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Digitalization and the environment: The role of information and communication technology and environmental taxes in European countries

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Abstract

This study examines the impacts of digitalization through information and communication technology (ICT) and environmental taxes on greenhouse gas (GHG) emissions in 23 European Union (EU) countries between 2000 and 2017. Using the Pooled Mean Group estimator, the empirical results provide evidence that ICT development and environmental taxes improve environmental sustainability while research and development investments and income per capita deteriorate environmental sustainability. Furthermore, the results based on the Dynamic Panel Threshold Regression model show that the relationship between ICT and GHG emissions is dependent on the level of environmental taxes. During the period of low environmental taxes, the effect of ICT on GHG emissions is positive and insignificant but once environmental taxes cross the threshold value, the effect of ICT becomes negatively related to greenhouse gas emissions. This suggests that the period of low environmental taxes does not support the environmental friendliness of ICT development in the European region. The policy implication of these findings is that ICT, environmental taxes, and renewable energy can be possibly stirred up to achieve long-term environmental sustainability in the EU region.

KEYWORDS
environmental sustainability, environmental taxes, ICT diffusion, income per capita, R&D investment, renewable energy

1 | INTRODUCTION

One of the recent global problems is the accelerated environmental destruction resulting from the use of conventional energy resources, which include fossil fuels. The increased CO_2 emissions caused by fossil fuel usage as a result of urban and industrial development have prompted regulators, experts, and policymakers at the international and national levels to pursue a variety of policies to reduce the pollutant effect of greenhouse gas (GHG) (Usman et al., 2020; Kirikkaleli & Adebayo, 2021; Rafindadi & Usman, 2019; Sarwar, 2019; Tufail et al., 2021; Usman, Akadiri, & Adeshola, 2020; Usman et al., 2019). The Treaty of Kyoto, which is the global environmental agreement negotiated by 37 developed nations, including the European Community, is one of the early initiatives of international policymakers, supporting an international pledge to combat global warming via a reduction in the accumulation of GHGs in the atmosphere. Following this treaty, the signatories were focused on reducing their GHG emissions at the national level by at least 5% between 2008 and 2012. While taking 1990 as a baseline, the level of emission reduction from 2013 to 2020 was set at 18% (International Energy Agency, 2015). Recently, the European Union (EU) Parliament raised the bar for the GHG reduction target from 30% to 40% of the 2005 levels by 2030 (European Parliament, 2023).

Along with the global efforts via the Paris Climate Conferences and Intergovernmental Panel on Climate Change (IPCC) to reduce global rising temperatures far below 2°C, there have been several calls at the level of individual countries to slow the pace of environmental destruction following an increase in growth and development. One of the measures used by different countries is by digitalizing the economy. Theoretically, digitalization can mitigate GHG emissions by reducing energy consumption through energy efficiency and energy savings. Smart applications of information and communication technology (ICT) dampen the pressure on energy utilization in production, consumption, and distribution (Ahmed & Le, 2021; Al-Mulali et al., 2015; Ozcan & Apergis, 2018; Rehman et al., 2021; Salahuddin & Gow, 2016). On the contrary, some studies debunk the negative relationship between ICT and emissions. For example, an increase in the pace of ICT development is said to have exerted pollutant emissions (Arshad et al., 2020; Godil et al., 2020; Haini, 2021; Malmodin & Lundén, 2018; Park et al., 2018; Salahuddin et al., 2016). The explanation given by this strand of literature is that the positive effect of ICT through the growth of energy demand and economic growth outweighs its negative effects, hence the overall effect is positive, that is, increasing environmental degradation measures.

As a strategy to slow the accumulation of GHG emissions, policymakers across the globe have adopted the use of environmental taxes, which include carbon tax, pollution tax, energy tax, resources tax, etc. Generally, in EU countries, carbon tax is a commonly used instrument to checkmate emission-induced production and consumption of goods. This kind of tax is also called the Emissions Trading Scheme. The emissions trading scheme can be implemented by imposing a levy based on the carbon content of the sales, distribution, or fossil fuels utilization. It can also be improved through a quota system which is normally known as cap-and-trade as demonstrated by Wolde-Rufael and Mulat-Weldemeskel (2023). In addition, investment in research and development (R&D) has been promoted by nations across the world as a way to develop and implement clean energy innovation and promote a long-term sustainable environment (Churchill et al., 2019; Paramati et al., 2021; Shahbaz et al., 2017). R&D investments will enhance production, reduce costs of production, and improve competitiveness as well as increase economic growth. Based on this understanding, EU countries, as of 2014, invested the sum of USD 4.3 billion on R&D in renewable energy and 1029 TWh on R&D in renewable energy as of 2019, which approximately accounts for about 37.5% of the total primary energy production.

Despite the accelerated pace of digitalization through ICT, adoption of environmental-based taxes, and R&D investment in renewable energy, there is still evidence of an increasing level of GHG emissions, leading to global warming and climatic changes. Given this background, our study aims to assess the effectiveness of ICT development and environmental taxes in reducing GHG emissions in EU countries over the period 2000 to 2017. Therefore, this study contributes to the existing literature in the following ways: First, the study sheds light on the effectiveness of ICT development and environmental taxes in lowering GHG emissions in the EU region. This understanding is crucial for achieving net-zero emission targets and carbon neutrality in this region. Second, we also examine how low or high environmental taxes affect the relationship between ICT and GHG emissions in European countries. Third, given a huge investment in R&D renewable energy over time, our study incorporates R&D investments, renewable energy, and economic growth as control variables to determine changes in GHG emissions over time. Fourth, the long-run and short-run estimates are obtained based on the Pooled Mean Group (PMG) estimation of dynamic heterogeneous panels, while a dynamic panel threshold model is applied to estimate how environmental taxes as a policy instrument influence the scale and form of the relationship ICT development has with GHG emissions in EU countries. This model controls for the likely endogeneity and serial correlation problems in the panel.

The paper is therefore organized into several sections. Following a concise introduction, the second section highlights the existing literature on environmental degradation and economic growth, environmental taxes and emissions, environmental degradation and ICT development, and environmental degradation and R&D expenditures. The third section outlines the data and methodology employed. The fourth section presents the empirical findings and discussion, while the fifth section concludes the paper and offers policy recommendations.

2 | LITERATURE REVIEW

This section explores the links between environmental indicators and the determinants (ICT, environmental-based taxes, renewable energy, research and development expenditures, and income per capita).

2.1 | Environmental degradation and economic growth nexus

A growing body of theoretical and empirical literature has emerged, aiming to examine the determinants of environmental pollution and devise mechanisms for its reduction. This literature is hinged on the relationship between economic growth and CO_2 emissions. Within the literature, three distinct lines of research have been identified with each focusing on different aspects of the relationship between these variables. The first line examines the validity of the Environmental Kuznets Curve (EKC). The second line investigates the nexus between energy consumption and economic productivity while the third line combines both the effect of economic productivity and energy on environmental degradation (Abbas et al., 2022; Ali et al., 2020; Pao & Tsai, 2011; Usman et al., 2019; Usman, Iorember et al., 2021).

The EKC hypothesis is an extension of the inequality–income relationship initially proposed by Kuznets (1955). According to Grossman and Krueger (1991), in the early stage of development, both production and pollution levels are low. As production increases, pollution also rises, and concerns about environmental quality are relatively marginal. Consequently, pollution increases at a faster rate than production, particularly during the transition from an agricultural to a manufacturing-based economy. However, as countries become more developed and individuals earn higher per capita incomes and experience increased technology, there is a heightened interest in environmental quality. Given empirical validity, a strong positive relationship between per capita income and environmental degradation has been found in several studies, particularly in developing economies

(Carson et al., 1997; Junyi, 2006; Ozturk & Acaravci, 2010). For instance, Carson et al. (1997) found evidence in support of the EKC hypothesis in the United States. This means that an increase in income per capita triggers air pollution to rise. Junyi (2006) validated the EKC hypothesis at the levels of provinces in China specifically between 1993 and 2002. Ozturk and Acaravci (2010) incorporated unemployment into the relationship between pollution and output while their results failed to support the EKC hypothesis but found a two-way causality between the variables.

In recent times, several studies have investigated how the environment responds to changes in income per capita by incorporating energy consumption into the EKC model. Shahbaz et al. (2017) added energy consumption and globalization in the EKC model for China. The study found evidence of the EKC for China. Usman et al. (2019) also included energy consumption and democracy to test the EKC hypothesis in India. It was discovered that the assumption of the EKC holds for the Indian economy. In the case of Nigeria, Ali et al. (2021) submitted that the case of EKC holds for Nigeria while energy consumption alongside agricultural innovation prompted emissions in Nigeria. Yiew et al. (2021), utilizing data from Mediterranean countries and considering their developmental levels and socioeconomic variables, echoed support for the EKC and highlighted further that countries with higher levels of production tend to have higher levels of pollution except France, which is an exception in the study. Additionally, Akhtar et al. (2023) find evidence supporting the EKC in several European countries but not in all captured in the study.

Furthermore, the interest in how income per capita and energy use affect the environment is reinforced by improved efficiency and advancements in productive technologies. Over time, some empirical studies have argued that the relationship between national output and pollution weakens due to improved energy efficiency, technological innovation, and a shift in energy consumption toward renewables (Balcilar et al., 2023a; Fæhn & Bruvoll, 2009; Mighri et al., 2022; Panayotou, 2003; Sarwar, Waheed, Aziz, & Apostu, 2022; Sarwar, Waheed, Farooq, & Sarwar, 2022; Vanli, 2023). By attaining a profitability threshold, enhancing productive efficiency, and prioritizing environmental quality, countries can adopt nature-friendly production practices, leading to a reduction in overall pollution. In this context, economic growth not only benefits the current population through higher per capita income but also supports future generations with improved income levels and a better-quality environment. Morelli (2020) and Eweade et al. (2022) observed that the relationship between CO_2 emissions and economic development is more significant in countries with larger populations and higher emission levels. This implies that policies aimed at reducing CO_2 emissions would have a greater impact on national output in developed countries compared to developing countries. Conversely, Salazar-Núñez (2020) finds divergent results in 15 countries. Erdoğan et al. (2019) finding failed to validate the EKC hypothesis in MENA countries. Dan'Asabe et al. (2021) analyzed the EKC for Great Britain using a dynamic panel with fixed effects. The results failed to support the EKC hypothesis. Also, Balcilar et al. (2023b) used a dataset for 34 countries in Africa to show that the environmental effect of economic growth and behaviors of foreign investors are dampened with the interaction of natural resource endowment.

Concerning the relationship between energy utilization and economic growth, extensive literature has proposed various theoretical formulations to support econometric estimations. For example, neoclassical growth models have been developed to predict reductions in pollutant emissions. In a recent study, Ferreira et al. (2020) developed an endogenous growth model incorporating subsidies and taxes, with pollution reduction knowledge playing a central role in achieving high production rates compatible with low emissions. Abbas et al. (2022) investigated the causal relationship between energy consumption and gross domestic product (GDP) across 30 OECD countries and 70 non-OECD countries. Their findings suggested that the two-way causality between energy consumption and GDP is more robust in OECD countries compared to developing countries. Balcilar et al. (2023a) showed on the basis of neoclassical growth empirics that an increase in green energy consumption and investment promotes growth without causing pollution in OECD countries. Also, a study by Akhtar et al. (2023) provides evidence of a long-term relationship between production, income levels, energy consumption, CO_2 emissions, and trade liberalization in Malaysia.

2.2 | Environmental taxes and environmental degradation nexus

The relationship between environmental taxes and environmental sustainability has been built within the framework of the double-divident hypothesis of Tullock (1967). According to this hypothesis, the use of environmental taxes has two benefits in the environment. First, it reduces pollutions perpetrated by the economic agents, and second, it increases economic efficiency and hence revenues. A number of studies have found the implementation of environmental tax reforms to be associated negatively with CO_2 emissions (Babatunde et al., 2017; Ghaith & Epplin, 2017; Hammar & Sjöström, 2011; Sundar et al., 2016; Tol, 2007; Usman & Alola, 2022). Tamura et al. (1996) further argue that environmental taxes lead to lower fossil fuel demand by increasing fossil fuel prices, thereby reducing carbon emissions. Reviewing the EU policies, Barker et al. (2001) suggested that environmental taxes are particularly effective in lowering carbon emissions when they complement member state policies and directives. While environmental taxes primarily target carbon emissions, they also encompass energy and fuel taxes, which help in achieving environmental protection as outlined and promoted by the Kyoto Protocol and Paris Climate Agreements initiated in 2005.

Furthermore, the effectiveness of environmental taxes is confirmed in several studies (Jiang & Shao, 2014; Lin & Li, 2011; Meng et al., 2013). Vera and Sauma (2015) analytically argue that environmental taxes implemented between 2014 and 2024 resulted in a 1% reduction in GHG emissions. Calderón et al. (2016) reported that environmental taxes are crucial in reducing not only carbon emissions but also promoting renewable energy deployment and energy efficiency. Moreover, on the basis of macroeconomic models, including computable general equilibrium (CGE) models, Leontief-type input-output model, GCAM model, and OSE 2000 model, numerous empirical studies have found environmental taxes as being instrumental in lowering environmental degradation (Scrimgeour et al., 2005; Tamura et al., 1999; Vera & Sauma, 2015). In a recent study by Miceikiene (2018), it was documented that environmental taxes promoted environmental quality and further highlighted the significance of prioritizing innovations in the energy and environmental sectors in order to enhance the effectiveness of taxes in curbing environmental challenges. Usman and Alola (2022) investigated the moderating effect of environmental-based taxes on the relationship between tourism and environmental degradation in European countries. They found evidence that the interaction of taxes and tourism lowers environmental degradation. Doğan et al. (2022) assessed how environmental taxes and green growth influence CO_2 emissions in 25 countries with high levels of environmental friendliness. The study divulged that green growth and environmental-based taxes as well as energy efficiency and renewable energy promote environmental sustainability at all quantile levels. Dogan et al. (2023) tested the effectiveness of energy taxes and total environmental taxes in promoting renewable energy in European countries while controlling for growth and oil prices. The results of the study suggested that both economic growth and oil prices promote renewable energy but all the categories of taxes reduce deployment of renewable energy. This possibly implies that the structures of the environmental taxes are not renewable energy driven.

2.3 | Environmental degradation and renewable energy nexus

The relationship between renewable energy and the environment has been well-established. The general position of the literature is that renewable energy deployment is a vehicle to achieve a sustainable environment (see Adebayo & Kirikkaleli, 2021; Usman et al., 2022). Chen et al. (2007) utilized the methodology proposed by Zhao et al. (2005) to estimate the ecological footprint in the context of China. Their analysis encompasses both renewable and non-renewable energy deployment, using data spanning from 1981 to 2001. The study found detrimental effects of fossil fuel consumption on the ecological footprint while renewable energy dampens the ecological footprint. In a different study, Al-Mulali et al. (2016) investigated the relationship between renewable energy and ecological footprint within the framework of the EKC. They analyzed data from 58 economies, including both developing and developed nations, covering the period from 1980 to 2009. Using various econometric techniques such as fixed effects regression and the generalized method of moments, the results indicated a positive association between renewable energy and ecological footprints. More recently, Destek and Sinha (2020) confirmed that the consumption of renewable energy contributes to an improvement in the ecological footprint, while the consumption of non-renewable energy was identified as a factor instigating environmental degradation.

Furthermore, Saidi and Omri (2020) for 15 OECD countries, Piłatowska et al. (2020) for Spain, Aydoğan and Vardar (2020) for E7 all show that renewable energy is negatively associated with CO_2 emissions. Musa et al. (2021) found the negative effect of renewable energy in lowering environmental degradation in EU countries. Also, Usman, Alola, and Ike (2021) established that renewable energy consumption and expenditure jointly reduce environmental degradation in the G7 countries, although the impact of renewable energy consumption is stronger on environmental degradation. More recently, Usman (2022; 2023) examined the role of renewables in dampening ecological footprints in Nigeria by controlling for internal conflict. The results fragrantly displayed that renewables promote a sustainable environment.

2.4 | Environmental degradation and ICT development nexus

In the context of the ICT revolution during the 1990s, several studies have found both positive and negative impacts of ICT on CO_2 emissions. Regarding the positive impact, Salahuddin et al. (2016) indicated that ICT stimulates a rising level of emissions in OECD countries, although their analysis did not establish a causal link between emissions and ICT. The study by Danish et al. (2018) partially supported the notion that ICT promotes environmental destruction. Their empirical findings further revealed that the interaction between ICT and GDP reduces emissions significantly. Raheem et al. (2020) demonstrated a positive long-term impact of ICT on emissions in G7 countries. This result is similar to Avom et al. (2020) who investigated the effects and transmission channels of ICT on CO_2 emissions in 21 sub-Saharan African countries and confirmed that ICT (measured by Internet penetration and mobile phones) significantly increases CO_2 emissions. A study on BRICS countries by Haseeb et al. (2019) and the Asia region by Lee and Brahmasrene (2014) found that ICT and its proxies contribute to increased CO_2 emissions in these countries.

In contrast, several studies have shown that ICT can possibly improve environmental quality through a reduction in energy utilization. For example, Zhang and Liu (2015) reported that ICT contributes to environmental sustainability in China, although regional disparities are observed in the effects of ICT on emissions. Using the quantile regression method, Chen et al. (2019) suggested that the development of ICT significantly dampens emissions in different provinces of China, although the effect varies across regions. Ahmed and Le (2021) examined the effects of ICT and the globalization index on CO_2 emissions in ASEAN-6 countries. The results showed an environmental improvement effect of ICT through a significant reduction in the level of emissions. Ahmed and Le (2021) investigated the impacts of the ICT index and various other variables on environmental sustainability in Latin American and Caribbean countries. It was discovered that ICT bolsters environmental quality by dampening the amount of energy consumed in these countries. Shahnazi and Dehghan Shabani (2019) analyzed the sectoral impacts of ICT on CO_2 emissions in the Iranian economy. Applying an appropriate econometric technique, they showed a negative effect of ICT on CO_2 emissions in the industrial sector, while the service and transportation sectors experienced a negative effect as well. N'dri et al. (2021) studied the association between ICT and CO_2 emissions in 85 developing nations and discovered that ICT mitigates emissions in low-income developing countries. Recently, Karlilar et al. (2023) examined the effectiveness of digitalization in promoting environmental sustainability in OECD countries between 2000 and 2018. The findings generally display the positive role of digitalization in environmental sustainability alongside other variables such as renewable energy, green innovation, and financial development.

2.5 | Research gap

Despite the growing interest in how ICT affects environmental sustainability, several challenges remain, such as the need to examine not only whether ICT development has improved environmental performance, but also whether low or high environmental taxes influence the relationship between ICT and GHG emissions in European countries. Moreover, we incorporate variables such as renewable energy, investment in R&D, and income per capita to control changes in GHG emissions in EU countries.

3 | DATA AND METHODOLOGY

This research opts to utilize annual data from 2000 to 2017 for 23 EU countries, namely Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, and the United Kingdom. These countries and periods are chosen based on the data availability. The GHG emission is measured in thousand tonnes of CO_2 equivalent. ICT is measured by individuals using the Internet to the total population. Renewable energy is the share of renewables to the total primary energy supply measured in thousand tonnes. R&D investment is measured in terms of R&D expenditure as a percentage of GDP, while income per capita (IPC) measured the real gross domestic production divided by the population. Table 1 presents the name, codes, and sources of the variable considered.

3.1 | Cross-section dependence test

There is a need to normalize the data used because of the difference in unit of measurement; it is required to transform this data by log form to minimize the series' possible disruptions. Cross-sectional issues tend to arise based on the relationship between countries with similar economic and social factors and other related factors. Cross-sectional dependence in panel data tends to cause results to be distorted and inconsistent (Dong et al., 2018). This study employed Pesaran (2007) scaled LM tests to verify the cross-sectional dependency.

$$Y_{it} = \propto_i + \beta_i X_{it} + e_{it} \tag{1}$$

TABLE 1 Variable, measurement, and source.

Variable and code	Measurement	Source
Greenhouse gas emissions (GHGC)	Major man-made greenhouse gases and emissions in thousand tonnes of CO_2 equivalent per capita	World Development Indicator
Information and communication technology (ICT)	Share of individuals using the Internet to the total population	World Development Indicator
Environmental taxes (ETX)	Total environmental taxes in million euro	European Commission database
Renewable energy (RENE)	Share of renewable energy to total primary energy supply measured in thousand tons (tons of oil equivalent)	Organization for Economic Co-operation and Development (OECD)
Research and development expenditures (R&D)	Research and development (R&D) expenditure as a percentage of GDP	World Development Indicator
Income per capita (IPC)	GDP (constant 2010 USD) per capita	World Development Indicator

Abbreviation: GDP, gross domestic product.
Source: Authors' computation.

$$\mathrm{COV}(\varepsilon_{it},\varepsilon_{ij}) \neq 0 \tag{2}$$

CD_{LM2} test is another approach to evaluate cross-sectional dependence, as seen below:

$$CD_{LM2} = \sqrt{\frac{1}{N(N-1)}}\left[\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T\widehat{P\rho}_{ij}\right] \sim N(0.1). \tag{3}$$

$\widehat{\rho}_{ij}{}^2$ denotes the estimated cross-sectional residual. Equation (4) illustrates the sum of the residual of the cross-sectional estimated. This test was introduced when N and T are large $T \to \infty \& N \to \infty)$ are usually asymptotically distributed. The CD LM test is defined below:

$$CD_{LM} = \sqrt{\frac{2T}{N(N-1)}}\left[\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T\widehat{P}_{ij}\right] \sim N(0.1) \tag{4}$$

It depends significantly on the amount of cross-sectional residual squares having a correlation coefficient. We utilize this test in a situation where $T > N$ and $N > T$. The null and alternative hypothesis for this test is similar to CD LM1 and CDLM2 tests. The formula is mirrored in Equation (4):

$$CD_{LM1adj} = \sqrt{\frac{1}{CD_{LM1}}}\left[\frac{(T-K)\rho_{ij}^2 \mu T_{ij}}{\sqrt{v_{ij}^2}}\right] \sim N(0.1) \tag{5}$$

Equation (5) defines Pesaran (2004).

3.2 | Unit root tests

For the panel data unit, this study employed IPS and CIPS panel unit roots. Im et al. (2003) developed the IPS adopt the first-order autoregressive parameter heterogeneity utilizing normalized t_bar, which is the limited distribution of ADF statistics:

$$Z_{t\_bar}(p;\beta) = \frac{\sqrt{N}\,[t_{bar_{NT}} - E(t_{iT})]}{\sqrt{V}(t_{iT})} \tag{6}$$

where the expected mean is denoted as $E(t_{iT})$, and variance denotes $V(t_{iT})$.

$$\widehat{CIPS} = \frac{1}{N}\sum_{i=1}^{n} \chi_i + \chi_i Y_{i,t-1} + \gamma_i \overline{y}_{t-1} + \sum_{l=0}^{p} \gamma_{il} \Delta \overline{Y_{t-l}} + \sum_{l=1}^{p} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it} \tag{7}$$

where $\overline{Y}_{t-1}$ and $\Delta\overline{Y_{t-l}}$ reflect the lag of the variable and the averages of the first difference. The null hypothesis advocates "non-stationarity," whereas the alternative hypothesis advocates "stationarity."

3.3 | Cointegration test

To ascertain the long-term equilibrium relationship among the variables in the research, a testing procedure that relies on error correction is applied, which is the cointegration testing procedure of Westerlund and

Edgerton (2007). This method is highly reliable than the cointegration testing procedures of Pedroni (2004) and Kao and Chiang (2001) since it is also suitable when errors are cross-section dependence (CSD). The following equations are the T-statistics of the Westerlund and Edgerton (2007) cointegration testing procedure:

$$G_t = \frac{1}{N}\sum_{i-1}^{N}\frac{\acute{\alpha}_i}{SE(\acute{\alpha}_i)} \tag{8}$$

$$G_\alpha = \frac{1}{N}\sum_{i-1}^{N}\frac{T\acute{\alpha}_i}{\acute{\alpha}_i(1)} \tag{9}$$

$$P_t = \frac{\acute{\alpha}}{SE(\acute{\alpha})} \tag{10}$$

$$P_\alpha = T\acute{\alpha} \tag{11}$$

where the group mean information is given in Equations (9) and (10) as G_t and G_α, respectively. Equations (11) and (12) depict the panel statistics (P_t and P_α). The null hypothesis, which states that evidence of no cointegrating interaction, is compared to the alternative hypothesis, which proposes that cointegration exists.

3.4 | Empirical model

In this study, we propose an empirical model to investigate the influence of ICT, environmental taxes, renewable energy, R&D, and income on GHGs in EU nations as follows:

$$\text{lnGHGC}_{it} = \delta_i + \alpha_{1i}\text{ICT}_{it} + \alpha_{2i}\text{ICT}_{it} + \alpha_{3i}\text{RENE}_{it} + \alpha_{4i}\text{R\&D}_{it} + \alpha_{5i}\text{lnIPC}_{it} + \varepsilon_{it} \tag{12}$$

where lnGHGC denotes the natural logarithm of GHG emissions per capita, ICT represents the information and communication technology, RENE is the renewable energy utilization, R&D measures investment in R&D, and IPC is the per capita GDP. The error term is represented by ε while i and t represent countries and time, respectively. According to Pesaran et al. (1999), the Autoregressive Distributed Lag (ARDL) model fits the maximum-likelihood PMG estimator for heterogeneous dynamic panels. Therefore, the PMG approach is preferred because it provides flexibility and unrestricted short-run responses across different groups while pooling the individual groups in the long run. By constraining the long-run elasticity to be equal across all panels, the likelihood-based PMG estimator ensures consistent and efficient estimates, particularly when homogeneity restrictions are confirmed. The model is defined in Equation (13) as follows:

$$\Delta(\text{lnGHGC})_{it} = \theta(\text{lnGHGC})_{i,t-1} + \vartheta' X_{i,t-1} + \sum_{m-1}^{t-1}\lambda ij\Delta(\text{lnGHGC})_{i,t-j} + \sum_{t-1}^{s-1}\lambda ij\Delta X_{i,t-j} + \mu_i + \varepsilon_{it} \tag{13}$$

where X denotes the regressors; ϑ' and λ_{ij} represent the coefficients in the long and short run, respectively. θ is the error correlation term (ECT). Furthermore, we explore the panel threshold model in order to evaluate how GHG emissions respond to ICT development during the lower and higher environmental taxes. To do this, we applied a threshold model advanced by Hansen (2000), which is expressed as follows:

$$\text{lnGHGC}_{i,t} = \alpha X_{i,t} + \mu_{i,t} + \begin{Bmatrix} \beta_1\text{ICT}_{i,t}, & Z_{i,t} \leq \gamma \\ \beta_2\text{ICT}_{i,t}, & Z_{i,t} > \gamma \end{Bmatrix} \tag{14}$$

where lnGHGC and lnICT, i and t remain as previously defined. X is the array of explanatory variables that are not regime-dependents; γ is the threshold value, Z is the threshold variable (environmental taxes) which is split into low and high periods, while μ simply shows the error term.

4 | RESULT AND DISCUSSION

Panel a of Table 2 showcases the descriptive statistics of the variables used. These descriptive statistics include mean, SD, minimum, maximum, skewness, and kurtosis. It is essential to evaluate the variables' measure of central tendency and dispersion over the period of this study. Specifically, ICT has the largest mean, that is, 61.969 while R&D investment has the lowest mean, that is, 1.636. The value of SD is high in the case of ICT renewable energy. This suggests that the spread out of the data points is far from the mean, and hence, the distribution has extreme values. For the rest of the variables, they are spread close to the mean, although the case of environmental taxes is 1.523, which is far from zero. Moreover, the skewness of the variables tends toward normal distribution with evidence that ICT, environmental taxes, and income per capita have a negative skewness while GHG emissions, renewable energy, and R&D are positively skewed. The value of the kurtosis is positive across the variables employed in this study. Hence, the Jarque–Bera statistics reject the null hypothesis of normal distribution. In addition, the outcome of the correlation analysis is illustrated in Table 3, Panel b. The correlation between GHG emissions and environmental taxes as well as GHG emissions and renewable energy is negative but only significant in the case of the latter. We also found a negative and significant correlation between environmental taxes and renewable energy, and also renewable energy and income per capita. The correlation between the rest of the variables is positive and statistically significant. A cursory look at the correlation matrix suggests no case of multi-collinearity in the variables.

The result of the Pasaran (2004) CSD test is depicted in Table 3. The results indicated a cross-sectional dependence since the test statistics are statistically significant for each of the variables used. A change in the pattern of any variables within any of the EU countries will inevitably impact the others. This observation implies a strong interconnection and interdependence among the EU nations, suggesting their closely intertwined relationships. In this context, we have to apply a model that can control for cross-sectional dependence.

The next phase of the analysis is to examine the stationarity properties of the variables. In doing this, we applied the IM-Pesaran-Shin unit root tests as summarized in Table 4, Panel a. We test the null hypothesis that there is no unit root in each of the variables used for this study. At levels, the variables such as GHG emissions, ICT, and environmental taxes have no unit root issue, while the remaining variables have it. We solve this issue by taking the difference between these variables (renewable energy, R&D, and income per capita). Moreover, since the CSD is evident in our case, adopting the first-generation unit root test could be misleading. As a result, we further adopt the cross-sectional via CIPS unit root tests, and the result of this test is also highlighted in Table 4, Panel B. The result showed that GHG emissions, ICT, and renewable energy have no unit root issue at levels, while environmental taxes, R&D, and income per capita have unit root issues at levels. However, after taking their first difference, their stationary property became stationary. Based on these results, we conclude that the variables in this study have a mixed order of integration.

The results of the bootstrapped version of the Westerlund co-integration test advanced by Westerlund and Edgerton (2007) are depicted in Table 5. For two of the statistics (Gt and Pt), we reject the null hypothesis of no co-integration at a 10% level of significance based on 200 bootstrap repetitions. Rejecting the null hypothesis, therefore, suggests a long-run association between GHG emission and its regressors captured in this study.

After we have established cross-sectional dependence and co-integration between the variables, we employed the Panel ARDL approach. As shown in Table 6, the ICT development has a negative and significant relationship with GHG emissions. On average, a 0.200% (long term) and 0.100% (short term) decrease in the level of GHG emissions is attributed to a change in ICT development. The results possibly suggest that ICT as widely used in all sectors helps to conserve the quantity of energy needed since technologies are strengthened. Another possible reason is that ICT

TABLE 2 Descriptive statistics and correlation matrix.

Panel a: Descriptive statistics						
	LNGHGC	ICT	LNETX	RENE	R&D	LNIPC
Mean	−4.642129	61.96935	8.543879	15.83900	1.636304	10.28915
Median	−4.656970	67.28500	8.641790	12.16925	1.451015	10.49395
Maximum	−3.585088	98.13670	11.06457	54.20100	3.907850	11.62600
Minimum	−5.411676	6.319060	4.648134	0.852867	0.360020	8.843100
SD	0.347645	23.29457	1.523584	11.85374	0.851043	0.617595
Skewness	0.443645	−0.598261	−0.209814	0.981516	0.656355	−0.213359
Kurtosis	3.127267	2.370863	2.287295	3.221000	2.523857	2.294131
Jarque–Bera	13.86003	31.52395	11.79961	67.31533	33.63614	11.73585
Probability	0.000978	0.000000	0.002740	0.000000	0.000000	0.002829
Sum	−1921.841	25655.31	3537.166	6557.348	677.4297	4259.707
Sum Sq. Dev.	49.91408	224109.1	958.6999	58031.09	299.1252	157.5279
Observations	414	414	414	414	414	414
Panel b: Correlation matrix						
Probability	**LNGHGC**	**ICT**	**LNETX**	**RENE**	**R&D**	**LNIPC**
LNGHGC	–					
ICT	0.047	–				
LNETX	−0.048	0.219***	–			
RENE	−0.457***	0.281***	−0.247***	–		
R&D	0.145***	0.512***	0.412***	0.379***	–	
LNIPC	0.500***	0.459***	0.503***	−0.091*	0.634***	–

Abbreviations: ETX, environmental taxes; GHGC, greenhouse gas emissions; ICT, information and communication technology; IPC, income per capita; R&D, research and development; RENE, renewable energy.

*** and * denote significance levels at 10% and 1%.

TABLE 3 Pesaran cross-sectional dependence test.

Variable	C–D test	*p*-Value	Average joint *T*	Mean ρ	Mean abs (ρ)
LNGHGC	35.679***	.000	18.00	0.53	0.72
ICT	64.347***	.000	18.00	0.95	0.95
LNETX	54.232***	.000	18.00	0.80	0.80
RENE	60.282***	.000	18.00	0.89	0.89
R&D	26.142***	.000	18.00	0.39	0.57
LNIPC	44.677***	.000	18.00	0.66	0.75

Note: The null hypothesis is that there is cross-sectional independence across countries in the panel.
Abbreviations: ETX, environmental taxes; GHGC, greenhouse gas emissions; ICT, information and communication technology; IPC, income per capita; R&D, research and development; RENE, renewable energy.
*** denotes significance at a 1% level.

TABLE 4 Panel unit root tests.

Variable	At levels Statistic	First difference Statistic
Panel a: IM-Pesaran-Shin unit root test		
LNGHGC	−4.3829***	−9.7967***
ICT	−2.9508***	−3.3789***
LNETX	−2.6579**	−9.3281***
RENE	−0.5569	−3.3969***
R&D	−0.8145	−3.5595***
LNIPC	−1.2653	−2.8313***
Panel b: CIPS unit root test		
LNGHGC	−2.632*	−3.910***
ICT	−3.075***	−4.280***
LNETX	−2.295	−3.896***
RENE	−2.765**	−3.877***
R&D	−2.059	−3.971***
LNIPC	−1.530	−2.587*

Abbreviations: ETX, environmental taxes; GHGC, greenhouse gas emissions; ICT, information and communication technology; IPC, income per capita; R&D, research and development; RENE, renewable energy.
***, **, and * denote significance at 1% and 5% level.

development creates adequate public awareness of the need to implement energy efficiency and energy transition. Empirically, inadequate public awareness of the government's energy policies is one of the major challenges confronting the full implementation of environmental and climate change policies (see Rafindadi, 2016). Therefore, increasing the use of ICTs such as the Internet can help provide environmental awareness to the people and hence deal with the challenges of environmental protection. Our outcome is consistent with Hussain et al. (2020), Ulucak and Khan (2020), and Santarius et al. (2020) who discovered a negative interaction between ICT and environmental degradation. On the contrary, the result established in this study is inconsistent with Raheem et al. (2020) for G7 economies, Arshad et al. (2020) for Asian economies, and Mirza et al. (2020) for 81 developing countries, who found that ICT development promotes environmental degradation.

TABLE 5 Panel cointegration tests.

Statistic	Value	Z-value	p-Value	Robust p-value
Gt	−2.406*	−0.978	.164	0.060
Ga	−4.380	4.587	1.000	0.140
Pt	−10.071*	−0.857	.196	0.080
Pa	−3.870	2.510	.994	0.245

Note: Lag length is zero with 200 bootstrap repetitions.
*Significance at 10% level.

TABLE 6 Short-run and long-run panel ARDL parameters.

Variables	(1) Long-run parameters	(2) Short-run parameters
ECT_{t-1}		−0.2924*** (0.05953)
D. ICT		−0.001085 (0.00091)
D. LNETAX		0.04210 (0.04385)
D. RENE		−0.007498** (0.003624)
D. R&D		−0.1160*** (0.03708)
D. LN		0.3850*** (0.07866)
ICT	−0.002201*** (0.00036)	
LNETAX	−0.2403*** (0.04247)	
RENE	−0.02020*** (0.001712)	
R&D	0.1220*** (0.01754)	
LNIPC	0.5644*** (0.08136)	
Constant		−2.3912*** (0.4867)
Observations	391	391
No. of countries	23	23

Note: SEs are in parentheses.
Abbreviations: ETX, environmental taxes; GHGC, greenhouse gas emissions; ICT, information and communication technology; IPC, income per capita; R&D, research and development; RENE, renewable energy.
***$p < .01$; **$p < .05$; *$p < .1$.

The coefficient of renewable energy shows that renewable energy consumption is negatively interacting with GHG emissions. On average, a 1% increase in renewable energy causes GHG emissions to reduce by 2% (long run) and 0.700% (short term). This suggests that renewable energy consumption has a decreasing effect on the level of GHG emissions in EU countries. By implication, our result implies that renewable energy technologies can sustain the environmental quality of the region since they are green and clean energy resources. The dominance of renewable energy will help resolve the issue of environmental deterioration. The negative effect of renewable energy is expected in the case of the EU region. This is because the region has put appropriate policies on the ground that help in the smooth transition to renewable energy consumption. At present, renewable energy contributed 35.7% of the region's primary energy use (European Commission, 2020). This notable achievement is attributed to the region's commitment to a sustainable environment as a signatory to the Kyoto Protocol and Paris Accord agreement. Therefore, this finding is consistent with Aydoğan and Vardar (2020) for E7 economies, Hao et al. (2021), Usman et al. (2020), Khan et al. (2020), and Usman (2023) for G7 countries. Also, our result aligns with Usman, Alola, and Sarkodie

(2020) for the United States, Iorember et al. (2020) for South Africa, Erdogan et al. (2020) in OECD countries, Musa et al. (2021) for EU-28 countries, Khan et al. (2017) for 34 high-income countries selected from America, Africa, Asia, and Europe, and Ali et al. (2020) for 100 selected countries around the world.

The result of the effect of environmental taxes shows that environmental tax has a negative relationship with GHG emissions, but this relationship is only significant in the long run. On average, a 0.240% increase in GHG emissions is caused by a 1% rise in environmental taxes in the long term. By these results, the implementation of environmental taxes by EU policymakers serves as a means to address the negative externalities associated with manufacturing and tourism activities and other pollution-induced activities in the long run. By levying environmental taxes and utilizing the revenue collected, countries can promote renewable energy, improve environmental quality, and work toward achieving sustainable development goals. This approach effectively signals to emitters that they must bear economic costs for their polluting activities, compelling them to adopt sustainable practices. Therefore, our findings are consistent with Doğan et al. (2022) and Dogan et al. (2023) where environmental taxes and energy taxes are seen as a way to reduce environmental degradation. The finding is also consistent with Usman and Alola (2022) where the interaction of environmental taxes and tourism promote environmental performance in the EU countries. Furthermore, our findings agree with Cheng et al. (2021) that environmental taxes not only contribute to ecological sustainability but also facilitate the attainment of SDG-7 (clean and affordable energy).

Furthermore, the coefficient of the R&D expenditures shows that in the long run, R&D is positively and significantly related to GHG emissions. On average, the level of GHG emissions increased by 12.20% following an increase in R&D in the long run. The implication for this result is that, as the level of R&D is increasing, there is a tendency that economic activity will as well increase, thereby increasing the level of GHG emissions in the long run. This effect is known in economics as the crowding-out effect of R&D on the environment. This outcome is in line with Fernández et al. (2018) and Churchill et al. (2019). However, in the short term, an increase in R&D dampens environmental destruction by 0.1160%. This finding offers competitive advantages and enhances short-term sustainability as demonstrated by Paramati et al. (2021). It also facilitates the transition from non-renewable energy sources to renewable energy sources (See Balcilar et al., 2023a). Furthermore, the long-run result disagrees with the recent study by Baloch et al. (2021) where energy innovation as a result of R&D promotes environmental quality in the OECD countries.

Furthermore, an increase in income per capita surprisingly exerts a positive influence on GHG emissions. On average, a 0.564% (long term) and 0.385% (short term) increase in GHG emissions is achieved by a 1% rise in income per capita. The explanation for the positive effect of income per capita could be due to the region's consumption pattern and energy structure. However, it is essential for policymakers to ensure that all EU nations remain committed to reducing environmental degradation by implementing rigorous environmental policies and promoting the adoption of renewable energy sources. Therefore, our result is consistent with Rafindadi and Usman (2019) for South Africa, Musa et al. (2021) for 28 EU countries, Usman et al. (2019) for India, and Usman et al. (2022) for G7 countries. However, this result is inconsistent with Paramati et al. (2021), who found income per capita to be influencing the environment negatively but insignificantly.

As already mentioned, to assess how environmental taxes affect the relationship between ICTs and GHG emissions, we applied a panel threshold model. To do this, we tested whether the threshold effect is single or double using the likelihood ratio (LR) test. As provided by Table 7, the null hypothesis of no threshold effect is rejected, which suggests that there is a threshold effect in the relationship. Further, we tested where the threshold effect is more than one. The result indicates that there is no statistical evidence to show that the threshold effect in the relationship is more than one. We estimated the threshold model using a bootstrap repetition of 300, which is the default setting. The threshold variable is environmental taxes and the results as shown in Table 8 simply mean that the threshold value is 6.8232, which is statistically significant while a 95% confidence interval, ranging from 6.8183 to 6.8336.

Furthermore, during the period of low environmental taxes, the effect of ICT on GHG emissions is positive and insignificant, while in the high environmental taxes, an increase in ICT dampens the level of GHG emissions thereby

TABLE 7 Likelihood ratio test for threshold effect.

Null hypothesis	RSS	MSE	Statistic	*p*-Value
H_0: No threshold ($K=0$)	1.1521	0.0029	67.14**	.0267
H_0: At most one threshold effect ($K=1$)	1.0603	0.0027	34.25	.2467

Abbreviations: MSE, mean squared error; RSS, residual sum of squares.
*denotes statistically significant at 10% level.

TABLE 8 Results of threshold effect.

Dependent variable = lnGHGC		
Variables	**Coefficient**	**SE**
Estimated threshold ($\hat{\gamma}$)	6.8232**	
95% Confidence interval	[6.8183, 6.8336]	
Regime-dependent regressors (ICTs)		
Low lnETX $\left(\hat{\beta}_1\right)$	0.0003	0.00041
High lnETX $\left(\hat{\beta}_2\right)$	−0.0018***	0.00028
Regime-independent regressors		
lnETX	0.0367*	0.0210
RENE	−0.0243***	0.0011
R&D	0.0369***	0.0176
lnIPC	0.3099***	0.0392
Constant	−7.7290***	0.3364
Number of observations	414	
Number of countries	23	
F(6,385)	232.90 (0.0000)	

Abbreviations: ETX, environmental taxes; GHGC, greenhouse gas emissions; ICT, information and communication technology; IPC, income per capita; R&D, research and development; RENE, renewable energy.
** and *** denote significance levels at 5% and 1%, respectively.

enhancing environmental sustainability. Specifically, during the period of high environmental taxes, a change in ICT would reduce GHG emissions by 0.0018%. This finding is consistent with Usman and Alola (2022) for EU countries. Moreover, the effect of renewable energy on GHG emissions remains negative and significant; meaning, an increase in renewable energy promotes environmental sustainability by condensing the amount of fossil fuel consumption. The effect of R&D investments and per capita income is positive, substantiating the results discussed earlier. The plausible explanation for the insignificance effect of environmental taxes in moderating the effect of ICT on GHG emissions is consequent upon the fact that high environmental taxes discourages ICT development.

5 | CONCLUSIONS AND POLICY IMPLICATIONS

This paper examined the impacts of digitalization through ICT development on environmental sustainability in EU countries. We incorporated control variables such as environmental taxes, renewable energy, R&D investment, and income per capita, and applied the PMG estimation technique to estimate the impact of the independent variables on the environment and further applied the panel threshold model to assess whether low or high environmental taxes have an influence on the relationship between ICT and GHG emissions in European countries. The empirical findings based on the PMG suggested that ICT development negatively impacted the measure of GHG emissions, which means that ICT development is environmentally friendly. The effects of environmental taxes and renewable energy were negative and significant, while R&D investment and income per capita were positively impacting environmental degradation. Furthermore, our findings revealed that during the period of low environmental taxes, an increase in ICT promotes GHG emissions, but during the period of high environmental taxes the effect of ICT on GHG emissions is not statistically significant.

Based on these findings, the following policy implications are formulated to help governments and policymakers achieve environmental sustainability in the region and attain environmental targets of sustainable development. First, since ICT development promotes environmental quality through the reduction of GHG emissions, there is a need for the government and policymakers to zealously increase the pace of digitalization in all sectors across European nations. This can be achieved by prioritizing investment in ICTs. Apart from increasing funding for ICT projects, high incentives and subsidies such as carbon tax credits and holidays can also be given to firms and companies that are investing in the ICT sector. Second, the government needs to stimulate the energy transition process, which emits little or no pollution. This can be facilitated by strengthening carbon pricing, carbon cap, and trade as well as subsidizing green energy activities from solar, hydrogen, wind, geothermal, and other renewable energy sources. Moreover, governments and policymakers should encourage public-private participation in the energy sector to guarantee sustainable renewable energy supply at affordable prices. Giving subsidies on green activities alone may not guarantee the availability, sustainability, and affordability of renewable energy for all; therefore, the joint participation of the public and private sectors in renewable energy supply is required. Third, since investment in R&D triggers an increase in GHG emissions, the government and its managers should invest more in renewable energy R&D in order to accelerate the pace toward environmental cleanliness in the EU region. If R&D investment is channeled toward renewable energy activities, the goal of green growth in the region is possibly achievable. Fourth, although the low regime of environmental taxes causes ICT to positively affect GHG emissions, the high regime of environmental taxes causes ICT to reduce GHG emissions. This suggests the need for policymakers to optimally use environmental taxes such as pollution tax, carbon tax, resources tax, etc. to achieve environmental sustainability in the region.

However, like any other study, one major limitation of this study is the use of ICT (number of Internet users) as a measurement of digitalization. We suggest that future research could construct an index of digitalization to cover variables such as Internet users, mobile cellular subscriptions, fixed telephone subscriptions, etc. This may capture the level of digitalization comprehensively. Second, the findings of this study may not apply to developing African or Asian countries because of their different economic characteristics. To this extent, future studies can apply datasets from these countries.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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