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The criticality of clean energy and ICT invesment in achieving environmental sustainability in the EU member states

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ABSTRACT

Defining and designing appropriate energy, economic and environmental policies that help minimize global carbon emissions remains a top priority for all governmental and non-governmental environmental organizations worldwide. In this digital age, the researcher has paid particular attention to his increasing use of ICT and its relevance to economic and environmental aspects. This paper addresses the sustainability challenges and energy security issues posed by rising energy demand, researchers and policymakers have identified clean future energy alternatives using the most recent data to provide important information for policymakers. The study focused on the key components of ICT investments to promote clean energy (renewables and nuclear) and carbon neutrality in a particular economy with the use of the most robust econometric panel data method for the latest available data sets to obtain reliable and efficient estimates. The study findings demonstrate that using renewable energy can help the EU achieve energy security while reducing greenhouse gas emissions. However, renewable energy deployment is still not substantial enough to mitigate environmental pollution in the presence of significant ICT investment in the EU member states.

1. Introduction

The global economy has increasingly relied on information and communication technologies (ICT), which have reshaped connectivity and productivity. As a result, research exploring the link between ICT and environmental sustainability has grown, recognizing both its positive and negative impacts. Economic growth is typically accompanied by rising energy consumption, which in turn heightens environmental challenges. The US Energy Information Administration (EIA, 2013) projected that global carbon emissions from energy use would rise from 31 billion tonnes in 2010 to 45 billion tonnes by 2040. The European Union (EU) provides a useful case study, with the European Regional Development Fund (ERDF) allocating approximately €20 billion to ICT investment between 2014 and 2020. According to UNCTAD (2023), international renewable energy projects nearly doubled from 36 in 2011 to 71, including initiatives delivering solar and wind power from Morocco to the UK. The COVID-19 pandemic further accelerated the demand for digital infrastructure, positioning the ICT sector as a key attractor of clean energy investments. However, energy price shocks have also disrupted energy-intensive industries, notably refining.

Pressing issue of climate change, with rising greenhouse gas emissions, especially CO_2, contributing significantly to global warming (Rogelj & Schleussner, 2019; Benzie & Persson, 2019). Pollution has become a global problem that requires conscious efforts to reduce CO2 emissions. Defining and designing appropriate energy, economic, and environmental policies that help minimize global carbon emissions remains a top priority for all governmental and non-governmental environmental organizations worldwide. In this digital age, the relevance of ICT's growing role has attracted research attention. While some studies highlight ICT's potential to reduce emissions through smarter technologies and energy efficiencies (Higón et al., 2017; Ollo-López & Aramendía-Muneta, 2012), others note its contribution to pollution, particularly through increased electricity consumption in expanding economies (Moyer & Hughes, 2012; Park et al., 2018; Lee & Brahmasrene, 2014). Empirical findings on ICT's environmental impact remain mixed. Many studies focus on the direct relationship between ICT and carbon emissions (Avom et al., 2020; Chen et al., 2019; Faisal et al., 2020; Godil et al., 2020), while fewer examine indirect or interactive effects involving mediating variables (Khan et al., 2022; Sharma et al., 2021). To tackle rising energy demand and promote sustainability, policymakers have turned to clean energy sources, including renewables and nuclear power. However, limited research explores how ICT investments influence the transition to clean energy within the EU, a region with some of the highest digital technology adoption and investment levels. This study addresses this gap using the most recent data and a robust panel data methodology to provide valuable insights for policymakers.

This study addresses the complex relationship between ICT investments, renewable energy utilization, and environmental sustainability, examining whether increasing investment in digital technology genuinely contributes to reducing carbon emissions or potentially increases environmental pressures. Understanding this relationship is crucial for formulating effective policies that leverage technology to achieve energy efficiency and emission reduction goals. Given the global urgency of addressing climate change, insights from this research are vital for promoting sustainable development through integrated energy and technology strategies. First and foremost, we believe this is the first study of its kind on the EU, using the most recent data to provide important information for policymakers. Second, no research has focused on the key components of ICT investments to promote clean energy and carbon neutrality in a particular economy. Third, the study uses the most robust econometric panel data method for the latest available data sets to obtain reliable and efficient estimates.

The approach handles heterogeneity, improving estimation precision, addressing endogeneity, and dynamic effects. Despite studies on the relationship between clean energy and environmental sustainability, the impact of ICT investment on the growing economic growth in the EU member states is less studied, among the largest block of countries with the highest adoption and investment in digital technologies. This study contributes to the existing body of literature by addressing the research questions, such as: What are the impacts of clean energy use on environmental quality within EU member states? What are the implications of rising energy demand on environmental sustainability, and how can policymakers address these challenges with ICT investments? This study provides nuanced insights into how investing in ICT impacts the adoption and usage of clean energy and achieves a sustainable environment. The remaining part of this paper is structured as follows: Section Two provides a literature review and hypotheses proposed, Section Three provides data and employs the econometric technique, Section Four presents the empirical analysis and discussion, and Section Five provides a conclusion.

2. Literature Review

Modernization, urbanization, and industrialization are the major driving forces of increasing environmental pollution and degradation in both developed and developing countries. Economic and development human activities such as transportation, construction, and waste are sources of CO2 emission and found that pollution substantially has massed economic growth (Borhan et al., 2012). Canadell et al (2007), Terhaar et al (2022) and Le Quéré et al (2014) found the critical role of CO2 emission in the global temperature rise by examining the level of CO2 emission, human-created heating was the primary contributor. Using India time series data between 1971 and 2006, suggested in the short run efforts to mitigate CO2 emissions could impact economic growth (Prakosa et al., 2024). The effect of the ICT industry on CO2 emission is disclosed firstly in developed countries with the perspective of emerging technology. ICT was revealed to contribute 2 percent of all human-induced CO2 generated from conventional energy sources, economic drivers, and transport activities. The ICT sector is subjected to any amount of CO2 emission stimulated from intermediate inputs, that is, ICT goods and services considered indirectly pollute the sector by integration into the sources sectors identified (Kelly & Adolph, 2008; Huang et al., 2023). Advanced ICT is suspected to be the last resort to mitigate climate change and stressed that increasing energy efficiency of ICT products and other component sectors is characterized as environmental-friendly implementation through the application of renewable energy sources (Ahmed & Shimada, 2019). Inconclusive results presented from the literature on environment deterioration and attention on renewable energy sources on CO2 emission led this study to be conducted to investigate the impacts of ICT investment, FDI, and renewable energy on CO2 emission reduction concerning the economic growth of SSA using advanced panel analysis. The main aim of the study is to explore the impacts of renewable energy-FDI-CO2 emission trilemma with the role of ICT investment.

2.1. Renewable energy, nuclear energy, and their impact on environmental sustainability

Climate change has become a global discussion topic due to environmental destruction caused by human activities for the sake of improving the economic growth of a country and human capital development (Mbow et al., 2017). Theoretical and empirical approaches link climate change and several factors including energy consumption, renewable and green energy, Foreign Direct Investment (FDI), trade, and urbanization (Khan et al., 2020; Khan et al., 2022). Further measures are considered for reducing CO2 emissions and enhancement of green or clean energy usage such as political stability, government policy effectiveness as well as information communication technology (ICT) advancement. Zhang et al (2024) found that increased utilization of renewable energy has a significant effect on CO2 emission in exploring the CO2 emission-renewable energy relationship in Pakistan between 1970 and 2012. Found that the higher usage of renewable energy in the short run contributes to decreasing CO2 emissions in the case of China by using the ARDL model (Koondhar et al., 2021). Ben Jebli & Ben Youssef (2017) found that renewable energy utilization, in the long run, enhances CO2 emission and reported no effect on CO2 emission in the short run due to renewable energy

Baek (2015) investigated the impacts of nuclear energy on CO2 emissions in major nuclear energy-producing countries and revealed that higher nuclear energy consumption decreases CO2 emissions using data from 1990 to 2013. Using panel Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators found that nuclear energy consumption does not influence CO2 emission using data from G7 countries from 1990 to 2018. However, a unidirectional long-run causality relationship between nuclear energy consumption and CO2 emission (Said and Mbarek, 2016). Said and Omri (2020) concluded nuclear energy consumption reduces CO2 emissions and mitigates CO2 emissions in OECD countries due to investment in nuclear energy development. Dong et al (2018) found the use of nuclear and renewable energy lowers CO2 emissions by using structural break-accommodative techniques whereby China’s clean energy resource augmentation helps control emissions and hence a sustainable environment. Soto & Martinez-Cobas (2024) found statistical evidence regarding nuclear and renewable energy curbing CO2 emissions by utilizing BRICS countries’ data. The CO2 emission inhibiting effect of nuclear energy was seen to be relatively lower in comparison to renewable energy.

2.2. ICT investment and carbon emissions

Bildirici et al (2022) found that ICT decreases CO2 emission in middle- and high-income countries but increases in low-income countries by using thin layer, Dynamic Ordinary Least Squares Estimator (DOLS), and Driscoll-Kraay logistic estimation method on global analysis spanning different areas. Jaunky (2011) discovered evidence that links EKC to CO2 and ICT in a 138 economies survey including developing and developed countries between 2001 and 2011. Established that technological advancement above a certain economic level in terms of the environment is favorable and reduces CO2 emission. Gürlek & Tuna (2018) examined the influence of CO2 emission due to ICT growth by examining the total impact via productivity effects, electricity consumption, and renewable energy cost. The integrated assessment model indicated the positive influence of ICT on total emission by considering fluctuations in energy prices and associated feedback mechanism. Major advanced and developing countries comprise 90 percent of the GDP, 58 percent global population, 78 percent of global trade, and 50 percent global total surface area.

Yoshino et al (2021) revealed an attempt of people to integrate nature in a friendly user manner which contributes emergence of ecological ideas and concerns them, consequently for environmental and social assistance adopting green energy options and shown consumer preference for solar energy over conventional power sources. Technology adoption norms indicate community support for new technology and previous studies showed the influence of adopting ICT on energy efficiency behavior in a community (Kapoor et al., 2021). Modern economic growth models recognize the significance of technical advancement in economic development and ICT’s potential to boost development due to maybe its impact on financial development (R. Chen & Majeed, 2024). However, in economic reform's absence, ICT might be detrimental to economic development. To our knowledge, few studies conducted to analyze the impact of ICT and renewable energy on environmental sustainability using composite measures. Calado et al (2021) investigated the ICT-environment nexus using a generalized method of moments (GMM) estimator that overlooked the issue of cross-sectional dependence. The skewness of data due to the employment of smartphone and internet penetration as metrics for ICT services under independent specifications. Instead of utilizing individual ICT, adoptions, and renewable energy impacts on environmental sustainability, the study constructed composites score and ICT assessment can be used to understand its role in conserving the environment and climate change contribution.

2.3. ICT investment and renewable energy

ICT provides tools and technologies to increase energy efficiency. The ICT industry promotes low-carbon lifestyles. ICT products have transformed and changed how people behave and how society works. People tend to use ICT products to make their work and life more convenient and efficient. At the same time, the use of ICT products promotes low-carbon lifestyles. Dematerialization is the result of ICT products such as e-papers and e-books, which has caused a shift from tangible to intangible resources to separate resource consumption from economic production. For example, letters have been replaced by e-mail, which is a near-instantaneous communication and consumes less energy and resources (Hilty et al., 2006). The ICT industry enables the transition to a low-carbon economy and contributes to reducing CE (C. Zhang & Liu, 2015). In today's modern economy, her ICT trade in commodities is believed to be responsible for many of the economic and environmental impacts. However, the magnitude and nature of the impact on trading partners may depend on the level of regional development. Some researchers have evaluated the economic, environmental, and energy-intensive impacts of trade in ICT products in developing (South) and developed (North) countries. Results show that increasing ICT imports increases carbon emissions, energy, and carbon intensity. When ICT flows are south-to-south and south-to-north, the intensity of the indicators mentioned is stronger than in north-to-other regions.

Intra-regional imports (north-north and south-south) increase his ICT and GDP production within the region, leading to positive economies of scale. Increased interregional (North-South) imports lead to decreased ICT and GDP production in ICT-importing country regions. Furthermore, an increase in intraregional imports leads to a negative compositional effect, while an improvement in interregional imports leads to a positive compositional effect. South-South and North-North trade increase the share of pollutant-intensive sectors. Some research suggests that ICT could further improve the performance of the financial sector by attracting investments in digital technologies that facilitate cross-border sales of services and an abundant and cheap labor force. It has been. To lift individuals out of poverty, people living in remote areas can easily access microcredit or participate in e-banking through ICT. The financial sector helps companies and industries develop new environmentally friendly technologies. As mentioned above, ICT plays an important role in stimulating financial sector activity and boosting economic growth.

The global economy's major energy source is the dependence on the global oil market which contributes almost 40 percent of the total quantity of fossil fuels used to meet the global energy demand (Ibn-Mohammed et al., 2021). The rise in oil prices leads to a switch to a clean energy source and/or energy-efficient approach and hence affect significantly the CO2 emission release i.e. oil price increase means to reduce CO2 emission. Global technology and infrastructure of ICT products have improved and massively developed tremendously over the years, and economic growth as a macro-aspect substantially changed by the technological advances which led to environmental destruction. Wang et al (2021) found that the impact of economic growth is dependent on environmental destruction and on how technologies are used to influence. This paper will investigate whether technological advancement improves or degrades environmental sustainability, it is possible to increase economic development by using ICT facilities and hence increase environmental sustainability.

In the dynamic intersection of clean energy and ICT, a notable research gap exists that this paper addresses head-on. Despite the escalating discourse on environmental sustainability, there remains a conspicuous lack of focused studies examining the critical components of ICT investments in promoting clean energy alternatives, such as renewables and nuclear, while concurrently striving for carbon neutrality across different economies. Previous literature has primarily highlighted the environmental ramifications of economic activities and the general impact of ICT on CO2 emissions but has often overlooked the nuanced analysis of how these investments can strategically facilitate cleaner energy transitions. This study not only fills this void by employing robust econometric panel data methods on the most recent datasets, but also sheds light on the intricate trilemma of renewable energy, foreign direct investment, and CO2 emissions with ICT, thus driving forward the conversation on achieving sustainable development amidst rising energy demands.

3. Method

This study uses a macro dataset of 28 European countries from 2000 to 2018. Renewable energy, nuclear energy, and ICT investment are the key variables of interest. Carbon dioxide (CO2) emission proxy environmental sustainability in the economies and Renewable energy measured using renewable energy consumption (% of total final energy consumption), while we capture nuclear energy use as an alternative and nuclear energy (% of total energy use). ICT investment is captured by Investment in ICT with private participation (current US$). The human capital development and financial development are controlled in the study. Domestic credit to the private sector (% of GDP) measures financial development, and human capital development is measured as the human capital index (HCI) (scale 0-1). All the variables are based on data from the World Development Indicators, except for green growth data sourced from the Organization for Economic Corporation and Development (OECD). Table 1 presents a description of the variables.

Table 1. Description of Variables

Variables	Definition	Source
CO2 emissions	CO2 emissions (metric tons per capita)	
GDP growth	GDP per capita (constant 2015 US$)	
Renewable energy use	Renewable energy consumption (% of total final energy consumption)	WDI
Nuclear energy use	Alternative and nuclear energy (% of total energy use)	
ICT investment	Investment in ICT with private participation (current US$)	
Human development	Human capital index (HCI)	
Financial development	Domestic credit to the private sector (% of GDP)	OECD
Trade openness	The sum of exports and imports as a share of GDP	
Total resource rents	Share of the sum of resource rents including oil, gas, mineral	

Note: WDI means World Development Indicator while OECD is organization of economic corporation and development.

The empirical study looks at how clean energy and ICT investment affect Carbon emissions. The empirical rigor of this work begins with the specification of the pooled OLS and static models. We begin by paying close attention to the specification of our static models for Carbon emissions, as shown in Equations (1). We employ OLS to estimate the equations, assuming that the regressors are unrelated to the composite error term ($\mu_i + \varepsilon_{it}$). This is only true under the presumption that the model takes into account all the variables that have an impact on both the regressors and the regress, which empirical studies show to be unrealistic (Leszczensky & Wolbring, 2019). Endogeneity occurs when OLS results are heterogeneity-biased as a result of OLS assumptions failing to hold true (Wooldridge, 2010).

$$CO2_{it} = \alpha_0 + \beta_1 re + \beta_2 ne + \beta_3 ICT\_inv_{it} + \beta_4 X_{it} + \varepsilon_{it} \quad (1)$$

We also use fixed and random effects estimators to estimate those equations. The two estimators differ in their assumption of the unobserved time-invariant factors (μ_i) correlating with the regressors. Unlike fixed effects estimators, random effects estimators do not assume that μ_i correlates with the regressors. After that, we ran the Hausman test to determine which of the FE and RE models is more appropriate for our results. The Hausman test yields p < .05, indicating that RE is the preferred model, and this is only indicated in the estimation part. Nonetheless, unlike fixed and random effect estimators, μ_i captures all time-invariant unobserved heterogeneity by correlating with the regressors, and as a result, fixed effect estimators are bias-free. The dynamic characteristics of green growth and the reverse causality between it and its causes may potentially contribute to endogeneity in the model. Because of this reverse causality, estimates in fixed and random effects estimators are biased. These estimators rely on strict exogeneity and correlation between error terms and regressors. This assumption, however, is erroneous due to the reverse causality between green growth and its regressors, which distorts model results (Leszczensky & Wolbring, 2019).

Dynamic causality is a major issue that needs to be addressed and is defined as a correlation between green growth's present and historical values. Equations (1) depict regression models without a lagged green growth variable, and the parameter estimations could be inconsistent due to a potential correlation between the lagged green growth variable and other regressors. Appropriate methodologies for estimating a dynamic panel model should be applied based on the dynamic nature of economic relationships (Baltagi, 2005). Meanwhile, the inclusion of the lag of green growth raise the risk of endogeneity. As $CO2_{it-1}$ depends on their ε_{it}, which is a function of the country-specific effect μ_i there is an issue with endogeneity. We address the potential for endogeneity to bias our estimates by employing the system GMM technique proposed by Arellano & Bover (1995) and in line with Bello et al (2023), we adopt a green growth function given in equation (2). The following are the dynamic models specified:

$$CO2_{it} = \alpha_0 + \beta_1 re_{it-1} + \beta_2 ne_{it-1} + \beta_3 ICT\_inv_{it-1} + \beta_4 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where $CO2_{it}$ signifies green growth, re indicates renewable energy, ne implies nuclear energy while ICT_inv denotes ICT investment. The control variables, such as trade, total natural resource rents, and financial development are expressed by X. i represents the country; t represents the time; μ_i represents the country-specific effects; $\boldsymbol{\varepsilon}$ represents the idiosyncratic error term. To justify the use of the GMM model, we performed post-estimation tests such as the Hasen-Sagan test, the Arrelano Bond test, and the overidentification of instruments test (LM test). These tests were meant to see whether: a) the residuals show signs of second-order serial correlation; (ii) our instruments are valid or exogenous; and (iii) our models are robust overall. This allows us to evaluate the consistency of our GMM estimates.

4. Results and Discussion

The descriptive statistics for the study variables are shown in Table 2. Trade Openness has the greatest mean value and is the most dispersed variable. In contrast, Total resource rents record the lowest value. Additionally, the Pearson correlation coefficient plots a line of best fit through the data of the two variables and measures the strength and bearing of affiliation between the two variables. Table 3 displays the correlation matrix. There is a significant positive and negative linear relationship between the independent and dependent variables.

Table 2. Calculations of Technical Analysis

Variable	Obs	Mean	Std. Dev	Min	Max
CO2	532	7.9196	3.7078	2.9270	25.6042
GDP (log)	532	10.1111	0.6674	8.422575	11.6299
re	532	16.4960	11.7727	0.0000	51.91
ne	532	13.4092	13.0149	0.0000	49.5904
ICT_inv (log)	532	6.9128	1.3670	2.7294	9.3509
Financial development	532	83.6209	38.5690	0.1861	201.2587
Trade openness	532	118.9769	64.5801	45.4187	360.1321
Total resource rents	532	0.5536	0.7334	0.0000	5.6956

Source: data processed

We employ Wooldridge (2010) test for autocorrelation, serial correlation, and multivariate normality among variables in panel data, F-statistics of 21.94 rejected the null hypothesis that of no first-order autocorrelation, Wald test rejected no serial correlation null hypothesis at 1% level of significance, and Doornik-Hansen chi-square statistics of 13.71 ascertain the non-normality. Thereafter, we employ Pesaran (2015) cross-sectional dependency (CSD) test to examine the presence of CSD among variables, Table 3 column (2) presents results related to the test, the null hypothesis was significantly rejected for all variables and results indicate that all variables have dependence across countries, and therefore, more robust estimates are needed to overcome CSD issues. Then, first-generational panel units root tests were employed, such as Levin-Lin-Chun (LLC) and Im-Pesaran-Shin (IPS), whereas Table 3 column (3) present results related to LLC and all variables significantly rejected the null hypothesis at a level while columns (4) and (5) present results related to IPS and only financial development variable rejected at the first difference, indicates a different order of integration of the selected set of variables. With the presence of CSD in the variables, the conventional unit root tests fail to provide accurate results, we employ the updated second-generational unit root test, such as cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented Dickey-Fuller (CADF) employed by Westerlund & Hosseinkouchack (2016), columns (6)-(9) present results of the respective tests, and the rejected null hypothesis indicates that variables are stationary and corroborate different orders of integration of variables.

Table 3. CSD and Unit Root Test Result

Variable	CSD^3	First-generation of Unit Root Test: LLC	IPS	
		Level	Level	First Diff
CO2	39.108***	-7.2981***	-9.2504***	-
GDP (log)	28.407***	-8.7236***	-11.3605***	-
re	23.421***	-6.8519***	-10.4012***	-
ne	21.403***	-13.5048***	-10.3859***	-
ICT_inv (log)	31.292***	-12.9261***	-9.1606***	-
Financial development	29.385***	-6.7683	-1.6823	-10.2755***
Trade openness	26.045***	-8.2602***	-8.5702***	-
Total resource rents	25.637***	-10.1354***	-9.1940***	-

Variable	Second-generation of Unit Root Test: CIPS		PESCADF	
	Level	First Diff	Level	First Diff
CO2	-5.325***	-	-3.933***	-
GDP (log)	-1.792	-5.282***	-3.586***	-
re	-1.128	-6.509***	-1.542	-3.827***
ne	-4.949***	-	-3.730***	-
ICT_inv (log)	-1.686	-6.838***	-1.620	-4.656***
Financial development	-4.494***	-	-3.407***	-
Trade openness	-1.045	-5.838***	-3.178***	-
Total resource rents	-5.294***	-	-3.943***	-

Note: Unit root tests include trend and constant deterministic; CIPS test includes Portmanteau (Q) test for white noise on lags criterion selection, critical values -3.67 (10%), -3.22 (5%), and -3.67 (1%) with the null hypothesis of homogenous non-stationary bi=0 for all i.

The Pesaran & Yamagata (2008) slope homogeneity test employed to examine the prospect of heterogeneity of long-run coefficients, significant coefficients of Delta, and adjusted Delta statistics of 9.817 and 8.051 respectively, rejected the null hypothesis of homogeneity at a 1% level of significance. The results indicate that the long-run coefficients are heterogeneous. We employ various cointegration tests to assess the existence of long-run relationships among the selected set of variables, we applied Kao (1999), Pedroni (2001) and Westerlund (2007) tests. Table 4 presents results related to the cointegration test, all statistics from the tests corroborate the presence of long-run relationships among the variables, null hypothesis was significantly rejected at different levels of significance even with the presence of CSD and heteroskedasticity. Westerlund (2007) found the tests have good small-sample properties with small size distortions and high power.

Table 4. Cointegration Test

Kao		Pedroni			Westerlund		
			Panel-spesific AR	Same AR parameter		Some panels	All panels
Modified DF t	3.143***	Modified PP t	6.547***	3.486***	VR	4.829***	8.268***
DF t	4.159***	PP t	-11.617***	-17.538***			
ADF t	5.280***	Augmented PP	-12.287***	-17.706***			
Unadjusted modified DF t	1.407*	Modified VR		-7.796***			
Unadjusted DF t	1.463**						

Source: data processed

Table 5 shows the outcomes for environmental sustainability. We discover that economic growth has a significant and positive influence on CO_2 emissions across all models, indicating that economic growth degrades environmental quality in the region.

Table 5. Results of static models compared with one-step system GMM GMM (Dependent variable: CO_2 emissions)

Variable	Pooled-OLS	Fixed Effects	Random Effects	GMM
CO_2				0.4756*** (0.1469)
GDP (log)	1.9986*** (0.2725)	1.1301*** (0.5352)	1.8557*** (0.4443)	1.8782*** (0.4892)
re	-0.1637*** (0.0132)	-0.1516*** (0.0198)	-0.1434*** (0.0186)	-0.1409*** (0.0268)
ne	-0.0441 (0.0097)	-0.0316 (0.0158)	-0.0505*** (0.0158)	-0.0446** (0.0204)
ICT_inv (log)	-1.6303*** (0.1521)	-0.0421* (0.0248)	-0.3964*** (0.1177)	-0.0089*** (0.0033)
Financial development	-0.0243*** (0.0037)	-0.0029 (0.0022)	-0.0024 (0.0022)	-0.0052* (0.0024)
Trade openness	0.0154*** (0.0036)	0.0252*** (0.0037)	0.0169*** (0.0034)	-0.1348 (0.1238)
Total resource rents	1.010764 (0.1777)	0.2749** (.1014)	0.2928*** (0.1017)	0.1735 (0.1479)
Constant	- 4.67663*** (0.2883)	4.6606*** (0.5474)	1.8407*** (0.82481)	2.7829** (1.0351)
Observations	372	372	372	367
R-squared	0.6123	0.6726		
Year dummies	yes	yes	yes	
Post-estimation Diagnostics:				
Breusch-pagan LM test			0.0000	
Hausman (P-value)		0.0002		
Hansen-Sargan (p-value)				0. 312
AR (1)				0.0000
AR (2)				0.181

Note: The parenthesis contains the robust standard errors. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Our findings are similar to those of Saidi & Omri (2020), Mikayilov et al (2018), and Naminse & Zhuang (2018). In contrast, all of the models suggest that renewable energy significantly improves environmental quality. This is in line with the conclusions reached by Usman et al (2022) and Azam et al (2021). This is proof that Europe's switch to renewable energy sources from fossil fuels has lessened environmental challenges while also reducing greenhouse gas emissions that cause climate change. While RE and GMM results support that nuclear energy use only marginally improves the region's environmental quality, Pooled-OLS and FE models both indicate that nuclear energy use is insignificant. Likewise, all of the models demonstrate that increasing ICT investment also raises environmental quality. The findings are congruent with those of Wang et al (2021) and Lu (2018). This indicates a clear reduction in the emissions intensity of ICT investments, demonstrating the high technology, high-quality development, and ongoing energy optimization of the ICT sector in the area. The models also support the critical contribution of economic growth to the enhancement of environmental quality. The findings agree with those of Usman et al (2022), Adams & Klobodu (2018) and Charfeddine & Khediri (2016). In contrast, Pooled-OLS, FE, and RE found no significant impact of trade openness on environmental quality. Whereas Pooled-OLS and GMM found natural resource rents to be inconsequential for environmental performance, FE and RE show significant results.

Table 6. Results of static models with interaction variables compared with one-step system GMM (Dependent variable: CO_2 emissions)

Variable	Pooled-OLS	Fixed effects	Random effects	GMM
CO2				0.4615** (0.1426)
GDP (log)	1.6975*** (0.2654)	1.5776*** (0.5227)	1.1035*** (0.4341)	1.0757*** (0.5423)
re	-0.4987*** (0.0577)	-0.3481*** (0.0421)	-0.3611*** (0.0408)	-0.2452*** (0.0603)
ne	-0.0553*** (0.0095)	-0.0267* (0.0153)	-0.0429** (0.0142)	-0.0397* (0.0209)
ICT_inv (log)	-1.3649*** (0.1908)	-0.7763*** (0.1707)	-1.0239*** (0.1581)	-0.3940* (0.2066)
ICT_INV*re	0.0506 (0.0850)	0.0299*** (0.0057)	0.0328*** (0.0056)	0.0145*** (0.0082)
Financial development	-0.0262*** (0.0035)	-0.00218 (0.0022)	-0.0218 (0.0214)	-0.0053* (0.0023)
Trade openness	0.0173*** (0.0034)	0.0187*** (0.0038)	0.0124*** (0.0034)	0.0082*** (0.0023)
Total resource rents	1.009871 (0.1699)	0.2404** (0.0978)	0.2747*** (0.0969)	0.1831 (0.1577)
Constant	-6.0607*** (1.6245)	135.109*** (0.5798)	1.1083*** (0.25118)	2.7829** (1.0351)
Observations	372	372	372	367
R-squared	0.7335	0.5423		
Year dummies	yes	yes	yes	
Post-estimation Diagnostics:				
Breusch-pagan LM test			0.0000	
Hausman (P-value)		0.0000		
Hansen-Sargan (p-value)				0. 512
AR (1)				0.0000
AR (2)				0.129

Note: The parenthesis contains the robust standard errors. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 6 reveals the results of the second model, which includes the moderation effect of ICT investment on renewable energy use. The model's results are similar to those in Table 4. The results of the model estimates presented concur that GDP growth in the EU increases carbon emissions. C02-emitting activities continue to be a part of economic growth in EU member states. Similar to the earlier findings, carbon emissions are negatively associated with renewable energy, nuclear energy, ICT investment, and financial development, suggesting that as the former improves, the latter declines. Additionally, according to Table 5, all models show a significant positive relationship between trade openness and carbon emissions, but only the FE and RE models demonstrate a significant positive relationship between natural resource rents and growth. The results of the interaction effect of ICT investment and renewable energy show a positive sign. The FE, RE, and GMM models demonstrate that carbon emissions increase by 0.0299%, 0.0328%, and 0.0145% despite increasing use of renewable energy. The positive interaction may reflect that ICT's facilitative role in renewable energy deployment leads to increased renewable energy capacity, but if the overall energy demand still grows or if renewable energy is not efficiently integrated into the grid, total emissions might still increase. As ICT infrastructure develops, it often requires significant energy. When expansion coincides with increased renewable energy use, the overall energy consumption might still rise due to the broader scale of ICT activities, leading to higher emissions despite renewable energy integration. The findings provide unequivocal proof that the integration of ICT and renewable energy is insufficient to reduce carbon emissions in the EU member states.

5. Conclusion

This study has explored the interconnections between ICT investment, renewable energy usage, and carbon emissions, shedding light on their implications for environmental sustainability within European economies. The findings support the hypothesis that increasing investments in ICT positively affect environmental quality by contributing to a reduction in carbon emissions. Additionally, the positive relationship between renewable energy consumption and improved environmental outcomes highlights the necessity of transitioning towards sustainable energy sources. Similar to this, the ICT sector has joined forces under several initiatives to address the rising carbon emissions, including the Global e-Sustainability Initiative (GeSI) and several industries and governmental standards to do so, including EnergyStar, 80 Plus, and the European Union's Restriction of Hazardous Substances Directive (RoHS). However, renewable energy deployment is still not substantial enough to mitigate environmental pollution in the presence of significant ICT investment in the EU member states.

The findings of this study underscore the critical need for European Union member states to integrate ICT more strategically into their environmental and energy policies to enhance sustainability outcomes. Policymakers should prioritise the digitalization of energy infrastructure through smart grids and real-time monitoring systems to optimize renewable energy integration and efficiency. Establishing clear incentives and standards for ICT-enabled clean energy solutions, such as AI-powered optimization tools and digital twin technologies, can accelerate low-carbon transitions in both the public and private sectors. Furthermore, sector-specific decarbonization targets should be introduced for ICT-intensive industries, alongside expanded investment in digital skills training to ensure a workforce capable of supporting green technological innovation. Coordinated policy frameworks that align the EU's digital and climate strategies will be essential to fully leverage ICT's potential in reducing emissions and achieving carbon neutrality across member states.

However, this research is not without its limitations. One key limitation lies in the reliance on available data, which may not capture all relevant nuances of the regional variations within European countries. Additionally, the investigation focused primarily on the direct correlation between the variables, potentially overlooking other confounding factors that may influence the observed relationships, such as economic policies, technological advancements, and socio-cultural dimensions. Future studies should aim to address these limitations by incorporating a more comprehensive set of variables that account for the broader socio-economic context. Furthermore, longitudinal studies could be beneficial to analyze the long-term effects of ICT investment and renewable energy use on carbon emissions and environmental sustainability. Expanding the geographic scope to include non-European countries could also amplify the understanding of these dynamics across different economic settings. Overall, continued research in this area is essential to refine strategies that effectively leverage ICT and renewable energy in the pursuit of sustainable development goals.

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