in a beneficial outcome for all.

The negative correlation between IQ and CBE indicates that robust, transparent, and accountable institutions can significantly reduce emissions. OECD nations need to enhance policy coherence, enforcement, and inter-agency collaboration to promote green taxes, carbon pricing, and environmental compliance. High-quality institutions reduce uncertainty and obstacles to implementation, thereby improving the efficiency and predictability of carbon reduction measures. This, in turn, boosts investor confidence and accelerates the adoption of climate-aligned financial instruments, such as green bonds and carbon trading. Additionally, IQ can facilitate digital transformation, which indirectly enhances environmental quality. As the demand for digital technologies grows, individuals and businesses become more willing to integrate them into their lives and operations. Consequently, they expect governments and institutions to take the lead in implementing measures for the responsible use of digitalization. Trust in these institutions is essential for the success of individuals and organizations. Therefore, increasing the use of digital technologies and enhancing institutional performance can help lower the costs associated with environmental degradation. Moreover, effective and accountable institutions can combat corruption and prioritize environmental conservation efforts through the use of digital technologies. The finding that IQ reduces CBE aligns with institutional environmentalist theory, emphasizing that the rule of law, good governance, and regulatory quality are key to encouraging sustainable consumption patterns in developed economies.

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The findings of this study present valuable policy implications for OECD countries and underscore the significant importance of developing economies in Asia and South America, where digitalization and CBE are increasing rapidly. Various elements of the DGE – such as investments in accessible internet infrastructure, the implementation of electronic payment systems, and the use of digital monitoring tools – are replicable and can enhance transparent carbon management. The success of these initiatives largely hinges on IQ, as a sound regulatory structure, transparent systems, and a robust governance framework empower countries to transform digital advancements into substantial emission reductions. These factors suggest that policy formulation in developing countries should integrate the growth of the DGE with targeted improvements in administrative capacity, regulatory consistency, and accountability frameworks to maximize environmental benefits.

The study indicates that economic growth results in increased emissions, which negatively affect environmental quality. Urbanization enhances economic productivity while also elevating emissions, posing a dual challenge for OECD countries. To tackle this issue, there is a need for strategic investments in infrastructure and incentives for carbon reduction. Furthermore, foreign direct investment (FDI) could contribute to higher consumption-based emissions due to carbon-intensive value chains. OECD countries ought to implement sustainability standards and encourage responsible sourcing from international partners. Additionally, improving industrial practices is essential for minimizing environmental impact.

The study examines the relationship between the digital economy and institutional quality in promoting environmental sustainability within the OECD. The analysis focuses on 21 OECD countries, primarily due to data availability. However, excluding other member states may limit the generalizability of the findings. Future research could expand the dataset, depending on available data, and it should include non-OECD economies to enhance generalizability. The study depends on national-level indicators, which could overlook variations within countries and dynamics specific to various sectors. Future studies should incorporate subnational or sector-specific data to uncover micro-level phenomena.

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