Assessment of the Impact of Digitalization on Air Pollution. Empirical Evidence from European Union Countries

Mihaela Maftei[1], Gina Cristina Dimian[2], Maria Denisa Vasilescu[3] and Marieta Olaru[4]
[1)2)3)4)] *Bucharest University of Economic Studies, Bucharest, Romania.*
E-mail: mihaela.maftei@ase.ro; E-mail: gina.dimian@csie.ase.ro
E-mail: maria.vasilescu@csie.ase.ro; E-mail: olaru.marieta@com.ase.ro.

Please cite this paper as:
Maftei, M., Dimian, G.C., Vasilescu, M.D. and Olaru, M., 2024. Assessment of the Impact of Digitalization on Air Pollution. Empirical Evidence from European Union Countries. In: R. Pamfilie, V. Dinu, C. Vasiliu, D. Pleşea, L. Tăchiciu eds. 2024. *10th BASIQ International Conference on New Trends in Sustainable Business and Consumption.* Almeria, Spain, 6-8 June 2024. Bucharest: Editura ASE, pp. 285-292
DOI: 10.24818/BASIQ/2024/10/034

Abstract

The study examines the direct impact of digitalization and other factors that promote economic growth on net greenhouse gas (GHG) emissions. It uses PS-PCSE specifications with period SUR weights on cross-country panel data from European Union (EU) countries spanning the years 2000 to 2020. The findings indicate that the implementation of digitalization has the potential to mitigate net greenhouse gas (GHG) emissions. This implies that the integration of digitalization with clean energy sources, environmentally sustainable innovations, and low carbon technologies is crucial to achieving a reduction in GHG emissions. If economic resources are directed toward digitalization and renewable development, the structure of energy use could be changed to favor renewable sources. This would reduce the negative effects of economic growth on environmental degradation. If countries can improve their contribution to the promotion of renewable energy consumption, ICT trade can play an important role in reducing pollution. Furthermore, the findings of the heterogeneity study highlight the existence of variations between member states of the European Union in terms of the influence of digitalization on pollution. Based on the results, some policy recommendations could be proposed to be included in the policy framework for the European Union that is encountering challenges in pollution control. First, governments should establish a favorable condition for digitalization and innovation by implementing regulations and a well-defined strategic framework. Furthermore, governments must adapt digital policies, programs, and initiatives to their specific economic activities and the complex nature of their businesses, considering the diverse impact of digitalization on greenhouse gas (GHG) emissions.

Keywords

Digitalization, GHG emissions, renewable energy consumption, innovation, ICT trade.

DOI: 10.24818/BASIQ/2024/10/034

Introduction

In recent times, there has been a growing trend towards employing digitalization and renewable energy sources throughout the economies of the European Union. This change is driven by the need to address environmental pollution and diversity concerns while also ensuring a reliable energy supply. According to Zhang et al. (2023), the utilization of renewable energy sources, the adoption of digital transformation, and the advancement of green technology play a significant role in the decarbonization process and the transition from conventional energy to clean energy. These factors contribute to the improvement of environmental quality during energy production and utilization.

The Information and Communication Technology (ICT) sector is currently experiencing rapid growth in terms of greenhouse gas emissions and energy management (European Commission, 2023). Although digitalization has direct and indirect impacts on environmental quality, such as its carbon footprint and its enabling and systemic effects, it also offers potential solutions for environmental protection and climate change mitigation (Hilty et al., 2006; Bieser et al., 2023). With an increasing number of Internet users, there is a corresponding increase in data traffic and consumer demand for digital gadgets, data centers, and other energy-intensive ICT equipment. This can lead to an increase in energy consumption and contribute to the carbon footprint of our digital society. The ICT sector has played a significant role in enhancing the competitiveness of knowledge-based and information-based economies (Vasilescu, Dimian and Gradinaru, 2023). It has brought about substantial transformations in the manufacturing and employment landscape throughout the European Union (EU) by facilitating and enhancing productivity and efficiency at the technological, operational, and labor levels. Consequently, this has generated innovative opportunities for the business environment (Maier, et al., 2016) to foster the development of novel products, production processes, and work practices.

There is an increasing demand to evaluate the impact of greenhouse gases (GHG) of the information and communication technology (ICT) sector and the capacity of ICT solutions, such as smart production, smart grid, smart transport, smart buildings, smart work, smart cities, smart travel, smart services and good sharing, to reduce GHG emissions in various economic sectors, including tourism, industry, transport, agriculture, and households (Malmodin and Bergmark, 2015; Lundén, et al., 2022). The objective of this study is to examine the influence of digitalization on greenhouse gas (GHG) emissions in a sample of 27 economies in the European Union from 2000 to 2020. To conduct a more thorough analysis of the impact of digitalization on air emissions, we separated EU countries into two subpanels based on their GHG emissions. This analysis aimed to find the specific characteristics of each subpanel that could potentially influence these effects. This study also looks at how digitalization affects greenhouse gas (GHG) emissions, focusing on the use of renewable energy. The aim is to formulate policy suggestions for the avoidance and control of air emissions, as well as for the preservation of the natural environment.

Hence, this study establishes connections with the existing literature in subsequent manners. This empirical study aims to provide information on the impact of digitalization on greenhouse gas (GHG) emissions in European Union (EU) countries. It employs a panel data approach to examine the influence of digitalization, specifically in terms of individuals' Internet usage and mobile cellular subscriptions, on GHG emissions across 27 EU countries. We also look at ICT trade, industry value added (IND), gross domestic expenditure on research and development (RD), and economic growth as control variables to analyze how GHG emissions have changed over time. This is because the economy and households have become more digitalized very quickly and widely in the last few decades. Furthermore, this study examines the influence of digitalization on greenhouse gas (GHG) emissions in two clusters of EU countries based on the extent of air pollution. This analysis provides a more comprehensive view of the potential effects of economic development and structure on GHG emissions.

The paper is structured into five sections. The first section covers the general discussion of the chosen topic. The following section includes a review of the literature on empirical studies concerning the impact of digitalization and renewable energy consumption on greenhouse gas emissions. The next section describes the estimation methodology and data sources. The fourth section includes a discussion of empirical results. Finally, the paper is concluded in the last section, where several policy implications and recommendations are proposed.

1. Literature review

Previous research has investigated the impact of digitalization on the quality of the environment. Nevertheless, there is a lack of agreement regarding the relation between digitalization and greenhouse gas (GHG) emissions, as well as the nature of digitalization's impact on the environment. Digitalization causes multiple effects on greenhouse gas (GHG) emissions, including direct, indirect, and systemic effects, as well as structural and behavioral changes (Lange, Pohl and Santarius, 2020). ICT manufacturing, usage, and disposal have direct implications that can be studied using a life cycle assessment approach. The carbon emissions resulting from ICT applications in many economic sectors are influenced by indirect impacts (Pohl, Hilty and Finkbeiner, 2019). According to Hilty, et al. (2006), the direct effects of digitalization have been found to contribute to a rise in greenhouse gas (GHG) emissions. However, indirect effects can lead to an increase in GHG emissions through rebound, obsolescence, or induction effects, or they can result in a reduction in GHG emissions through enabling effects such as optimization and substitution effects. According to Pohl, Hilty and Finkbeiner (2019), macroscale effects relate to changes in the structure of economies and societies resulting from economic development or evolutions in lifestyles, habits, and practices.

The research findings have identified two primary streams that establish a direct correlation between digitalization, environmental quality, and pollution. The authors have identified that the implementation of digitalization has the potential to enhance environmental quality by mitigating carbon emissions resulting from the widespread adoption of digitalization and the process of digital transformation. The rise of digitalization has revolutionized the management, procedures, and technologies used by diverse economic sectors. Furthermore, the process of digitalization has significantly changed the behavior and habits of the population by allowing online shopping, remote work, electronic banking, electronic government, digital public services, electronic commerce, and communication through smart devices. As a result, there has been a reduction in transportation and traffic congestion (Irfan, et al., 2022; Ha, 2022). Tzeremes, Dogan and Alavijeh (2023) conducted a study to examine the correlation between renewable energy, economic growth, CO2 emissions, and digitalization in BRICS countries during the period 2000–2017, using the GMM-PVAR methodology for their analysis. The results demonstrate that digitalization plays a crucial role in promoting renewable energy, thus facilitating the transition to clean energy and reducing carbon emissions. In their study, Haseeb, et al. (2019) examined the influence of ICT on environmental quality in BRICS countries between 1994 and 2014. They used DSUR to analyze the data and found that both digitalization and GDP have a mitigating effect on CO2, leading to an improvement in environmental quality. Zhao, et al. (2022) conducted a study to evaluate the impact of digitalization on pollution and energy efficiency in growing Asian economies between 1990 and 2019, using the ARDL-PMG model for their analysis. Evidence shows that digitalization has a mitigating effect on carbon emissions and improves energy efficiency over an extended period. Aldakhil, et al. (2019) examined the impact of digitalization, advanced technologies, and growth-specific factors on CO2 emissions in South Asia between 1975 and 2016. The findings suggest that digitalization and research development (RD) have a substantial impact on reducing CO2 emissions. However, an increase in CO2 emissions is observed when considering ICT exports and added industrial value. Furthermore, the interaction effect of ICT and RD leads to an increase in carbon emissions. Haini (2021) investigated the impact of digitalization and human capital on carbon dioxide (CO2) emissions in ASEAN economies between 1996 and 2019. Data indicate that digitalization has a mitigating effect on CO2 emissions, but human capital has a leading effect on CO2 emissions. The influence of digitalization and human capital on environmental performance and green growth in China from 1990 to 2019 was also investigated by Chen, Sohail and Yang (2022). The results indicate that ICT has a long-term effect in decreasing CO2 emissions and fostering environmentally sustainable economic growth. On the other hand, education has a long-term effect of reducing CO2 emissions, but it does not have a major impact on green growth.

Furthermore, several studies have suggested that the digitalization process may have adverse effects on environmental quality. These effects are mainly due to various factors, such as increased pollutants emissions (Amri, 2018), a shortage in energy efficiency in ICT goods and services (Lee and Brahmasrene, 2014; Arshad, Robaina and Botelho, 2020; Ramzan et al., 2022), the extended life cycle of ICT products and the subsequent increase in production and consumption (Thanh, et al., 2022), and a decrease in the adoption of environmentally friendly information and communication technologies (Park, Meng and Baloch, 2018). Magazzino et al. (2021) investigated the correlation between digitalization, electricity usage, economic expansion, and environmental contamination in 16 EU economies spanning the years 1990 to 2017. The findings suggest the presence of a unidirectional causal relationship between digitalization and electricity use, leading to an increase in CO2 emissions. In their study, Imran, et al. (2021) examined the correlation between digitalization, poverty alleviation, and ecological deterioration in Pakistan during the period 1975 to 2018 using the ARDL model. The findings indicate that digitalization facilitates poverty alleviation while also exacerbating CO2 emissions. This implies that the promotion of environmentally friendly ICT infrastructure could lead to the achievement of poverty reduction and environmental sustainability goals. Zeeshan, et al. (2022) examined the correlation between digitalization, renewable energy use, and environmental quality in six South-East Asian countries spanning the years 2000 to 2018. The results suggest that digitalization leads to environmental degradation, while renewable energy improves environmental quality. Chang, Taghizadeh-Hesary and Saydaliev (2022) obtained comparable results in 10 developed countries between 1990 and 2019, while Batool et al. (2022) reached similar results in 10 developing economies in East and South Asia between 1985 and 2020.

2. Research Methodology

2.1. Data

The main objective of our quantitative analysis is to investigate the impact of digitalization on net greenhouse gas (GHG) emissions in 27 European countries. The explained variable is net GHG emissions (CO2 tons per capita) GHGE, and the main independent variables are individuals using the Internet (% of the population) - INT and mobile cellular subscriptions (per 100 people) - MOB. The control variables are GDP per capita (constant 2015 US$) - GDP, industry value added (% of GDP) - IND, ICT trade (% of total goods) - ICT, and gross domestic expenditure on RD by sector (% of GDP) - RD. All variables were used in the form of natural logarithms.

The 27 countries of the European Union and a period of 21 years (2000–2020) were included in our panel, except for renewable energy consumption, whose period of 20 years (2000–2019). The sources of our data are Eurostat and the World Bank.

2.2. Methods

The econometric procedure involved two steps:

a) *applying panel unit root tests*. The results of the first generation of panel unit root tests (based on the cross-sectional independence hypothesis and the null hypothesis of nonstationarity) were then verified with the second generation of tests (based on the cross-sectional dependency hypothesis and the hypothesis of a factor structure) (Hurlin and Mignon, 2007). According to the tests, all variables were used in the models as I(0).

b) *applying a Period SUR Panel Corrected Standard Error (PS-PCSE) model* (Beck and Katz estimator) to deal with heteroskedasticity and with temporal and spatial dependence in the residuals (Hoechle, 2007).

The benchmark regressions are as follows:

$$lnGHGE_{i,t} = \alpha + \beta_1 lnINT_{i,t} + \beta_2 lnGDP_{i,t} + \beta_3 lnICT_{i,t} + \beta_4 lnIND_{i,t} + \beta_5 lnRD_{i,t} + u_{i,t} \quad (1)$$

$$lnGHGE_{i,t} = \alpha + \beta_1 lnMOB_{i,t} + \beta_2 lnGDP_{i,t} + \beta_3 lnICT_{i,t} + \beta_4 lnIND_{i,t} + \beta_5 lnRD_{i,t} + u_{i,t} \quad (2)$$

3. Results and Discussion

Table 1 displays the direct effect of digitalization on net greenhouse gas emissions (columns M1-M3 for the INT variable and columns M4-M6 for the MOB variable). The results of the traditional panel models: mixed effects (OLS) and random effects (RE) are subjects of columns M1 and M2 for the INT variable and M4 and M5 for the MOB variable. The results of the PS-PCSE specification (columns M3 and M6) are further interpreted, bearing in mind that they deal with heteroskedasticity and with temporal and spatial dependence in the residuals. It should be noted that all three models (OLS, FE, and PS-PCSE) lead to convergent conclusions.

Table no. 1. The results of the benchmark models

Methods	**OLS**	**RE**	**PS-PCSE**	**OLS**	**RE**	**PS-PCSE**
Model	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
lnINT	-0.120***	-0.051*	-0.110***	-	-	-
lnMOB	-	-	-	-0.021	0.001	-0.023*
lnGDP	0.568***	0.402***	0.526***	0.557***	0.309***	0.533***
lnICT	0.097***	0.271***	0.087***	0.094***	0.279***	0.090***
lnIND	0.174*	0.141	0.175***	0.226**	0.200*	0.220***
lnRD	-0.223***	-0.033	-0.178***	-0.265***	-0.051	-0.215***
C	-3.887***	-2.874***	-3.427***	-4.299***	-2.356***	-3.986***
R-squared	0.273	0.203	0.662	0.262	0.198	0.663
Hausman test	-	4.700 (0.539)	-	-	4.715 (0.452)	-
Pesaran CD Test	-	-	1.389 (0.165)	-	-	1.429 (0.153)
Cross sections	27	27	27	27	27	27
Period	2000-2020	2000-2020	2000-2020	2000-2020	2000-2020	2000-2020

*Notes: *** and ** denote statistical significance at 1% and 5%, respectively.*

Source: Our processing using Eurostat and World Bank Data

With a confidence level of 99%, there is a significant negative correlation between INT and GHGE. This means that an increase of 1% in internet access leads to a 0.110% decrease in net greenhouse gas emissions. According to Huang, et al. (2022), it can be inferred that the member states of the European Union have achieved a state of saturation in terms of Internet penetration. The Internet, which encompasses various aspects such as e-services, e-government, e-business, remote work, and online meetings, exhibits low energy intensity and mitigates the need for transportation. Consequently, this has resulted in the conservation of energy and fossil fuels, as well as the reduction of carbon dioxide (CO_2) emissions. The results align with the findings of Haldar and Sethi (2022) in 16 developing economies, Ozcan and Apergis

(2018) in 20 developing countries, and Lin and Zhou (2021) in China. In contrast, our findings are in opposition to the findings of Park, Meng and Baloch (2018) in European countries, as well as Batool, et al. (2022) in ten developing countries spanning East Asia and South Asia. In contrast, the association between MOB and GHGE, while exhibiting a negative relationship, is found to be statistically weak and lacks statistical significance at the 95% confidence level. Research and development efforts, which encompass digital transformation and the use of green and efficient technology, are primarily focused on improving environmental quality. The findings of Nguyen, Pham and Tram (2020) in their study on 13 selected G-20 nations and Ganda (2019) on selected OECD countries indicate that a 1% increase in RD spending leads to a decrease in net greenhouse gas emissions by 0.178% and 0.215%, respectively. However, ICT trade and IND contribute to the increase in greenhouse gas (GHG) emissions in the six models, suggesting that EU members are not sufficiently engaged in trading and adopting clean and energy-efficient technology. Evans and Mesagan (2022) achieved similar results in Africa, while Aldakhil, et al. (2019) achieved similar results in South Asia. All six models find a positive impact of GDP on greenhouse gas emissions. This implies that income growth can result in higher emissions due to the development of industrial production and increased energy consumption (Chien, et al., 2021). Furthermore, EU economies have not yet disrupted the positive relationship between development and pollution (Guaita Martínez, et al., 2022).

To improve understanding of the influence of digitalization on pollution, a heterogeneity analysis was performed by grouping the countries of the European Union into two distinct panels based on their respective levels of pollution. There are 13 countries in the European Union (EU) that fall under the category of above-average polluters (AAP). These countries, namely Austria, Belgium, Cyprus, Czechia, Denmark, Estonia, Finland, Germany, Greece, Ireland, Luxembourg, the Netherlands and Poland, exhibited annual average greenhouse gas (GHG) emissions (measured in CO2 tons per capita) that exceeded the average emissions of the group of 27 EU countries during the analyzed period. There are 14 countries in the European Union (EU) that fall below the average polluter (BAP) category. These countries, namely Bulgaria, Croatia, France, Hungary, Italy, Latvia, Lithuania, Malta, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden, exhibited annual average greenhouse gas (GHG) emissions (measured in CO2 tons per capita) that were lower than the average emissions of the group of 27 EU countries during the analyzed period. The direct impact of digitalization on net greenhouse gas emissions is presented in Table 2, with columns M7 and M8 representing below average polluters and columns M9 and M10 representing above average polluters.

Table no. 2. Heterogeneity analysis

Groups	Below-average polluters -BAP		Above-average polluters AAP	
Model	M7	M8	M9	M10
lnINT	-0.083***	-	-0.087***	-
lnMOB	-	0.066***	-	-0.048***
lnGDP	0.224***	0.175***	0.361***	0.357***
lnICT	0.019***	0.026***	0.198***	0.199***
lnIND	0.180***	0.220***	-0.086***	-0.062***
lnRD	-0.179***	-0.192***	-0.203***	-0.233***
C	-0.753***	-1.036***	-1.068***	-1.229***
R-squared	0.846	0.914	0.994	0.990
Pesaran CD Test	0.525 (0.600)	-0.139 (0.900)	0.112 (0.911)	-0.079 (0.937)
Cross sections	14	14	13	13
Period	2000-2020	2000-2020	2000-2020	2000-2020

Source: Our processing using Eurostat and World Bank Data

The findings of the heterogeneity analysis align with the results observed throughout the European Union, indicating a negative correlation between digitalization and net greenhouse gas (GHG) emissions when digitalization is quantified using the INT variable. Findings become inconclusive when digitization is examined from the perspective of the MOB variable. In BAP countries, a 1% increase in mobile cellular subscriptions causes pollution to increase by approximately 0.07%, like Haldar and Sethi (2022) in 16 emerging countries, while in AAP countries, a 1% increase in mobile cellular subscriptions leads to a 0.05% decrease in pollution, consistent with Danish (2019) in 59 Belt and Road economies. The primary determinant of the reduction of pollution, both directly and indirectly through the encouragement of renewable energy consumption, is unquestionably the gross domestic expenditure on renewable development (RD), as supported by Khan and Ximei (2022). The impact of the industrial sector on greenhouse gas (GHG) emissions is more pronounced in AAP countries than in other countries. Research and innovation efforts in clean technology, energy efficiency, and renewable energy may be responsible for the negative association between the industrial sector and greenhouse gas emissions. The results align with the findings of Chen and Lei (2018) in economies that have comparatively higher levels of CO2 emissions.

Conclusions

The study examines the direct impact of digitalization and other factors that promote economic growth on net greenhouse gas (GHG) emissions. It uses data from cross-country panels from EU countries spanning the years 2000 to 2020. PS-PCSE specifications with period SUR weights have been used for this purpose. The findings indicate that the implementation of digitalization has the potential to effectively mitigate net greenhouse gas (GHG) emissions. This implies that the integration of digitalization with clean energy sources, environmentally sustainable innovations, and low carbon technologies is crucial to achieving a reduction in GHG emissions. The allocation of economic resources towards the advancement of digitalization and research and development has the potential to enhance the structure of energy consumption in favor of renewable sources, thus alleviating the adverse impacts of economic expansion on environmental degradation. If countries can improve their contribution to the promotion of renewable energy consumption, ICT trade can play a crucial role in reducing pollution. Furthermore, the findings of the heterogeneity study indicate the existence of variations between member states of the European Union in terms of the influence of digitalization on pollution.

Based on the aforementioned findings, it is possible to integrate some policy recommendations into the policy framework for countries in the European Union that face challenges in the realm of pollution control. First, it is essential for government officials to establish a favorable environment for digitalization and innovation by implementing regulations and a well-defined strategic framework. Furthermore, considering the diverse impact of digitalization on greenhouse gas (GHG) emissions, it is important for governments to adopt digital policies, programs, and initiatives that correspond to their specific economic activities and the intricate nature of their businesses.

References

Aldakhil, A.M., Zaheer, A., Younas, S., Nassani, A.A., Abro, M.M.Q. and Zaman, K., 2019. Efficiently managing green information and communication technologies, high-technology exports, and research and development expenditures: A case study. *Journal of Cleaner Production*, 240, p.118164. https://doi.org/10.1016/j.jclepro.2019.118164.

Amri, F., 2018. Carbon dioxide emissions, total factor productivity, ICT, trade, financial development, and energy consumption: testing environmental Kuznets curve hypothesis for Tunisia. *Environmental Science and Pollution Research*, 25(33), pp.33691–33701. https://doi.org/10.1007/s11356-018-3331-1.

Arshad, Z., Robaina, M. and Botelho, A., 2020. The role of ICT in energy consumption and environment: an empirical investigation of Asian economies with cluster analysis. *Environmental Science and Pollution Research*, 27(26), pp.32913–32932. https://doi.org/10.1007/s11356-020-09229-7.

Batool, Z., Raza, S.M.F., Ali, S. and Abidin, S.Z.U., 2022. ICT, renewable energy, financial development, and CO2 emissions in developing countries of East and South Asia. *Environmental Science and Pollution Research*, 29(23), pp.35025–35035. https://doi.org/10.1007/s11356-022-18664-7.

Bieser, J.C.T., Hintemann, R., Hilty, L.M. and Beucker, S., 2023. A review of assessments of the greenhouse gas footprint and abatement potential of information and communication technology. *Environmental Impact Assessment Review*, 99(March 2023), p.107033. https://doi.org/10.1016/j.eiar.2022.107033.

Chang, L., Taghizadeh-Hesary, F. and Saydaliev, H.B., 2022. How do ICT and renewable energy impact sustainable development? *Renewable Energy*, 199(November 2022), pp.123–131. https://doi.org/10.1016/j.renene.2022.08.082.

Chen, S., Sohail, M.T. and Yang, M., 2022. Examining the effects of information and communications technology on green growth and environmental performance, socio-economic and environmental cost of technology generation: A pathway toward environment sustainability. *Frontiers in Psychology*, 13(September 2022), pp. 999045. https://doi.org/10.3389/fpsyg.2022.999045.

Chen, W. and Lei, Y., 2018. The impacts of renewable energy and technological innovation on environment-energy-growth nexus: New evidence from a panel quantile regression. *Renewable Energy*, 123(August 2018), pp.1–14. https://doi.org/10.1016/j.renene.2018.02.026.

Chien, F., Anwar, A., Hsu, C.C., Sharif, A., Razzaq, A. and Sinha, A., 2021. The role of information and communication technology in encountering environmental degradation: Proposing an SDG framework for the BRICS countries. *Technology in Society*, 65(March), p.101587. https://doi.org/10.1016/j.techsoc.2021.101587.

Danish, 2019. Effects of information and communication technology and real income on CO2 emissions: The experience of countries along Belt and Road. *Telematics and Informatics*, 45(September 2019), p.101300. https://doi.org/10.1016/j.tele.2019.101300.

European Commission, 2023. *Rolling Plan for ICT standardisation*. [online] Available at: <https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/ict-environmental-impact-0> [Accessed 29 April 2023].

Evans, O. and Mesagan, E.P., 2022. ICT-trade and pollution in Africa: Do governance and regulation matter? *Journal of Policy Modeling*, 44(3), pp.511–531. https://doi.org/10.1016/j.jpolmod.2022.06.003.

Ganda, F., 2019. The impact of innovation and technology investments on carbon emissions in selected organisation for economic Co-operation and development countries. *Journal of Cleaner Production*, 217, pp.469–483. https://doi.org/10.1016/j.jclepro.2019.01.235.

Guaita Martínez, J.M., Puertas, R., Martín Martín, J.M. and Ribeiro-Soriano, D., 2022. Digitalization, innovation and environmental policies aimed at achieving sustainable production. *Sustainable Production and Consumption*, 32, pp.92–100. https://doi.org/10.1016/j.spc.2022.03.035.

Ha, L.T., 2022. Are digital business and digital public services a driver for better energy security? Evidence from a European sample. *Environmental Science and Pollution Research*, 29(18), pp.27232–27256. https://doi.org/10.1007/s11356-021-17843-2.

Haini, H., 2021. Examining the impact of ICT, human capital and carbon emissions: Evidence from the ASEAN economies. *International Economics*, 166(March), pp.116–125. https://doi.org/10.1016/j.inteco.2021.03.003.

Haldar, A. and Sethi, N., 2022. Environmental effects of Information and Communication Technology - Exploring the roles of renewable energy, innovation, trade and financial development. *Renewable and Sustainable Energy Reviews*, 153(January 2022), p.111754. https://doi.org/10.1016/j.rser.2021.111754.

Haseeb, A., Xia, E., Saud, S., Ahmad, A. and Khurshid, H., 2019. Does information and communication technologies improve environmental quality in the era of globalization? An empirical analysis. *Environmental Science and Pollution Research*, 26(9), pp.8594–8608. https://doi.org/10.1007/s11356-019-04296-x.

Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M. and Wäger, P.A., 2006. The relevance of information and communication technologies for environmental sustainability - A prospective simulation study. *Environmental Modelling and Software*, 21(11), pp.1618–1629. https://doi.org/10.1016/j.envsoft.2006.05.007.

Hoechle, D., 2007. Robust standard errors for panel regressions with cross-sectional dependence. *Stata Journal*, 7(3), pp.281–312. https://doi.org/10.1177/1536867x0700700301.

Huang, Y., Haseeb, M., Usman, M. and Ozturk, I., 2022. Dynamic association between ICT, renewable energy, economic complexity and ecological footprint: Is there any difference between E-7 (developing) and G-7 (developed) countries? *Technology in Society*, 68(August 2021), p.101853. https://doi.org/10.1016/j.techsoc.2021.101853.

Hurlin, C. and Mignon, V., 2007. *Second Generation Panel Unit Root Tests*. halshs-00159842. [online] Available at: <https://halshs.archives-ouvertes.fr/halshs-00159842>.

Imran, M., Khan, K.B., Zaman, K., Musah, M.B., Sudiapermana, E., Aziz, A.R.A., Embong, R., Hassan, Z. Bin, Jabor, M.K. and Anis, S.N.M., 2021. Achieving pro-poor growth and environmental sustainability agenda through information technologies: as right as rain. *Environmental Science and Pollution Research*, 28(30), pp.41000–41015. https://doi.org/10.1007/s11356-021-13630-1.

Irfan, M., Chen, Z., Adebayo, T.S. and Al-Faryan, M.A.S., 2022. Socio-economic and technological drivers of sustainability and resources management: Demonstrating the role of information and communications technology and financial development using advanced wavelet coherence approach. *Resources Policy*, 79(October), p.103038. https://doi.org/10.1016/j.resourpol.2022.103038.

Khan, A. and Ximei, W., 2022. Digital Economy and Environmental Sustainability: Do Information Communication and Technology (ICT) and Economic Complexity Matter? *International Journal of Environmental Research and Public Health*, 19(19). https://doi.org/10.3390/ijerph191912301.

Lange, S., Pohl, J. and Santarius, T., 2020. Digitalization and energy consumption. Does ICT reduce energy demand? *Ecological Economics*, 176(June), p.106760. https://doi.org/10.1016/j.ecolecon.2020.106760.

Lee, J.W. and Brahmasrene, T., 2014. ICT, CO2 Emissions and Economic Growth: Evidence from a Panel of ASEAN. *Global Economic Review*, 43(2), pp.93–109. https://doi.org/10.1080/1226508X.2014.917803.

Lin, B. and Zhou, Y., 2021. Does the Internet development affect energy and carbon emission performance? *Sustainable Production and Consumption*, 28, pp.1–10. https://doi.org/10.1016/j.spc.2021.03.016.

Lundén, D., Malmodin, J., Bergmark, P. and Lövehagen, N., 2022. Electricity Consumption and Operational Carbon Emissions of European Telecom Network Operators. *Sustainability*, 14(5), pp.1–27. https://doi.org/10.3390/su14052637.

Magazzino, C., Porrini, D., Fusco, G. and Schneider, N., 2021. Investigating the link among ICT, electricity consumption, air pollution, and economic growth in EU countries. *Energy Sources, Part B: Economics, Planning and Policy*, 16(11–12), pp.976–998. https://doi.org/10.1080/15567249.2020.1868622.

Maier, D., Maftei, M., Irmer, S.-J. and Golowko, N., 2016. Challenges regarding innovation management in the current global competition. In: D. Popescu, ed. *2016 International Conference on Production Research - Regional Conference Africa, Europe and the Middle East (ICPR-AEM 2016) and 4th International Conference on Quality and Innovation in Engineering and Management (QIEM 2016)*. Technical Univ Cluj-Napoca. pp.157–161.

Malmodin, J. and Bergmark, P., 2015. Exploring the effect of ICT solutions on GHG emissions in 2030. In: *Proceedings of EnviroInfo and ICT for Sustainability 2015*. Paris: Atlantis Press. pp.37–46. https://doi.org/10.2991/ict4s-env-15.2015.5.

Nguyen, T.T., Pham, T.A.T. and Tram, H.T.X., 2020. Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries. *Journal of Environmental Management*, 261(March), p.110162. https://doi.org/10.1016/j.jenvman.2020.110162.

Ozcan, B. and Apergis, N., 2018. The impact of internet use on air pollution: Evidence from emerging countries. *Environmental Science and Pollution Research*, 25(5), pp.4174–4189. https://doi.org/10.1007/s11356-017-0825-1.

Park, Y., Meng, F. and Baloch, M.A., 2018. The effect of ICT, financial development, growth, and trade openness on CO2 emissions: an empirical analysis. *Environmental Science and Pollution Research*, 25(30), pp.30708–30719. https://doi.org/10.1007/s11356-018-3108-6.

Pohl, J., Hilty, L.M. and Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher order effects of ICT application : A review of different approaches. *Journal of Cleaner Production*,] 219, pp.698–712. https://doi.org/10.1016/j.jclepro.2019.02.018.

Ramzan, M., Raza, S.A., Usman, M., Sharma, G.D. and Iqbal, H.A., 2022. Environmental cost of non-renewable energy and economic progress: Do ICT and financial development mitigate some burden? *Journal of Cleaner Production*, [online] 333(December 2021), p.130066. https://doi.org/10.1016/j.jclepro.2021.130066.

Thanh, T.T., Ha, L.T., Dung, H.P. and Huong, T.T.L., 2022. *Impacts of digitalization on energy security: evidence from European countries. Environment, Development and Sustainability*. 25, pp.11599–11644. https://doi.org/10.1007/s10668-022-02545-7.

Tzeremes, P., Dogan, E. and Alavijeh, N.K., 2023. Analyzing the nexus between energy transition, environment and ICT: A step towards COP26 targets. *Journal of Environmental Management*, 326(PA), p.116598. https://doi.org/10.1016/j.jenvman.2022.116598.

Vasilescu, M.D., Dimian, G.C. and Gradinaru, G.I., 2023. Green entrepreneurship in challenging times: a quantitative approach for European countries. *Economic Research-Ekonomska Istrazivanja* , 36(1), pp.1828–1847. https://doi.org/10.1080/1331677X.2022.2093767.

Zeeshan, M., Han, J., Rehman, A., Ullah, I. and Mubashir, M., 2022. Exploring the Role of Information Communication Technology and Renewable Energy in Environmental Quality of South-East Asian Emerging Economies. *Frontiers in Environmental Science*, 10(June), pp.1–11. https://doi.org/10.3389/fenvs.2022.917468.

Zhang, X., Shi, X., Khan, Y., Hassan, T. and Marie, M., 2023. Carbon Neutrality Challenge: Analyse the Role of Energy Productivity, Renewable Energy, and Collaboration in Climate Mitigation Technology in OECD Economies. *Sustainability*, 15(4). https://doi.org/10.3390/su15043447.

Zhao, S., Hafeez, M., Faisal, C.M.N., Muhammad, C. and Faisal, N., 2022. Does ICT diffusion lead to energy efficiency and environmental sustainability in emerging Asian economies? *Environmental Science and Pollution Research*, 29(8), pp.12198–12207. https://doi.org/10.1007/s11356-021-16560-0.