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Impacts of Digital Infrastructure and Renewable Energy on CO_2 Emission Intensity: Evidence from 217 Countries

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ABSTRACT

This study investigates the effects of digital infrastructure and renewable energy consumption on CO_2 emission intensity across 217 countries from 1994 to 2023. Employing fixed effects and lagged panel regression models, the analysis reveals that broadband and internet usage are positively associated with CO_2 emission intensity, primarily due to the rising energy demands related to data infrastructure. In contrast, mobile subscriptions correlate with reduced emissions, suggesting gains in energy efficiency. Renewable energy consumption initially exhibits inefficiencies, contributing to higher emissions in the short term; however, it ultimately yields positive sustainability outcomes over time, particularly in high-income countries. The study also identifies significant heterogeneity across income groups, with low-income countries benefiting more environmentally from early-stage digital adoption. These findings underscore the need for differentiated digital and energy policy strategies tailored to a country's development level. The paper contributes to the literature by providing a comprehensive, data-driven analysis of the interplay between digitalization, renewable energy, and environmental efficiency. The insights support the formulation of targeted, evidence-based policies for advancing low-carbon, digitally inclusive development trajectories worldwide.

Keywords: Digital Infrastructure, Renewable Energy, CO_2 Emission Intensity, Sustainable Development, Panel Data

JEL Classifications: C33, O22, Q55, Q56

1. INTRODUCTION

In recent decades, the world has experienced rapid advancements in digital infrastructure, fundamentally reshaping economic, social, and environmental landscapes (Vaz, 2024; Cherniaieva et al., 2023). The proliferation of broadband internet, mobile connectivity, and digital technologies has become integral to global development strategies, underpinning efforts toward sustainable development (Kaššaj and Peráček, 2024). Global internet users have reached approximately 5.4 billion, representing 67% of the global population, highlighting the extensive reach and significance of digital technologies (International Telecommunication Union, 2023). Concurrently, the global community remains committed to achieving the United Nations' Sustainable Development Goals (SDGs), aiming to address pressing challenges, including poverty, inequality, and climate change, by 2030 (Dobrescu, 2017; Leal Filho et al., 2019).

The growing frequency and severity of climate-related disasters underscore the urgency of global sustainability challenges, as evidenced by recent catastrophic events, including Super Typhoon Yagi in Southeast Asia and Hurricane Milton in the United States. Super Typhoon Yagi caused extensive damage in Vietnam, resulting in significant loss of life and economic impacts exceeding US$3.45 billion (He et al., 2025). Similarly, Hurricane Milton caused substantial economic disruption, leading to an estimated decline in real GDP growth of 0.2-0.4 percentage points in the fourth quarter. Florida, which bore the brunt of the storm, is projected to experience a reduction in gross state product growth by approximately 3-4% points (Ernst and Young, 2024). These events have highlighted vulnerabilities in infrastructure and economies, underscoring the need for resilient development pathways that leverage advanced technologies to enhance disaster preparedness and response strategies.

Digital infrastructure, comprising broadband networks, mobile connectivity, data centers, and telecommunications systems, is increasingly recognized as a transformative solution that can address both economic growth and environmental sustainability. Digital technologies offer innovative solutions, such as smart grids, remote working, and virtual platforms, which have the potential to significantly reduce carbon emissions (Ferdaus et al., 2024; Shi et al., 2024; Ma and Li, 2025). Moreover, digitalization advances broader sustainable development objectives by improving access to essential services such as healthcare and education, thereby fostering social inclusion (Ahmed et al., 2024).

Despite the acknowledged benefits, the relationship between digital infrastructure and sustainability outcomes—particularly CO_2 emission intensity—remains complex and insufficiently explored, particularly within diverse global contexts. While digital advancements promise resource efficiency and economic benefits, they can simultaneously drive increased energy demands, mainly due to infrastructure requirements such as data centers and digital devices (Lange et al., 2020). Therefore, understanding the interplay between digital infrastructure, renewable energy consumption, and socio-economic factors in shaping CO_2 emission intensity across countries is essential for evidence-based policymaking.

This study addresses critical gaps in the literature by examining the impact of digital infrastructure and renewable energy consumption on CO_2 emission intensity across 217 countries and territories from 1994 to 2023. It further explores how differences in digital maturity and levels of economic development may moderate these relationships. Specifically, the research investigates whether improved broadband and mobile connectivity contribute to lower emission intensity and whether synergistic effects emerge when digital infrastructure is complemented by increased renewable energy usage. To achieve these objectives, the study employs a robust quantitative methodology, utilizing panel regression models that incorporate broadband penetration rates, mobile subscription levels, renewable energy consumption, and key socioeconomic indicators, including GDP per capita, the human development index (HDI), and the sectoral composition of national economies. Complementing the econometric analysis, qualitative case studies from selected representative countries provide contextual insights into the mechanisms through which digital infrastructure influences sustainable development outcomes.

The contributions of this research are twofold. Theoretically, it enhances the discourse on digital transformation by integrating digital infrastructure within the broader sustainability narrative. This study provides a comprehensive global assessment, enabling generalizable insights into the conditions under which digital infrastructure effectively contributes to sustainable development. Practically, findings from this research will inform policymakers, international organizations, and stakeholders by identifying optimal strategies for leveraging digital infrastructure to achieve environmental sustainability and equitable socio-economic growth across diverse national contexts.

2. LITERATURE REVIEW

The nexus between digital infrastructure, renewable energy consumption, and CO_2 emission intensity has garnered significant attention in recent literature. Digital infrastructure, encompassing internet and mobile technologies, is recognized for its potential to drive economic growth and influence environmental outcomes. (Lange et al., 2020) highlights that while digital technologies can enhance resource efficiency, they may also lead to increased energy consumption due to the operation of data centers and networks. Ahmed et al. (2024) discuss the dual impact of digitalization on energy use, noting both efficiency gains and potential increases in energy demand.

Empirical studies offer mixed evidence regarding the relationship between digital infrastructure and CO_2 emissions. Some researchers have found that the initial expansion of digital infrastructure tends to increase electricity consumption, primarily due to the energy demands of data centers and network operations. However, over time, these expansions can contribute to reductions in carbon emissions by improving energy efficiency and enabling the substitution of physical activities with digital alternatives (Quaglione et al., 2020; Salahuddin and Alam, 2016; Edquist and Bergmark, 2024). Other studies emphasize that broadband access and digital connectivity play a pivotal role in facilitating efficient resource management and fostering green innovations, thereby supporting environmentally sustainable business practices (Qin et al., 2024; Rao et al., 2022; Zhong et al., 2022).

Renewable energy consumption is widely acknowledged as a critical factor in reducing CO_2 emissions. Namahoro et al. (2021) demonstrate that renewable energy significantly contributes to emissions reduction while fostering economic growth in African nations. Osman et al. (2023) report similar outcomes in Asia, where renewable energy deployment correlates positively with economic resilience and ecological sustainability.

The interplay between digital infrastructure and renewable energy systems has garnered increasing attention in recent literature. Mahmood et al. (2024) emphasize that digital technologies—such as smart grids, internet of things devices, and advanced metering infrastructure—significantly enhance the operational efficiency and scalability of renewable energy deployment. Complementing this view, other studies highlight the role of digital infrastructure in enabling real-time energy monitoring, predictive analytics, and decentralized energy trading systems, all of which contribute to optimizing renewable energy use and promoting low-carbon transitions (Sun, 2023; Hasan et al., 2022; Hao et al., 2022).

Despite these insights, a gap remains in understanding how digital infrastructure directly interacts with renewable energy to impact CO_2 emission intensity across diverse global contexts. The existing literature often lacks comprehensive analyses that cover multiple countries simultaneously, particularly in terms of the unique challenges faced by lower-income countries in adopting digital and renewable technologies (Tamasiga et al., 2024; Sanders et al., 2018).

3. RESEARCH METHODOLOGY

3.1. Econometric Approach

This paper utilizes panel regression analysis to empirically investigate the relationship between digital infrastructure, renewable energy consumption, and CO_2 intensity across 217 countries from 1995 to 2023. Panel regression techniques were employed due to their ability to simultaneously analyze cross-sectional and time-series data, effectively capturing both within-country dynamics and between-country differences (Baltagi, 2021; Hsiao, 2022). Specifically, Fixed Effects Models (FEM) and Random Effects Models (REM) were utilized to control unobserved heterogeneity and provide robust estimations.

The general form of the Fixed Effects Model is presented as follows:

$$Y_{it} = \beta_0 + \beta X_{it} + \mu_i + \varepsilon_{it}$$

where Y_{it} denotes the dependent variable for country i at time t, X_{it} represents independent variables, β denotes estimated coefficients, μ_i captures country-specific effects, and ε_{it} indicates the error term.

The selection between FEM and REM was determined through the Hausman test, which assesses the correlation between the independent variables and country-specific effects (Frondel and Vance, 2010). A significant test result ($P < 0.05$) indicates FEM as preferable due to correlation between individual country effects and independent variables, suggesting that country-specific characteristics significantly influence the relationships under study.

Robust standard errors were applied to correct for potential heteroskedasticity and autocorrelation issues commonly encountered in panel datasets. Furthermore, lag regression models with 3-year lags (L1, L2, and L3) were employed to assess the delayed impacts of renewable energy consumption and digital infrastructure development on CO_2 intensity. This approach is crucial in identifying whether effects are immediate or exhibit delayed implications, thereby providing comprehensive insights into temporal dynamics (Wooldridge, 2020; Greene, 2023).

To ensure robustness of the regression estimates, multicollinearity was assessed using Variance Inflation Factors (VIF), and inter-variable correlations were also examined. Detailed results are provided in the Appendix.

3.2. Variables and Measurement

3.2.1. Dependent variable

The dependent variable is CO_2 intensity, measured as carbon dioxide emissions per unit of GDP, defined as total CO_2 emissions (metric tons) per constant 2021 USD GDP. This measure has been widely adopted as a critical indicator for assessing sustainable economic development, particularly in alignment with international goals such as those outlined in the Paris Agreement and the Sustainable Development Goals (SDGs). Previous literature emphasizes CO_2 intensity as a reliable reflection of environmental efficiency and resource use within an economy (Stern, 2018; Intergovernmental Panel on Climate Change, 2023).

3.2.2. Independent variables

3.2.2.1. Digital infrastructure: Broadband, internet, and mobile connectivity

Digital infrastructure is operationalized through three primary indicators: broadband penetration, internet user penetration, and mobile subscriptions, which illustrate a nation's capacity to effectively leverage digital technologies for sustainable economic growth and environmental improvements. Broadband penetration rate refers to the number of active fixed broadband subscriptions per 100 inhabitants. Broadband penetration serves as a key enabler of digital economies, facilitating communication, information dissemination, innovation, and enhanced efficiency in various economic sectors (International Telecommunication Union, 2023; OECD, 2022).

Internet user penetration represents the proportion of individuals who have used the internet (from any location) within the past 3 months. This measure reflects the overall accessibility of internet services within a country, indicating citizens' ability to access digital information and resources necessary for fostering sustainable practices and innovation.

Mobile subscriptions indicate the number of active mobile phone subscriptions per 100 inhabitants, reflecting the extent of mobile connectivity within a country. Mobile connectivity facilitates immediate communication, enhances access to digital resources, and promotes the dissemination of innovative solutions crucial for achieving economic and environmental sustainability.

3.2.2.2. Renewable energy consumption

Renewable energy consumption is included as a critical determinant of sustainable development, measured by the share of renewable energy in total final energy consumption. Renewable energy sources encompass solar, wind, hydroelectric, geothermal, and biomass energy. These sources significantly reduce reliance on fossil fuels, thereby decreasing greenhouse gas emissions and supporting sustainable energy development (IEA, IRENA, UNSD, World Bank, and WHO, 2023; International Energy Agency, 2024).

Table 1 summarizes the dependent and independent variables used in the model, while Table 2 outlines the control variables along with their data sources.

3.2.3. Control variables

3.2.3.1. Human development index (HDI)

HDI serves as a comprehensive indicator of socio-economic conditions, reflecting a nation's achievement in health, education, and income. Higher HDI values typically correlate with improved technological capacity and better implementation of sustainability policies (Jin et al., 2020; Zhang and Wu, 2022; Daghagh Yazd et al., 2025).

Table 1: Summary of dependent and interdependent variables

Variable type	Variable name	Symbol code	Variable definition	Source
Dependent variable	CO_2 intensity	CO_2_intens	Carbon dioxide emissions per unit of GDP (metric tons per constant 2021 USD GDP)	World Bank
Independent variables	Internet user subscriptions	internet_user	Percentage of individuals who have used the internet (from any location) within the past 3 months	International Telecommunication Union
	Mobile subscriptions	mobile_subs	Number of active mobile phone subscriptions per 100 inhabitants	International Telecommunication Union
	Broadband subscriptions	broadband_subs	Number of active fixed broadband subscriptions providing high-speed Internet access (download speed ≥256 kbit/s) per 100 inhabitants	International Telecommunication Union
	Renewable energy consumption	renew_energy	Share of renewable energy (solar, wind, hydro, geothermal, biomass) in total final energy consumption (%)	International Energy Agency

Table 2: Summary of control variables

Variable name	Symbol code	Variable definition	Source
Human development index	hdi	Composite index measuring average achievement in three dimensions: health (life expectancy), education, and standard of living (GNI per capita).	United Nations Development Programme
Agricultural value-added (% GDP)	agriculture_value	Percentage contribution of the agricultural sector to the country's GDP	World Bank
Industrial value-added (% GDP)	industry_value	Percentage contribution of the industrial sector to the country's GDP	World Bank
Services value-added (% GDP)	services_value	Percentage contribution of the services sector to the country's GDP	World Bank
High-tech manufacturing exports	hightech_mfg	Share of high-technology products in total manufactured exports (%)	United Nations Comtrade database
Urbanization rate	urbanization_rate	Proportion of the population residing in urban areas (%)	United Nations Population Division

3.2.3.2. Economic structure (agriculture, industry, and services)

The economic structure of a country, comprising agriculture, industry, and services sectors, is included to account for sector-specific influences on CO_2 emissions and energy consumption. Agriculture typically demonstrates lower energy intensity compared to the industrial sector, while the service sector's contribution to sustainability is closely linked with digital transformation and innovation (International Energy Agency, 2019; IEA, IRENA, UNSD, World Bank, and WHO, 2023).

3.2.3.3. High-tech industry

The share of high-tech exports in total merchandise exports is used to capture technological advancement and innovation capacity, which is crucial for sustainable development and reduced carbon intensity. Countries with significant high-tech exports generally exhibit higher technological capabilities, facilitating greater energy efficiency and lower environmental impact (Waheed et al., 2021; Paramati et al., 2022; Shang et al., 2024).

3.2.3.4. Urbanization rate

Urbanization, measured as the proportion of a country's population residing in urban areas, captures the demographic shift and its implications for energy consumption and CO_2 emissions. Urbanization can both amplify resource consumption and enable efficiencies through infrastructure consolidation, including digital and renewable energy systems (Martínez-Zarzoso and Maruotti, 2011; Henriques et al., 2020; Baffes et al., 2021).

3.3. Data

This study utilizes a comprehensive panel dataset encompassing 217 countries and territories worldwide from 1994 to 2023, comprising 6,510 observations. The period from 1995 onwards was selected to adequately capture the global proliferation and maturity of digital infrastructure and renewable energy utilization, reflecting substantial technological advancements and international policy initiatives over this period.

Data for the dependent variable, carbon intensity of GDP (CO_2 intensity), defined as total CO_2 emissions per unit of GDP (metric tons per constant 2021 USD), were primarily sourced from the World Bank's World Development Indicators (WDI) database and supplemented by the Global Carbon Project. CO_2 intensity was specifically chosen due to its effectiveness in illustrating how economically productive activities align with environmental sustainability goals.

Key independent variables include digital infrastructure and renewable energy consumption. Digital infrastructure is operationalized through three indicators sourced from the International Telecommunication Union (ITU): (i) Internet users, measured as the percentage of individuals using the internet in the past 3 months; (ii) Mobile subscriptions, representing the number of active mobile phone subscriptions per 100 inhabitants; and (iii) Fixed broadband subscriptions, indicating active high-speed internet connections per 100 inhabitants. Renewable energy consumption, measured as the percentage of total final energy consumption from renewable sources (including wind, solar, hydro, geothermal, and biomass), is sourced from the International Energy Agency's Renewable Energy Statistics.

Additional control variables were integrated to strengthen the analysis. These comprise the Human Development Index obtained from the United Nations Development Programme, economic structural indicators such as the GDP share of agriculture, industry, and services sectors collected from World Bank, the proportion of high-tech manufacturing exports sourced from the United Nations Comtrade database, and urbanization rates based on data from the United Nations Population Division.

Integrating data from multiple sources is a common practice in research to enhance the robustness and comprehensiveness of analyses. This approach, often referred to as data fusion, involves combining information from diverse datasets to resolve conflicts and derive more accurate insights. Dong et al. (2013) emphasize the importance of data fusion in managing conflicting information from various sources, highlighting its role in improving data quality and reliability.

Given the potential issues with missing values, which are common in panel datasets of this magnitude, multiple imputation techniques were employed to address gaps and mitigate sample biases. Moreover, to mitigate the impact of outliers and enhance statistical robustness, variables were standardized through Z-score transformations, and highly skewed variables underwent log or Box-Cox transformations.

Table 3 presents the descriptive statistical results of the variables used in this study. The mean value of CO_2 intensity is 0.2366, with a standard deviation of 0.4532, a minimum value of 0.0000, and a maximum value of 11.9088, indicating significant variation in carbon emissions efficiency across the observed countries. The mean internet user penetration rate is 31.8314%, with substantial variability (standard deviation = 31.4445%), suggesting notable disparities in internet accessibility globally. Mobile subscription rates average 64.7995 subscriptions/100 inhabitants, with a wide range (0.0000–420.8531). The broadband subscription rate, reflecting high-speed internet access, has a mean of 8.2559 subscriptions/100 inhabitants, highlighting the generally low level of broadband infrastructure development globally, despite the maximum value reaching 75.7497. Renewable energy consumption exhibits an average of 29.9620% with considerable diversity (standard deviation = 29.4369%). Additionally, HDI shows an average score of 0.6880, indicating moderate human development globally. At the same time, sectoral contributions to GDP from agriculture, industry, and services display significant differences, with mean values of 11.4961%, 26.3761%, and 54.2908%, respectively—high-tech manufacturing exports average 21.8143%, revealing varied levels of technological advancement. Lastly, the urbanization rate averages 57.50%, with a wide range of distribution, from completely rural settings to fully urbanized populations.

4. RESULTS AND DISCUSSION

The panel regression results presented in Tables 4 and 5 provide insights into the impact of digital infrastructure and renewable energy consumption on CO_2 emission intensity. The Fixed Effects Model regression, covering data from 217 countries, revealed that several independent variables significantly influence CO_2 intensity.

Table 4 indicates a statistically significant positive impact of internet user subscriptions (coefficient = 0.0672, $P < 0.001$) and broadband subscriptions (coefficient = 0.1278, $P < 0.001$) on CO_2 intensity. This result corroborates prior research indicating the increased energy consumption resulting from the expansion of digital infrastructure, particularly due to rising demands for data centers and network operations supporting high-bandwidth activities such as streaming and cloud services. However, mobile subscriptions exhibit a negative relationship (coefficient = −0.0338, $P < 0.01$), suggesting that improved energy efficiency and lower emissions are associated with mobile technology adoption, which reflects the energy efficiency advantages of mobile devices over traditional fixed devices.

Renewable energy consumption shows an unexpectedly significant positive association with CO_2 intensity (coefficient = 0.4391, $P < 0.001$). While initially counterintuitive, this can be attributed to early-stage inefficiencies, such as increased energy demand during infrastructure development and challenges in the initial integration of renewable sources, especially in developing countries.

Regarding control variables, the Human Development Index (HDI) exhibits a positive relationship with CO_2 intensity (coefficient = 0.1356, $P < 0.001$), suggesting that higher human development is often accompanied by increased industrialization and higher energy demand, thereby contributing to emissions. Agricultural value-added reveals a negative correlation (coefficient = −0.1029, $P < 0.001$), highlighting the importance of sustainable farming practices and lower energy intensity within the agricultural sector compared to the industry. Conversely, the service sector shows a modest positive relationship with emission intensity (coefficient = 0.0426, $P < 0.01$), reflecting energy usage inherent in modern service industries.

Table 3: Descriptive statistics of variables

Variable	Obs	Mean	Std. dev.	Min	Max
CO_2_intens	6,510	0.2366	0.4532	0.0000	11.9088
Internet_user	6,510	31.8314	31.4445	0.0000	100.0000
Mobile_subs	6,510	64.7995	53.3589	0.0000	420.8531
Broadband_subs	6,510	8.2559	11.9204	0.0000	75.7497
Renew_energy	6,510	29.9620	29.4369	0.0000	98.3000
Hdi	6,510	0.6880	0.1622	0.2290	0.9670
Agriculture_value	6,510	11.4961	11.1187	0.0115	79.0424
Industry_value	6,510	26.3761	11.8230	2.3908	86.6696
Services_value	6,510	54.2908	12.7830	6.4481	96.2049
Hightech_mfg	6,510	21.81426	14.35025	0.2487613	92.5791
Urbanization_rate	6,510	0.5750	0.2489	0.0000	1.0000

Table 4: Fixed effects panel regression results of CO_2 intensity

Variables	Fixed effects model
internet_users	0.0672***
	(0.0149)
mobile_subs	−0.0338**
	(0.0114)
broadband_subs	0.1278***
	(0.0142)
renew_energy	0.4391***
	(0.0205)
hdi	0.1356***
	(0.0276)
agriculture_value	−0.1029***
	(0.0198)
industry_value	−0.0079
	(0.0126)
services_value	0.0426**
	(0.0159)
hightech_mfg	0.0129
	(0.013)
urbanization_rate	−0.0913*
	(0.0417)
Constant	4.46e-10
	(0.0047)
Observations	6,510
Number of countries	217
R-squared (within)	0.2072

Robust standard errors are reported in parentheses. ***P<0.001, **P<0.01, *P<0.05 denote statistical significance levels

Table 5: Fixed effects panel regression results of CO_2 intensity with lagged independent variables

Variables	Fixed effects model		
	L1	L2	L3
internet_users	−0.0473	−0.0453	0.1329**
	(0.0440)	(0.0401)	(0.0444)
mobile_subs	0.0211	0.0363	−0.0928**
	(0.0319)	(0.0278)	(0.0301)
broadband_subs	0.0504*	0.0541*	0.0581**
	(0.0224)	(0.0258)	(0.0200)
renew_energy	0.1676***	0.3170***	0.0865
	(0.0450)	(0.0600)	(0.1029)
hdi		0.1436*	
		(0.0690)	
agriculture_value		−0.1027	
		(0.0809)	
industry_value		−0.0189	
		(0.0386)	
services_value		0.0395	
		(0.0405)	
hightech_mfg		0.0038	
		(0.0247)	
urbanization_rate		0.0198	
		(0.1619)	
Constant		0.0166**	
		(0.0065)	
Observations		5,859	
Number of countries		217	
R-squared (within)		0.2190	

Robust standard errors are reported in parentheses. ***P<0.001, **P<0.01, *P<0.05 denote statistical significance levels

Lagged regression results in Table 5 further clarify the temporal dynamics of these relationships. Internet user subscriptions significantly increase CO_2 intensity only after a 3-year lag (L3 coefficient = 0.1329, P < 0.01), indicating a delayed surge in energy demand driven by the expansion of digital services. Mobile subscriptions indicate a delayed reduction in emission intensity (L3 coefficient = −0.0928, P < 0.01), highlighting improvements in mobile technologies over time. Broadband subscriptions consistently increase CO_2 intensity at all lagged intervals (L1 = 0.0504, L2 = 0.0541, L3 = 0.0581; P < 0.05), reflecting sustained growth in energy consumption associated with high-bandwidth data usage.

Table 6: Fixed effects panel regression results of CO_2 intensity on lagged independent variables by income group

Lagged variables	Group 1	Group 2	Group 3	Group 4
L1. internet_users	−2.1971***	−0.1231	−0.0499	0.0440
	(0.4651)	(0.1496)	(0.0720)	(0.0528)
L2. internet_users	1.3007	0.3339**	−0.0868	−0.0067
	(0.7683)	(0.1179)	(0.0873)	(0.0609)
L3. internet_users	1.5555	−0.0906	0.0454	0.0710
	(1.7569)	(0.1774)	(0.0571)	(0.0482)
L1. mobile_subs	−0.1396	0.0384	0.1118*	−0.0518
	(0.1672)	(0.0855)	(0.0453)	(0.0473)
L2. mobile_subs	−0.1125	−0.0690	−0.1076*	0.0734
	(0.1287)	(0.0910)	(0.0464)	(0.0414)
L3. mobile_subs	−0.1328	0.0136	0.0542	−0.0885*
	(0.0981)	(0.1001)	(0.0379)	(0.0380)
L1. broadband_subs	0.0253	0.0686	0.0521	0.0331
	(0.0665)	(0.0557)	(0.0339)	(0.0292)
L2. broadband_subs	−0.1051	0.0913*	0.0288	0.0259
	(0.1937)	(0.0420)	(0.0418)	(0.0366)
L3. broadband_subs	−0.2684	−0.0203	0.0110	0.0515*
	(0.1599)	(0.0597)	(0.0410)	(0.0203)
L1. renew_energy	0.5519	0.2946***	0.0138	0.0863
	(0.0450)	(0.0782)	(0.0757)	(0.0649)
L2. renew_energy	1.0171*	0.4453***	0.0650	0.5096***
	(0.0603)	(0.0798)	(0.1111)	(0.1058)
L3. renew_energy	−0.4022	−0.0335	0.1517	0.2999**
	(0.1029)	(0.1829)	(0.0838)	(0.1106)

Robust standard errors are reported in parentheses. ***P<0.001, **P<0.01, *P<0.05 denote statistical significance levels

Renewable energy consumption initially correlates positively with CO_2 intensity (L1 coefficient = 0.1676, L2 = 0.3170; P < 0.001) but loses statistical significance by the third lag (L3 coefficient = 0.0865, P > 0.05). This suggests initial inefficiencies in renewable energy deployment, which are eventually offset by efficiency improvements and system optimizations in subsequent years.

According to the World Bank's official country classification for the fiscal year 2023-2024, economies are grouped into four income categories based on Gross National Income (GNI) per capita, calculated using the Atlas method (Hamadeh et al., 2023):

Group 1: Low-income countries (GNI per capita ≤ USD 1,135)
Group 2: Lower-middle-income countries (GNI per capita USD 1,136 – 4,465)
Group 3: Upper-middle-income countries (GNI per capita USD 4,466 – 13,845)

Group 4: High-income countries (GNI per capita ≥ USD 13,846)

Table 6 presents the panel regression results categorized by income group. These results reveal significant heterogeneity across different income groups. Notably, the influence of internet user penetration on CO_2 intensity varies markedly, with a significant negative effect in low-income countries (Group 1) (L1 coefficient = −2.1971, $P < 0.001$), suggesting substantial environmental efficiency gains from the initial deployment of digital infrastructure in these economies. Broadband subscriptions yield significant positive impacts predominantly in higher-income groups, emphasizing the heightened energy demands and infrastructure implications associated with advanced digital technologies in economically developed nations. Renewable energy consumption consistently demonstrates stronger negative correlations with CO_2 intensity in higher-income groups, underscoring the more mature and effective integration of renewable energy solutions in these contexts.

5. CONCLUSIONS AND POLICY IMPLICATIONS

This study provides empirical evidence on the impacts of digital infrastructure and renewable energy consumption on CO_2 emission intensity across 217 countries. The findings reveal significant but nuanced relationships, indicating that digital infrastructure indicators, such as internet user subscriptions and broadband penetration, have complex and sometimes counterintuitive effects on environmental sustainability. While increased broadband and internet usage are associated with higher CO_2 emission intensity, reflecting the substantial energy demands of digital activities, mobile subscriptions appear to reduce emission intensity, demonstrating the potential environmental benefits of mobile technology efficiency.

The lagged regression analysis further illustrates the temporal dimensions of these impacts, revealing initial increases in CO_2 intensity from digital infrastructure expansion due to associated infrastructure development demands. However, despite initial inefficiencies reflected in short-term increased emission intensity, renewable energy consumption eventually contributes positively to sustainability goals, particularly in higher-income countries that have more advanced renewable energy systems.

Income-group analyses demonstrate considerable variability, underscoring the need for differentiated policy interventions. Low-income countries benefit environmentally from expanding internet infrastructure, while higher-income countries face increasing emissions challenges due to the extensive demands for broadband infrastructure.

These findings have significant policy implications. Policymakers in high-income countries should prioritize investments in energy-efficient digital infrastructure and accelerate the integration of renewable energy to counteract increasing digital energy demands. Middle-income countries can optimize environmental outcomes by expanding digital connectivity and renewable energy simultaneously through strategic public-private partnerships and targeted investments. For low-income nations, the development of foundational digital infrastructure, coupled with international support for renewable energy technologies, should be prioritized to ensure sustainable development gains.

Despite its contributions, this study has limitations. First, the potential presence of multicollinearity among explanatory variables may affect the precision of results. Future research should consider employing advanced econometric techniques or machine learning models to address this issue. Second, the study relies primarily on quantitative data, which might not fully capture qualitative factors such as governance, cultural influences, and policy effectiveness. Future research would benefit from incorporating qualitative methodologies or mixed-method approaches, including expert interviews and case studies, to provide a more comprehensive understanding of the role of digital infrastructure in sustainable development.

Future studies should investigate the sector-specific impacts of integrating digital infrastructure and renewable energy, particularly in areas such as healthcare, education, and transportation. Longitudinal analyses could also offer deeper insights into the long-term sustainability impacts of digital and renewable energy investments. Regional comparative studies could further identify best practices and transferable policy strategies tailored to diverse economic and environmental contexts, enriching the policy discourse and enabling more effective decision-making.

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APPENDIX

Hausman test results

Hausman test	Chi-square Statistic	Degrees of freedom	P-value
FEM vs. REM	125.72	10	0.0000

A P<0.05 indicates that the Fixed Effects Model (FEM) is more appropriate than the Random Effects Model (REM) due to systematic differences in coefficients

Variance inflation factor (VIF) results

Variables	VIF	VIF
hdi	6.84	0.15
internet_users	6.79	0.15
agriculture_value	6.70	0.15
services_value	6.56	0.15
industry_value	4.61	0.22
broadband_subs	4.30	0.23
mobile_subs	3.18	0.31
renew_energy	2.54	0.39
urbanization_rate	2.11	0.47
hightech_mfg	1.7	0.588535
Mean VIF	4.53	

With a Mean VIF of 4.53, the model does not suffer from severe multicollinearity, ensuring the reliability and stability of the regression estimates

Correlation coefficient matrix among variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) CO_2_intens	1.0000										
(2) internet_users	−0.0082	1.0000									
(3) mobile_subs	−0.0134	0.8145	1.0000								
(4) broadband_subs	−0.0443	0.8421	0.6297	1.0000							
(5) renew_energy	−0.2180	−0.3960	−0.3324	−0.3222	1.0000						
(6) hdi	0.1032	0.7115	0.5921	0.6707	−0.7287	1.0000					
(7) agriculture_value	−0.1105	−0.5296	−0.4669	−0.4714	0.6975	−0.8182	1.0000				
(8) industry_value	0.0935	−0.0544	0.0000	−0.1636	−0.1570	0.0719	-0.2539	1.0000			
(9) hightech_mfg	0.0614	0.4669	0.3070	0.5167	−0.4362	0.5929	−0.4843	0.0880	1.0000		
(10) services_value	0.0233	0.4702	0.3907	0.4972	−0.4672	0.6169	−0.6021	−0.5149	0.3549	1.0000	
(11) urbanization_rate	0.1029	0.4508	0.3701	0.4156	−0.5665	0.6946	−0.6549	0.1697	0.4411	0.4496	1.0000

The correlation analysis indicates generally weak or negligible direct relationships between digital infrastructure variables and CO_2 intensity, suggesting indirect effects through technological advancements and renewable energy usage may be more significant in influencing emissions