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# Digital Technologies and the Energy Transition: Integrating ICT for Sustainable Development Goals

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## ABSTRACT

This study investigates the influence of information and communication technologies (ICT) on sustainable development within the framework of the Environmental Kuznets Curve (EKC) hypothesis in the context of European Economic Area (EEA) countries. Specifically, it evaluates how ICT integration into the energy sector contributes to the achievement of sustainable development goals (SDGs). The analysis focuses on 13 EEA countries over the period 2005-2024 and employs a Panel Vector Autoregression (Panel-VAR) model. The central hypothesis is that ICT adoption can serve as a pivotal driver of sustainability, not only by enhancing energy efficiency but also by fostering digital innovation and reducing environmental degradation. The empirical results confirm the existence of a modified EKC in the EEA context and show that ICT exerts a positive and statistically significant long-run impact on sustainability indicators. In particular, ICT supports the development of smart energy systems that facilitate more efficient production, consumption, and storage of energy, thereby leading to lower $CO_2$ emissions. This paper makes a novel contribution by integrating digital transformation into the EKC framework and highlighting bidirectional relationships between ICT, the energy transition, and sustainable development. The findings offer valuable policy implications, suggesting that investments in digital infrastructure and energy innovation can play a crucial role in achieving long-term sustainability objectives across the EEA region.

**Keywords:** ICT Development, Energy Transition, $CO_2$ Emissions, Environmental Kuznets Curve, Sustainable Development Goals, Panel Vector Autoregression, European Economic Area
**JEL Classifications:** O33, Q01, Q56, C33, Q43, Q53

## 1. INTRODUCTION

The global energy landscape is undergoing a profound transformation, characterized by a gradual shift from fossil fuels to green and renewable energy sources. This transition is driven by the deployment of innovative clean technologies—such as electric vehicles, wind turbines, and solar photovoltaics and is paralleled by rapid advancements in digital technologies, including high-performance computing, connected devices, and smart grids (REN21, 2023; IEA, 2023). Energy companies are increasingly expected to accelerate this transformation by phasing out carbon-intensive fuels while enhancing the efficiency and reliability of renewable energy systems (European Commission, 2022).

Simultaneously, the widespread adoption of information and communication technologies (ICT) across the European ECONOMIC AREA (EEA) has led to significant improvements in communication, productivity, and sector-specific research, particularly within the energy sector (IEA, 2024). Foundational studies by Datta and Bonnet (2018), and Motlagh et al. (2020) have identified the energy industry as a pioneer in implementing Industry 4.0 solutions. More recent contributions have advanced our understanding of the ICT-energy nexus, emphasizing both the opportunities and the trade-offs involved. For instance, Wang et al. (2023) highlight how digitalization can enhance grid flexibility and demand forecasting. At the same time, they raise concerns about the energy intensity of data centers and the environmental burden of electronic waste (Swiatowiec-Szczepanska and Stępień, 2022; Wang et al., 2023; Cheng et al., 2024; Adebayo et al., 2025).

While firms are increasingly leveraging ICT for both environmental and operational gains, the overall ecological impact of these technologies remains a subject of debate. Major concerns include the high electricity consumption of digital infrastructure, the extraction of critical raw materials, and the complex challenges surrounding the disposal and recycling of electronic and electrical equipment (Wang et al., 2023). Accordingly, ICT adoption generates first-order effects such as rising volumes of e-waste alongside second-order effects that promote energy efficiency and support smarter production and consumption systems (Weigel and Fischedick, 2019; Lee et al., 2023 and Adebayo et al., 2025).

This study contributes to the existing literature by investigating the dynamic interrelationships between ICT adoption, energy transition, and sustainable development across thirteen EEA countries (Austria, Belgium, Denmark, Finland, Germany, Greece, Ireland, Italy, Lithuania, Luxembourg, Norway, Portugal, and Spain) during the period 2005-2024. By extending the environmental Kuznets curve (EKC) framework to include ICT indicators, and applying a panel vector autoregression (Panel-VAR) approach, we aim to capture both the direct and indirect effects of digital transformation on $CO_2$ emissions and the progress toward achieving sustainable development goals (SDGs).

The remainder of this paper is structured as follows: Section 2 reviews the literature on the interplay between digitalization, energy transition, and sustainable development. Section 3 outlines the methodological framework. Section 4 presents the empirical findings and discussion. Section 5 concludes with key insights and policy recommendations.

## 2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

### 2.1. The Nexus between Energy Transition and Sustainable Development

Since the early 1990s, energy policies have increasingly sought to reconcile economic growth with environmental protection, promoting cleaner technologies and greater efficiency (IEA, 2023).

The UN Sustainable Development Goals (UN, 2016) marked a turning point, especially Goal 7, which stresses access to modern energy and the wider adoption of renewables. Thus, the energy transition requires a shift away from fossil fuels toward a diversified energy mix that addresses both climate and development challenges (Allen et al., 2021). This transformation also fosters innovation, resource efficiency, and broader SDG progress (REN21, 2023).

Recent reports continue to confirm the central role of energy in sustainable development: for instance, the Tracking SDG 7: Energy Progress Report 2025 emphasizes that achieving universal access to affordable, reliable, and renewable energy is still a major global challenge (IRENA, 2025). Similarly, the World Energy Outlook 2024 outlines key trends in energy demand, emissions, and supply that will shape the coming decade (IEA, 2024).

Recent academic studies further reinforce the critical link: Wang and Liu (2025) argues that energy transition is essential for long-term sustainable growth and environmental balance. Tian et al. (2024) systematically reviews the interplay between energy transition and economic development, highlighting both opportunities and tensions in recent empirical studies.

At the institutional and policy level, the Fostering Effective Energy Transition 2025 report highlights how geopolitical, financial, and structural barriers continue to challenge the pace of transition. The World Economic Forum's recent work underscores that energy security must be carefully balanced with decarbonization goals in current geopolitical contexts (WEF, 2025).

Thus, considering both the classical theoretical foundations and the most recent empirical and policy evidence, we see a strong basis for positing:

Based on this evidence, we formulate our first hypothesis ($H_1$): The energy transition is crucial for sustainable development.

### 2.2. Energy Impacts of ICT

The information and communication technology (ICT) sector influences energy use in multiple ways. On one side, it enables dematerialization, improves energy efficiency, and facilitates renewable energy deployment (Lee et al., 2023). Virtual conferencing, smart grids, and other digital solutions reduce emissions by optimizing systems and lowering transport needs (Coroama et al., 2012; Weigel and Fischedick, 2019). Moreover, the integration of AI, IoT, and blockchain technologies aligns with long-term energy efficiency targets (Swiatowiec Szczepanska and Stępień, 2022).

Conversely, ICT's rapid growth raises electricity demand, particularly through data centers and communication networks. Without mitigation, global ICT-related energy consumption could surge by 2030 (IEA, 2023). Additionally, ICT generates environmental challenges, including dependence on rare raw materials and rising e-waste (Wang et al., 2023; Mondejar et al., 2021).

Recent studies underscore the dual impact of ICT on energy dynamics. Malmodin et al. (2024) estimate that the ICT sector accounted for approximately 4% of global electricity consumption and 1.4% of global greenhouse gas emissions in 2020. Adebayo et al. (2025) highlight that increased ICT adoption in developing countries can simultaneously increase energy demand and $CO_2$ emissions, underscoring the need for sustainable ICT practices.

These findings lead us to propose two hypotheses: $H_2$: Digitization promotes the energy transition. $H_3$: ICT expansion increases electricity consumption and $CO_2$ emission.

### 2.3. ICT and Sustainable Development

Digital technologies have reshaped development strategies by boosting productivity, enhancing access to essential services,

**Table 1: Descriptive statistics of variables**

| Statistic | ANS | GDP | GDP$^2$ | ICT | FE | DRE |
|---|---|---|---|---|---|---|
| Mean | 5.79 | 1.080 | 15.877 | 76.434 | 67.973 | 0.374 |
| Median | 5.27 | 1.578 | 4.170 | 81.000 | 22.863 | 0.148 |
| Maximum | 6.19 | 25.176 | 633.843 | 98.000 | 326.291 | 4.090 |
| Minimum | −3.13 | −14.838 | 0 | 23.000 | 3.133 | −2.934 |
| Standard deviation | 1.31 | 3.844594 | 49.91068 | 16.25508 | 86.71561 | 0.942735 |
| Skewness | 2.53 | 0.292069 | 9.745801 | −0.892991 | 1.491748 | 1.171939 |
| Kurtosis | 8.77 | 11.81 | 116.32 | 3.151985 | 3.873810 | 6.785221 |
| Jarque-Bera | 509.2739 | 672.4517 | 114050.6 | 27.71066 | 83.35882 | 170.9618 |
| Probability | 0.000000 | 0.000000 | 0.000000 | 0.000001 | 0.000000 | 0.000000 |
| Sum | 1.20E+18 | 223.7515 | 3286.725 | 15822.00 | 14070.50 | 77.61576 |
| Sum squared deviation | 3.56E+34 | 3044.867 | 513161.6 | 54430.87 | 1549037 | 183.0822 |

Source: Results of Eviews 10

**Table 2: Correlation matrix**

| | ANS | GDP | GDP$^2$ | ICT | FE | DRE |
|---|---|---|---|---|---|---|
| ANS | 1.000 | | | | | |
| GDP | 0.014 | 1.000 | | | | |
| GDP$^2$ | −0.088 | 0.253 | 1.000 | | | |
| ICT | 0.011 | 0.038 | 0.040 | 1.000 | | |
| FE | 0.083 | 0.053 | 0.107 | 0.042 | 1.000 | |
| DRE | 0.047 | 0.010 | 0.066 | 0.087 | 0.041 | 1.000 |

Source: Eviews Results

and supporting environmental objectives; (Sachs et al., 2019). However, the environmental footprint of ICT remains significant. Device production and disposal contribute to pollution, resource depletion, and a growing volume of e-waste, with toxic substances such as mercury and lead exacerbating environmental risks (Wang et al., 2023; Salahuddin and Alam, 2015). Recent studies further highlight the dual impact of ICT on sustainable development: the 2024 Digital Economy Report by UNCTAD emphasizes the urgent need for environmentally sustainable and inclusive digitalization strategies, noting that digital technology relies heavily on raw materials and growing energy consumption, while the ICT Environmental Impact Rolling Plan 2024 by the European Commission estimates that digital transformation can reduce 15-20% of total GHG emissions but contributes 2.1-3.9% of total emissions, with e-waste being the fastest-growing waste category (UNCTAD, 2024; European Commission, 2024). Similarly, Cheng et al. (2024) demonstrate how ICT-enabled solutions, such as smart water pipeline monitoring systems, can advance sustainability objectives. Drawing on this discussion, we put forward the additional hypotheses: $H_5$: ICT improves welfare and sustainability.

## 3. MATERIALS AND METHODS

This study contributes to the empirical literature by introducing Information and Communication Technology into the KCM model and using the Panel-VAR technique to assess the simultaneous impacts of the study variables.

Panel VAR takes into account the cross-sectional dimension that favours the explanation of economic phenomena and makes these models able of capturing static and dynamic interdependencies. Moreover, before specifying the model, the estimation of the VAR panel is similar to that of standard VARs because it requires the determination of the optimal lag (p).

This section is devoted to presenting the model, the variables, descriptive statistics, the correlation matrix, unit root tests and the estimated model.

### 3.1. Data

The variables in the study are dependent and consist of Information and Communication Technology (ICT), renewable energy (RE) and fossil energy (FE) consumptions, economic growth (GDP) and adjusted net savings (ANS). Adjusted net savings (ANS) and gross domestic product (GDP) growth were obtained from the World Bank database. Renewable energy (RE) and fossil energy (FE) were extracted from the IEA database. The ICT variable is taken from the OECD database.

The variables are defined as follows:

- Information and communication technologies (ICT): present the field of telematics, i.e. computer, multimedia, audiovisual, telecommunications and Internet techniques that allow users to communicate, access information sources, manipulate, store, transmit and produce information in different forms: Music, text, image, sound, video and interactive graphic interface.
- Adjusted net savings ANS: Is a sustainability indicator developed by the World Bank in 1998/1999 to express the change in a country’s economic, human and natural capital at the end of a production cycle. According to green accounting and World Bank calculations, ANS is equal to net national savings plus education expenditures, minus the depletion of energy, mineral and forest resources, and minus the damage caused by carbon dioxide and particulate emissions.
- Fossil energy (FE): The energy produced from a fossil fuel, which is a chemical compound rich in hydrogen and carbon. It is the combustion of coal, oil or natural gas. These energies are essential to ensure the production of electricity, transportation, heating. Fossil energy takes millions of years to build up. The extraction of fossil fuels and their combustion are the main cause of $CO_2$ emissions and global warming.
- Renewable energies (RE): The energy sources based on inexhaustible resources that renew themselves fairly quickly and can be considered as inexhaustible on a human time scale, so that their use has no effect on their future availability. There

are several types of renewable energy, produced from different sources such as biomass, solar energy, hydroelectricity, wind energy and geothermal energy.

- Gross domestic product (GDP): GDP growth (annual %) is the economic indicator that deducts the sum of the gross value added of all resident producers in an economy, plus all taxes on products and minus subsidies not included in the value of products. This indicator is the annual percentage growth rate of GDP at market prices based on constant local currencies. Aggregate data are based on constant U.S. dollars since 2010. It is calculated without making deductions for the depreciation of manufactured goods or the loss of value or degradation of natural resources.
- GDP per capita squared: GDP per capita squared measures the average GDP per capita over the long term. This income corresponds to income in the downward phase of the EKC.
- The study sample covers 13 EEA countries (Austria, Belgium, Denmark, Finland, Germany, Greece, Ireland, Italy, Lithuania, Luxembourg, Norway, Portugal and Spain) for the period 2005-2024. Table 1 summarizes the descriptive statistics of the variables.

The results obtained in Table 1 show that the standard deviation (SD) of FE is the highest and that of ANS low. The Skewness coefficients are not zero, so the distribution is not symmetric. The value of Skewness for the variable ICT is negative which corresponds to a leftward spread of the distribution. Conversely, for the other variables, the value of Skewness is positive, so the distribution is right-skewed and it is characterized by a strong dispersion on the right. The Kurtosis is positive which indicates that the queues have several observations that in a Gaussian distribution, the queues of the distribution are thicker than the queues of the normal distribution. The distribution is flatter than the normal distribution.

### 3.2. Correlation Matrix

The correlation matrix allows a pairwise analysis of the correlations between the variables in the study. This matrix reveals the problem of multicollinearity when the correlation coefficients are >0.5. Table 2 shows correlation coefficients <0.5, indicating that there is no problem of multicollinearity between the variables.

### 3.3. Unit Root Tests

We perform Levin et al. (2001), ADF-Fisher (Maddala and Wu, 2001) and PP- Fisher-type (Choi, 2001) tests to investigate the stationarity of the variables. The null hypothesis implies the presence of a unit root.

The results in Table 3 show that the majority of the unit root tests provided probabilities <5% for the variables ANS, GDP, GDP2, ICT and FE, so they are stationary; I (0). While the variable RE is not stationary (probabilities >5%) and it becomes stationary after differentiation, it is then integrated at order 1; I (1).

### 3.4. Panel-VAR Estimation

We estimate a Panel-VAR model using 5 endogenous variables, which is represented as follows:

**Table 3: Unit root tests**

| VAR. | Levin, Lin and Chu | | | ADF-Fisher Chi-square | | | PP-Fisher-type | | |
|---|---|---|---|---|---|---|---|---|---|
| | No constant No trend | Constant | Constant and trend | No constant No trend | Constant | Constant and trend | No constant No trend | Constant | Constant and trend |
| ANS | 0.43 (0.669) | −2.68*** (0.003) | −4.10*** (0.000) | 31.57 (0.292) | 46.47** (0.015) | 59.08*** (0.000) | 33.14 (0.230) | 55.34** (0.001) | 73.88*** (0.000) |
| GDP | −7.97*** (0.000) | −3.28*** (0.000) | −1.41* (0.079) | 101.37*** (0.000) | 63.31*** (0.000) | 37.20 (0.114) | 94.86*** (0.000) | 50.71*** (0.005) | 31.34 (0.302) |
| GDP2 | 70.20*** (0.000) | −2.74*** (0.003) | −3.22*** (0.000) | 66.41*** (0.000) | 58.83*** (0.000) | 55.71*** (0.001) | -7.06*** (0.000) | 69.82*** (0.000) | 58.86*** (0.000) |
| ICT | 0.35 (1.000) | 209.68*** (0.000) | 99.34*** (0.000) | 3.01*** (1.000) | 129.49*** (0.000) | 76.30 (0.035) | 6.09 (1.000) | −10.99 (0.000) | −6.11 (0.000) |
| FE | 101.4*** (0.000) | 15.60 (0.971) | 51.64*** (0.004) | 94.48*** (0.000) | 15.08 (0.977) | 47.41** (0.012) | −7.95*** (0.000) | 0.22 (0.588) | −2.39*** (0.008) |
| RE | 2.28 (1.000) | 39.61* (0.071) | 44.81** (0.023) | 2.24 (1.000) | 23.79 (0.692) | 32.73 (0.245) | 8.47 (1.000) | −0.94 (0.172) | −2.74*** (0.003) |
| DRE | 155.1*** (0.000) | 172.0*** (0.000) | 162.23*** (0.000) | 109.97*** (0.000) | 143.74*** (0.000) | 113.4*** (0.000) | −7.14*** (0.000) | −13.5*** (0.000) | −12.1*** (0.000) |

Source: Results of Eviews 10. (*) (**) (***): We accept stationarity at 10%, 5% and 1% respectively

$$\mathrm{ANS}_{\mathrm{it}} = \alpha_1 + \sum_{j=1}^{P} \beta_{1iJ}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{j=1}^{P} \delta_{1ij}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{p-1}^{P} \varphi_{1ij} GDP^2{}_{\mathrm{it-j}} + \sum_{j=1}^{P} \tau_{1ij} ICT_{\mathrm{it-j}} + \sum_{j=1}^{P} \sigma_{1ij} FE_{\mathrm{it-j}} + \sum_{j=1}^{P} \vartheta_{1ij} DRE_{\mathrm{it-j}} + \mu_{1it} \quad (1)$$

$$\mathrm{GDP}_{\mathrm{it}} = \alpha_2 + \sum_{\mathrm{j=1}}^{\mathrm{P}} \beta_{\mathrm{2iJ}}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \delta_{\mathrm{2ij}}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{\mathrm{p-1}}^{\mathrm{P}} \varphi_{\mathrm{2ij}}\mathrm{GDP}^2{}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \tau_{\mathrm{2ij}}\mathrm{ICT}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \sigma_{\mathrm{2ij}}\mathrm{FE}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \vartheta_{\mathrm{2ij}}\mathrm{DRE}_{\mathrm{it-j}} + \mu_{\mathrm{2it}} \quad (2)$$

$$\mathrm{GDP}^2{}_{\mathrm{it}} = \alpha_3 + \sum_{\mathrm{j=1}}^{\mathrm{P}} \beta_{\mathrm{3iJ}}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \delta_{\mathrm{3ij}}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{\mathrm{p-1}}^{\mathrm{P}} \varphi_{\mathrm{3ij}}\mathrm{GDP}^2{}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \tau_{\mathrm{3ij}}\mathrm{ICT}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \sigma_{\mathrm{3ij}}\mathrm{FE}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \vartheta_{\mathrm{3ij}}\mathrm{DRE}_{\mathrm{it-j}} + \mu_{\mathrm{3it}} \quad (3)$$

$$\mathrm{ICT}_{\mathrm{it}} = \alpha_4 + \sum_{\mathrm{j=1}}^{\mathrm{P}} \beta_{\mathrm{4iJ}}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \delta_{\mathrm{4ij}}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{\mathrm{p-1}}^{\mathrm{P}} \varphi_{\mathrm{4ij}}\mathrm{GDP}^2{}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \tau_{\mathrm{4ij}}\mathrm{ICT}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \sigma_{\mathrm{4ij}}\mathrm{FE}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \vartheta_{\mathrm{4ij}}\mathrm{DRE}_{\mathrm{it-j}} + \mu_{\mathrm{4it}} \quad (4)$$

$$\mathrm{FE}_{\mathrm{it}} = \alpha_5 + \sum_{\mathrm{j=1}}^{\mathrm{P}} \beta_{\mathrm{5iJ}}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \delta_{\mathrm{5ij}}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{\mathrm{p-1}}^{\mathrm{P}} \varphi_{\mathrm{5ij}}\mathrm{GDP}^2{}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \tau_{\mathrm{5ij}}\mathrm{ICT}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \sigma_{\mathrm{5ij}}\mathrm{FE}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \vartheta_{\mathrm{5ij}}\mathrm{DRE}_{\mathrm{it-j}} + \mu_{\mathrm{5it}} \quad (5)$$

$$\mathrm{DRE}_{\mathrm{it}} = \alpha_6 + \sum_{\mathrm{j=1}}^{\mathrm{P}} \beta_{\mathrm{6iJ}}\mathrm{ANS}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \delta_{\mathrm{6ij}}\mathrm{GDP}_{\mathrm{it-j}} + \sum_{\mathrm{p-1}}^{\mathrm{P}} \varphi_{\mathrm{6ij}}\mathrm{GDP}^2{}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \tau_{\mathrm{6ij}}\mathrm{ICT}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \sigma_{\mathrm{6ij}}\mathrm{FE}_{\mathrm{it-j}} + \sum_{\mathrm{j=1}}^{\mathrm{P}} \vartheta_{\mathrm{6ij}}\mathrm{DRE}_{\mathrm{it-j}} + \mu_{\mathrm{4it}} \quad (6)$$

The order P chosen is the one that minimizes the information criterion (Akaike, Schwartz).

With α, β, δ, φ, τ, σ, and ϑ are estimation parameters, P is the order of delay determined by the Schwarz information criterion, and $\mu_{\mathrm{it}}$ is the error term. The equations are estimated using Eviews software. Tables 4 and 5 present the results of the model estimation and the corresponding validity tests, respectively. We performed the Granger causality test in Table 5, to show the existence of unidirectional or bidirectional causality relationships between the variables in the model.

## 4. RESULTS AND DISCUSSION

Table 6 presents the results from the estimation of the panel VAR model. In the first equation, the coefficients show the effects of the explanatory variables on adjusted net savings. The coefficient of GDP is positive and statistically significant, while the squared GDP term ($\mathrm{GDP}^2$) is negative and significant. These findings validate the environmental Kuznets curve (EKC) hypothesis, which posits an inverted U-shaped relationship between economic growth and environmental quality.

In the early phases of development, economic expansion tends to exacerbate environmental degradation due to industrialization and increased resource consumption. However, after surpassing a critical income threshold, rising GDP facilitates greater investment in sustainable technologies, environmental regulations, and social welfare programs. This transition improves both environmental performance and the quality of life, consistent with the theoretical insights of Kamoun et al. (2019).

Table 6 illustrates a unidirectional causal relationship from FE and RE to ANS. The estimation results shows that FE has a positive and significant impact on ANS after one period, an increase in electricity consumption of 1% leads to the improvement of ANS by 0.51%, but the effect becomes negative by −0.38% after two periods. The increase in FE consumption leads to an increase in industrial production and economic growth, but generates GHG emissions with negative effects on the environment and people's well-being (Kamoun et al., 2019). However, the consumption of clean energy leads to a decrease in $\mathrm{CO}_2$ emissions and environmental degradation, supporting the findings of recent studies (Wang et al., 2023).

There is a significant negative bidirectional relationship between FE and RE, which can be explained by the substitution of FEs by REs, allowing the validation of the transition policies in the

**Table 4: Validity tests of panel VAR estimations**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Normality tests of residuals | | | | |
| **Equations** | **ANS** | **GDP** | **GDP²** | **ICT** | **FE** | **DRE** | **Joint** |
| Jarque-Bera Probabilité | 0.562*** | 3.145*** | 4.566*** | 4.872*** | 4.987*** | 2.235*** | 7,75***0.18 |
| Probability | 0.72 | 0.31 | 0.29 | 0.42 | 0.74 | 0.65 | 0.64 |
| **Autocorrelation tests of residuals** | | **LM statistics** | | | | **Portmanteau statistics** | |
| Statistics | | 31.76*** | | | | 421.12*** | |
| Probability | | 0.26 | | | | 0.87 | |
| **Homoscedasticity : White test** | | **Without cross terms** | | | | **With cross terms** | |
| Statistic | | 176*** | | | | 276*** | |
| Probability | | 0.32 | | | | 0.54 | |

Source: Results of Eviews 10

**Table 5: Granger causality**

| Variable | ANS | | GDP | | GDP² | | ICT | | FE | | DRE | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Excluded | Chi-square | Probability | Chi-square | Probability | Chi-square | Probability | Chi-square | Probability | Chi-square | Probability | Chi-square | Probability |
| ANS | | | 0.76 | 0.68 | 0.06 | 0.96 | 2.430 | 0.11 | 1.67 | 0.43 | 0.15 | 0.92 |
| GDP | 3.84** | 0.037 | | | 4.36 | 0.11 | 2.50 | 0.28 | 0.38 | 0.82 | 0.74 | 0.68 |
| GDP² | 2.11** | 0.04 | 5.22 | 0.07* | | | 0.16 | 0.92 | 0.9 | 0.95 | 0.08 | 0.95 |
| ICT | 1.76* | 0.09 | 3.45 | 0.01** | 2.97 | 0.22 | | | 2.44** | 0.01 | 11.19** | 0.04 |
| FE | 28.09*** | 0.00 | 2.49 | 0.02** | 0.22 | 0.89 | 4.84* | 0.08 | | | 56.91*** | 0.00 |
| DRE | 8.94** | 0.01 | 3.21 | 0.09* | 0.08 | 0.95 | 1.02 | 0.59 | 11.27*** | 0.00 | | |
| All | 55.97 | 0.00 | 10.14 | 0.02 | 8.57 | 0.57 | 11.77 | 0.30 | 13.04 | 0.02 | 120.47 | 0.00 |

(*) (**) (***): We reject $H_0$ for absence of causality at 10%, 5% and 1% respectively

EEA towards clean energy. Energy transition is about shifting to a new energy mix capable of meeting the challenges of the energy system (Wang et al., 2023).

On the other hand, the effect of RE on ANS is significant and positive for both periods. The increase in RE use leads to the improvement of ANS by 0.16% and 0.46% respectively. These results are consistent with the work of Allen et al. (2021), which maintain that the primary objective of the energy transition is to pursue sustainable development and achieve its objectives on a global scale.

We therefore retain hypothesis 1, which postulates that "the energy transition is crucial for sustainable development." The results also show a significant and positive effect of ICT on economic growth. An increase in Internet usage of 1% leads to an improvement in GDP of 0.24%. Digitization increases profitability through cost optimization and business performance in line with the work of Lee et al., 2023, who stated that ICT are technologies that lead to other innovations, contributing to economic growth.

Furthermore, the results show that the effect of ICT is significant and positive on RE. A 1% increase in internet usage leads to an increase in electricity consumption from RE of 0.12% and 0.23% after 1 and 2 periods, respectively. New technologies improve energy efficiency and reduce renewable energy costs, thus contributing to the energy transition in line with the work of Lee et al. (2023) and supported by Wang et al. (2023).

Therefore, hypothesis 2 is verified: "ICT promotes the energy transition."

However, ICT positively and significantly affects the FE variable. A 1% increase in the number of Internet users leads to an increase in electricity consumption of up to 0.04% after one period and 0.02% after two periods. This is because the widespread expansion of ICT leads to a significant increase in the demand for electricity, especially the demand for personal computers, data centers, and communication networks. This confirms the results of the work who state that digital transformation leads to a dramatic increase in electricity consumption (Ait-Daoud et al., 2010). Therefore, we accept hypothesis 3: "ICT leads to an increase in electricity consumption."

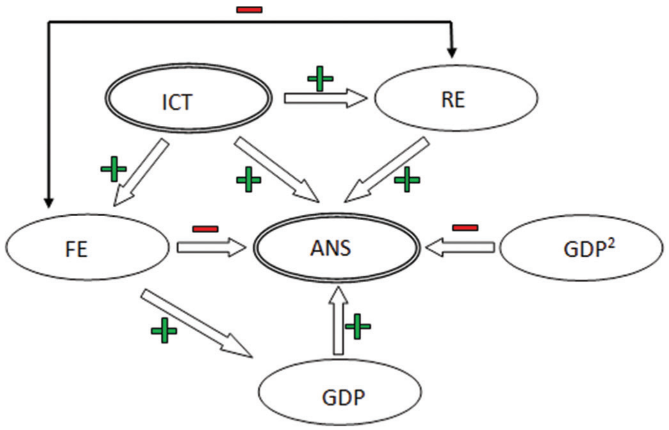
The results of the causality test in Table 5 and Figure 1 confirm the results of the Panel-VAR model estimation. Based on the observed results of the Granger causality test, there is a unidirectional causal relationship from ICT to ANS. Table 6 of Panel-VAR estimation shows that ICT negatively affects ANS, with a 1% increase in the number of internet users decreasing viability by 0.13%. However, after two periods, the sign of the coefficient becomes positive by 0.07%. This can be explained by the fact that in the short term, ICT production requires a lot of electricity and a number of toxic and non-renewable resources such as mercury and lead, which are very dangerous and harmful elements for the environment. In addition, the disposal of waste electronic and electrical computer goods leads to environmental pollution these results align with the work of Salahuddin and Alam (2015), Malmodin et al. (2024) and Adebayo et al. (2025). Thus, hypothesis 3 "ICT expansion increases electricity consumption and $CO_2$ emission" is validated in the short term.

**Table 6: Panel-VAR estimation**

| Vector autoregression estimates | | | | | | |
|---|---|---|---|---|---|---|
| t-statistics in [ ] | | | | | | |
| **Variable** | **ANS** | **GDP** | **$GDP^2$** | **ICT** | **FE** | **DRE** |
| ANS (−1) | 0.407*** (6.04) | 3.81 (−0.66) | 1.14 (−0.08) | −4.12 (−1.36) | 1.07 (−1.23) | 5.38 (0.22) |
| ANS (−2) | **0.284* (4.06)** | 0 (0.19) | 1.74 (0.25) | −1.48 (−0.54) | 3.23 (0.69) | 2.99 (0.32) |
| GDP (−1) | **1.54*** (3.06)** | 0.275*** (3.91) | 1.834 (1.30) | −0.001 (−0.01) | 0.05 (0.52) | −0.003 (−0.13) |
| GDP (−2) | **1.53** (2.11)** | −0.185** (−2.06) | 0.06 (0.04) | 0.025 (0.46) | 0.019 (0.20) | 0.016 (0.90) |
| $GDP^2$ (−1) | **−2.89** (−2.03)** | 0.002 (0.39) | 0.022 (0.25) | 0.00 (−0.00) | 0.001 (0.118) | 0.00 (0.20) |
| $GDP^2$(−2) | **−2.76** (−2.31)** | 0.012** (2.11) | 0.122 (1.44) | 0.001 (0.23) | −0.001 (−0.256) | 0.001 (−0.20) |
| ICT (−1) | **−0.13** (−2.26)** | **0.167** (−2.28)** | 0.831 (0.53) | 1.454 (23.69) | **0.048*** (4.92)** | **0.12** (2.52)** |
| ICT (−2) | **0.07*** (2.75)** | **0.24** (2.37)** | −0.69 (−0.44) | −0.445*** (−7.07) | **0.029** (2.23)** | **0.23*** (3.63)** |
| FE (−1) | **0.51*** (5.89)** | **1.2** (2.27)** | −0.442 (−0.39) | −0.047 (−1.05) | 0.537*** (−7.00) | **−0.08*** (−5.66)** |
| FE (−2) | **−0.38*** (−5.65)** | **1.28***** (2.75) | 0.387 (0.35) | 0.054 (1.23) | 0.449*** (5.92) | **−0.09*** (−6.09)** |
| DRE (−1) | **0.16*** (4.78)** | −0.24 (−0.68) | −1.20 (−0.22) | 0.13 (0.62) | **−1.11*** (−3.05)** | −0.32*** (−4.54) |
| DRE (−2) | **0.46*** (4.4)** | −0.329 (−0.97) | 1.099 (0.21) | −0.066 (−0.3) | **−0.815** (−2.35)** | −0.193*** (−2.83) |
| R-squared | 0.844 | 0.58 | 0.036 | 0.97 | 0.99 | 0.67 |

Source: Results of Eviews 10. (*) (**) (***): We accept the significance of the coefficients at the 10% threshold 5% and 1% respectively

**Figure 1:** Causality relationships



Source: Authors

Nevertheless, in the long run, ICT improves the well-being of individuals and thus has a positive effect on sustainability. Our results confirm the work of Swiatowiec-Szczepanska and Stępień, (2022). Wang et al. (2023), Cheng et al. (2024) and Adebayo et al. (2025). Therefore, the results provide validation for hypothesis 5 in the long run, which states that "digital technologies improve well-being and sustainability."

The results in Table 4 show the robustness of the estimated Panel-VAR model. The statistics of the Jarque-Bera test and the joint test allow us to accept the null hypothesis of the normality of the residuals. According to the LM and Portmanteau tests, the residuals of the model are not autocorrelated and they are homoscedastic according to the White test which assumes the null hypothesis of homoscedasticity. The residuals are white Gaussian noise.

## 5. CONCLUSION AND POLICY IMPLICATIONS

This study applied the EKC function using panel data from 13 EEA countries over the period 2005-2020 to examine the dynamic relationships between several variables: ANS, GDP, $GDP^2$, ICT, RE, and FE. We utilized the panel vector autoregressive model (Panel-VAR) approach and the Granger causality test. The estimation results confirm the inverted U-shape of the EKC and highlight the positive impact of renewable energy (RE) generation on sustainability, while fossil energy (FE) has a negative long-term effect. Additionally, the findings reveal a negative bidirectional causal relationship between RE and FE, validating the substitution of FE with RE as part of the energy transition solution.

Regarding the impact of ICT on sustainable development, we identified a negative short-term effect and a positive long-term effect. The short-term negative effect can be attributed to the fact that ICT production relies on fossil fuels and toxic materials, which negatively affect the environment and human well-being. However, ICT has a positive long-term impact on ANS, as it plays a crucial role in driving a range of societal and economic benefits, including improved quality of life and overall well-being. The direct effect of ICT and technological innovation on sustainability can be seen in the widespread use of computers, connected phones and watches, tablets, and other household robots, all of which enhance the lives of both individuals and professionals. The indirect impact of digitalization on sustainability is evident in the support for intelligent energy systems that ensure energy efficiency, using tools to better manage the consumption, production, and storage of clean energy, thus reducing $CO_2$ emissions and improving environmental conditions.

The energy transition serves as a critical strategy for combating climate change and safeguarding the environment for future generations. Indeed, the impacts of clean energy, its finite nature, and the growing awareness among governments and households are all poised to drive sustainable development. Furthermore, innovative technologies necessitate more fundamental research to address the existing gaps in knowledge across several fields, including energy, the environment, social issues, and sustainability. Continued investment in research and development is essential for advancing the transition to a sustainable future.

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