Examining the Influence of Digitalization and Innovation on Improving Energy Structure toward Renewables. Evidence from the European Union

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Abstract

The article investigates the effects of digitalization and innovation on energy consumption and structure in the 27 countries of the European Union during 2000–2023. This article uses the Autoregressive Distributed Lag (ARDL) model to test the influence of the level of digitalization and the potential for innovation on energy consumption (primary, final, and renewable) while controlling for certain factors expected to have a significant impact on energy consumption (economic development and structure, prices, and trade dynamics). The results indicate that in the long run, both the level of digitalization and the innovation potential influence energy consumption. However, these drivers have the most significant and straightforward impact on the energy structure by increasing the share of renewable energy in final consumption. Additionally, ICT exports, economic structural changes, and inflation boost renewable energy shares. The study includes factors specific to the situation of the EU in the empirical analysis, such as investments in research and development and ICT exports and imports, to determine their role in the balance of the energy market. These results imply that EU economies should implement and enhance innovation, research and development, and education policies to facilitate the transition to clean energy. Additionally, EU nations should regard ICT trade as crucial in their green energy policies.

Keywords

Digitalization, innovation, ICT trade, energy consumption and structure, renewable energy, research and development.

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Introduction

The European Union is restructuring its power industry, which is expected to emerge in the next few years and become its primary focal point. The energy and climate policies and the European Union (EU) packages aim to make Europe the first continent to achieve climate neutrality. The EU will accomplish this by ensuring energy security, reducing carbon emissions, promoting energy efficiency, achieving a fully integrated internal market, and promoting research and innovation (European Commission, 2022; European Parliament, 2022). Russian foreign policy actions propelled the entire concept, which originated from the aspiration to convert Europe into a continent with zero emissions by utilizing gas as a temporary resource. During a crucial period, Europe must seek resolutions to ensure reliable supply and promote progress in renewable energy sources.

Undeniably, the field of study is not resistant to opposing findings. This is why, further comprehensive analysis centered on various countries are essential to grasp the extent of market transformation. The

European Union's energy consumption accounts for 75% of its emissions is constituting an important factor in establishing sustainable economic development and growth. Digitalization advancement has a direct impact on energy consumption by facilitating the growth of information and communication technology (ICT) infrastructure, devices, and data traffic (Salahuddin and Alam, 2015). The impact of digitalization and innovation on energy consumption and renewable energy consumption (REN) is significant. This influence is primarily attributed to their effects on energy intensity, energy efficiency, changes in economic structure, and economic growth. These effects are facilitated by technological innovation, green technologies, digital transformation, and the presence of a highly skilled labor force (Wang, et al., 2022; Akram, et al., 2023; Zhou, et al., 2023). The expansion of innovation and digitalization has been found to improve energy efficiency and lower energy intensity, leading to a subsequent decrease in energy consumption (Ishida, 2015; Xu, et al., 2022). It is widely recognized that energy efficiency plays a crucial role as an initial measure in reducing energy consumption (Husaini and Lean, 2022). Furthermore, the use of digitalization and innovation mechanisms fosters the generation of renewable resources and the implementation of carbon capture and storage technologies.

Given the context mentioned above, the objective of our study is to examine the influence of digitalization and innovation on energy consumption and energy structure, specifically the proportion of renewable energy consumption in overall energy consumption in the European Union. The role of energy consumption in economic growth is of utmost importance, as it serves as a crucial input for the production of commodities and services that are strongly associated with industrialization, technological advancement, and overall economic development. Therefore, our paper presents two novel ideas:

1. Its analysis focuses on the European Union as a distinct case study, as it diverges from other countries or groups of countries in two key aspects. Firstly, the European Union adopts a policy that prioritizes the equilibrium of the energy market. Second, it proposes solutions that prioritize investments in research and innovation.
2. Drawing from the latest findings in the field of energy research, this study incorporates elements of its empirical examination that are unique to the European Union (EU). These factors include investments in research and development, as well as in the export and import of information and communication technologies. The objective is to determine to what extent these factors contribute to the equilibrium of the energy market.

The paper is organized into five distinct sections. The first section provides a comprehensive analysis of the selected subject matter. The following section presents a comprehensive examination of the existing body of literature related to empirical investigations on the effects of digitalization and innovation on energy consumption, energy structure, and sustainable economic development. The third section delineates the methods employed for estimation and the sources of data used. The fourth section covers an analysis of empirical findings. The final part of the article presents several policy implications and recommendations.

1. Literature review

Due to the rapid advancement of digitalization, numerous scholarly investigations have focused on examining the correlation between digitalization and energy usage. The existing body of research has identified a variety of significant impacts of digitalization on energy consumption. These include both direct and indirect effects arising from the production, usage, and disposal of information and communication technologies (Xu, Zhong and Li, 2022). Additionally, there are substitution and income effects associated with digitalization (Takase and Murota, 2004; Khayyat, et al., 2016), as well as effects on environmental quality (Hilty, et al., 2006). Furthermore, studies have found that digitalization has growth and sectoral effects (Salahuddin and Alam, 2016; Lange, et al., 2020). The impact of digitalization on energy usage might vary, with both advantageous and disadvantageous outcomes contingent on the manner in which it is managed, applied, and used (Bergman and Foxon, 2023).

Many studies have substantiated the advantageous impacts of digitalization on energy consumption. In their research, Xu, et al. (2022) used SYS-GMM and mediating effect models to look at the global effects of digitalization on energy and how these effects work. The results validate that the digitization has the capacity to decrease energy intensity and consumption while simultaneously enhancing energy structure. Husaini and Lean (2022) used the CS-ARDL technique to investigate the influence of digitalization on energy consumption in five ASEAN countries. The findings of the study suggest that digitization leads to a reduction in energy usage over time, both in general and from specific sources. Furthermore, Ishida (2015) assesses the long-lasting correlation between digitalization, energy consumption, and economic

growth in Japan employing the ARDL-bound testing methodology. The results indicate that the digital transformation of enterprises and public domains leads to a decrease in primary energy consumption, energy intensity, and carbon dioxide emissions.

The primary factor contributing to the rise in energy consumption during digital transformation is the substantial growth in the quantity and utilization of ICT devices, together with the corresponding infrastructure (Bergman and Foxon, 2023). Ren, et al. (2021) conducted a study that examined the relationship between internet advancement and energy consumption in China. The results emphasize that digitalization has a favorable effect on the extent of energy consumption and a negative effect on the structure and power of energy consumption. Salahuddin and Alam (2015; 2016) analyzing the link between digitization and power usage in Australia and the OECD countries. The observations resulted indicate that the long-term impact of digitalization on electricity use has not yet identified the foreseen advantages of its expansion. Bildirici, et al. (2022) explored, in a recent study, the correlation between digitalization, energy intensity, economic growth, carbon dioxide (CO2) emissions, and energy consumption within the G7 nations. The observations indicate a one-way causal relationship from digitalization to energy consumption, furthermore from CO2 emissions to digitalization and energy efficiency.

In the transition to sustainable energy, digitalization and innovation play a crucial role (Xu, Zhong and Li, 2022). The energy structure can be optimized by integrating wind and solar power as renewable energy sources and green technology into the energy system having as result an improved environmental quality and reduced dependence on fossil fuels. In addition, the green transition can be enabled by different factors, including innovations, technical advancements, and structural changes within the economy (Khurshid, et al., 2022). The digitalization process has the prospective to facilitate the dematerialization of economic sectors, promote innovation in the energy sector, and provide intelligent solutions to energy-related challenges (Dehghan Shabani and Shahnazi, 2019). Moreover, digitalization advancement of the countries can be propelled by an increase in renewable energy consumption (Thanh, et al., 2023). In addition, advances in data storage, processing, and dissemination resulting from digitalization have a beneficial impact on the advancement of renewable energy technology through research and development efforts. Most studies have indicated that digitalization and innovation have positive impacts on the consumption of renewable energy. Akram, et al. (2023) investigated the impact of digitalization on the use of renewable energy and the promotion of green growth in five polluting economies. The findings suggest that the Internet has a positive impact on the use of renewable energy and the promotion of green growth, both in the short and long term.

As an element of eco innovation, energy innovation, has an impact on renewable energy adoption by the development of renewable energy technologies and inventions (Wiebe, 2016). Technological boosts have the potential to enhance energy use efficiency and eliminate the toxic emissions (Wang and Wang, 2020). In their research, Solarin, et al. (2022) observed and analyzed the effects of technical innovation on green growth. Their results suggested a substantial positive relationship between renewable energy innovation and renewable energy production. Irandoust (2018) conducted a study based on the four Nordic countries to investigate the direct causal relationship between technical innovation and renewable energy. The results of his study emphasize that innovation influences the use of renewable energy and, ultimately, stimulates innovation. Moreover, other researches have pointed out that RD significantly improves environmental quality in the long term, exceeding its short-term effects (Dogan and Pata, 2022). This is the result of its decisive role in the development of the renewable energy technologies and building infrastructure (Khoshnevis Yazdi and Shakouri, 2017).

2. Research Methodology

This study employed the Auto-Regressive Distributed Lag (ARDL) model to investigate the factors influencing energy consumption. The ARDL model integrates the features of two dynamic models: AR (auto regressive) and DL (distributed lag), allowing to find among the explanatory variables (X_t) the lagged dependent variable (Y_{t-p}) and the past values of the independent variable (X_{t-p}). The general structure of an ARDL model is outlined as follows.

$$Y_t = \varphi + \sum_{i=1}^{p} a_i Y_{t-i} + \sum_{j=0}^{q} b_j X_{t-j} + e_t \qquad (1)$$

where $e_t \sim iid\ (0, \sigma)$.

The ARDL model makes it possible to estimate the short-run dynamics and the long-run effects for cointegrated series or even integrated at different orders (Pesaran, et al., 1997; Pesaran and Shin, 1999). Cointegration between series assumes the existence of one or more long-run equilibrium relations between them, which relations can be combined with the short-run dynamics of these series in an error-correction model. Therefore, the following specification presents the ARDL model, in the form of an ECM or a VEC, which presumes the presence of a cointegration relationship between series:

$$\Delta Y_t = \sum_{i=1}^{p-1} \alpha_i \Delta Y_{t-i} + \sum_{j=0}^{q-1} \beta_j \Delta X_{t-j} + \varphi[Y_{t-1} - (\pi_0 + \pi_1 X_{t-1})] + e_t \quad (2)$$

where α and β indicate the short-run coefficients linked to the lagged dependent variable and the explanatory variables, while π signifies the long-run coefficients, and φ represents the pace of adjustment towards the long-run equilibrium (Samargandi, Fidrmuc and Ghosh, 2014).

In this study, the dependent variable is primary and final energy consumption (PEN and FEN), measured in tons of oil equivalent (TOE) per capita, representing the scale of energy consumption, and the share of renewable energy consumption to total final energy consumption (REN), representing the structure of energy consumption. Explanatory variables include digitalization, innovation, economic development, and ICT trade. Digitalization is estimated through internet users (% of population) (INT) and mobile cellular subscriptions (per 100 people) (MOB). Innovation potential is assessed through RD expenditures (% GDP) and the share of the population aged 25-34 who have completed tertiary studies (TED). ICT goods trade (exports/imports as % of total goods exports/imports), respectively, ICTEX and ICTIM, is evidence of innovation potential and digitalization. GDP per capita (constant 2015 US$) and inflation (annual consumer price index%) (INF) are used to evaluate economic development. The ratio of services to industry value added (GVAS), the proxy of economic structure, also known as the upgrading of the industrial structure, reflects the switch from traditional industries with low efficiency and value added to knowledge-intensive or technology-intensive industries with high efficiency and value added. Data sources are World Development Indicators (World Bank, 2025) and Eurostat (European Commission, 2025).

3. Results and Discussion

Table no. 1 reports the results of the ARDL model for primary energy consumption (PEN), final energy consumption (FEN), and renewable energy consumption (REN). It is worth mentioning that the error correction coefficients are negative and highly significant (-0.088 for both PEN and FEN and -0.125 for REN). The highest speed of adjustment towards the long-run equilibrium is exhibited by REN, with 12.5% of the equilibrium error corrected in each period.

In the long run, both the level of digitalization and the innovation potential will have a significant impact on energy consumption. The most important factors proved to be INT and RD, with significant coefficients at a confidence level of 99%. INT has a significant negative effect both on primary energy consumption and final energy consumption, similar to the results of Salahuddin and Alam (2016), Ren, et al. (2021), Bildirici, et al. (2022), but in contrast to Dehghan Shabani and Shahnazi (2019), Husaini and Lean (2022), yet a significant positive effect on energy structure toward increasing the share of renewable energy consumption in final energy consumption, in line with Xu, et al. (2022), Akram, et al. (2023) and Zhou, et al. (2023). RD exhibits a significant positive effect on all three dependent variables (primary, final, and renewable consumption). It should be noted that REN is the most responsive to an increase in gross domestic expenditure on RD (with an influence coefficient of 0.305), consistent with Kocsis and Kiss (2014), Bano, et al. (2022), and Wu and Song (2023). These findings suggest that digitalization and innovation stimulate the deployment of renewable energy, consistent with Geng and Ji (2016) and Irandoust (2018). Therefore, technological factors have an important contribution to the energy transition in addition to economic and environmental factors (Tzeremes, Dogan and Alavijeh, 2023), with product and process innovation being important determinants in the adoption of energy efficiency technologies (Gerstlberger, et al., 2016).

Table no. 1. ARDL Estimation

Dependent Variable	D(lnPEN)	D(lnFEN)	D(lnREN)
Long-run estimation			
lnINT	-0.545*** (-6.694)	-0.542*** (-7.818)	0.506*** (5.118)
lnMOB	-0.152 (-1.623)	0.179** (2.590)	0.426*** (3.945)
lnRD	0.209*** (4.856)	0.124*** (3.720)	0.305*** (3.401)
lnTED	0.131** (2.050)	0.186*** (3.253)	0.190** (2.224)
lnGDP	0.643*** (16.281)	0.495*** (19.825)	-0.673*** (-7.554)
lnINF	-0.668*** (-6.534)	-0.760*** (-10.250)	1.387*** (7.884)
lnGVAS	0.002 (0.039)	0.210*** (5.140)	0.343*** (2.924)
lnICTEX	-0.027 (-0.525)	0.014 (0.387)	0.621*** (6.904)
lnICTIM	0.188** (1.977)	0.037 (0.547)	-1.242*** (-9.986)
Short-run estimation			
Cointeq	-0.088*** (-3.160	-0.088** (-2.192)	-0.125*** (-5.088)
D(lnINT)	-0.021 (-0.516)	0.030 (1.023)	-0.064 (-0.533)
D(lnMOB)	-0.075 (-1.291)	-0.065* (-1.739)	0.020 (0.155)
D(lnRD)	-0.056 (-0.805)	-0.024 (-0.424)	0.023 (0.156)
D(lnTED)	0.060 (0.843)	0.023 (0.342)	-0.544*** (-4.070)
D(lnGDP)	0.579*** (7.841)	0.686*** (7.954)	-0.648 (-1.627)
D(lnINF)	0.448** (2.582)	0.488*** (2.792)	-0.131 (-0.175)
D(lnGVAS)	-0.011 (-0.107)	0.077 (1.246)	-0.106 (-0.470)
D(lnICTEX)	-0.046 (-1.319	-0.045 (-1.474)	-0.031 (-0.280)
D(lnICTIM)	0.051*** (1.033)	0.076* (1.940)	0.079 (0.641)

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

Source: Our processing using Eurostat and World Bank Data

INF has the expected influence on PEN, FEN and REN (a negative impact on primary and energy consumption and a positive impact on the energy structure to increase the share of renewable energy), with the highest influence coefficient exhibited in relation to REN (1.387), in line with Wang, et al. (2023). The level of economic development increases energy consumption and has a negative impact on the energy structure toward renewable energy, consistent with Camacho Ballesta, et al. (2022), but in contrast to Saint Akadiri, et al. (2019), Asiedu, et al. (2021), Polcyn, et al. (2022) and Saint Wu and Song (2023), suggesting that the EU has not yet been able to overcome the negative relationship between GDP and sustainability, despite the positive impact of digitalization, innovation, and environmental policies (Guaita Martínez, et al., 2022). However, the results of the study by Komarnicka and Murawska (2021) and Pejović, et al. (2021) reveal that there is no significant correlation between the level of economic development of EU countries and the share of renewable energy in total and by economic sector. Structural changes in the direction of increasing the ratio of services/industry have the opposite effect and are conducive to expanding the proportion of renewable energy (a positive significant influence coefficient of 0.343), consistent with Ren, et al. (2021).

Conclusions

The aim of this paper is to examine the impact of digitalization and innovation on the EU energy market. The current energy context in the EU must be explored due to its ambition to reduce the dependency on Russian gas and accelerate the transition to green energy. The added value of our paper is given by the holistic view of EU policy that tries to concentrate significant investments in the RD in the energy field by REPowerEU. This paper also introduces a comprehensive evaluation of the specific factors that shape energy consumption and its structure in the EU. Our main results back up recent research that points out that digitalization has a positive effect on the structure of the energy market (it is changing towards renewables) and lowering energy use. Similar findings from other studies emphasize that the positive impact depends on the application of digitalization. Thus, in the EU, the impact of digitalization is obvious in favor of reducing energy consumption and increasing renewables in the consumption structure, which is supported by EU policy investment. Our results indicate that long-term EU energy policy will lead not only to a significant decrease in overall consumption but also to a significant increase in the energy consumption structure of renewables. Even if there is not much to negotiate when speaking of decreasing energy consumption because it is directly related to economic growth (although price evolution has also had a significant impact on consumption), an improved production structure based on increasing renewable share is possible, the latest being sensitive to a larger number of factors: digitalization, innovation, industry upgrades, and technological progress.

These conclusions lead to some policy implications for achieving EU objectives. The European Union can reduce energy consumption through digitalization if it concentrates investments and research in this direction, respectively, in the green technological advance. Given the strong link to economic growth, it is unlikely that energy consumption will be reduced radically. However, our results indicate that investing in research and development will eventually increase the share of renewable energy. Our findings on the influence of ICT trade on energy further substantiate this. Exports demonstrate a significant positive impact on the share of renewable energy in final energy consumption, whereas a significant negative impact on the energy structure results from a lagging innovation that requires imports.

The current study also has some limitations. This study focuses on the impact of digitalization and innovation at the regional level in EU countries, ignoring country-wise analysis; however, the impact may be considerably different in other economies worldwide due to their different economic characteristics. Future research should extend the scope of analysis to include a broader range of economies, allowing for cross-country comparisons. Because digitalization and renewable energy consumption are relatively new issues, data collection has been limited to the use of the internet and mobile to measure digitalization in the last two decades. Future studies could use modern measures for digitalization such as robots, IoT, and artificial intelligence. Furthermore, a larger data collection can increase the study model's broadness.

References

Saint Akadiri, S., Alola, A.A., Akadiri, A.C. and Alola, U.V., 2019. Renewable energy consumption in the EU-28 countries: Policy toward pollution mitigation and economic sustainability. *Energy Policy*, 132(June), pp.803–810. https://doi.org/10.1016/j.enpol.2019.06.040.

Akram, M.W., Ahmed, D., Trunina, A., Hamid, K. and Hafeez, M., 2023. How do financial fragility and ICT penetration affect renewable energy consumption and green growth in top-polluting economies? *Environmental Science and Pollution Research*, 30(13), pp.38810–38818. https://doi.org/10.1007/s11356-022-24978-3.

Asiedu, B.A., Hassan, A.A. and Bein, M.A., 2021. Renewable energy, non-renewable energy, and economic growth: evidence from 26 European countries. *Environmental Science and Pollution Research*, 28(9), pp.11119–11128. https://doi.org/10.1007/s11356-020-11186-0.

Bano, S., Liu, L. and Khan, A., 2022. Dynamic influence of aging, industrial innovations, and ICT on tourism development and renewable energy consumption in BRICS economies. *Renewable Energy*, 192, pp.431–442. https://doi.org/10.1016/j.renene.2022.04.134.

Bergman, N. and Foxon, T.J., 2023. Drivers and effects of digitalization on energy demand in low-carbon scenarios. *Climate Policy*, 23(3), pp.329–342. https://doi.org/10.1080/14693062.2022.2145260.

Bildirici, M.E., Castanho, R.A., Kayıkçı, F. and Genç, S.Y., 2022. ICT, Energy Intensity, and CO2 Emission Nexus. *Energies*, 15(13), pp.1–15. https://doi.org/10.3390/en15134567.

Camacho Ballesta, J.A., da Silva Almeida, L. and Rodríguez, M., 2022. An analysis of the main driving factors of renewable energy consumption in the European Union. *Environmental Science and Pollution Research*, 29(23), pp.35110–35123. https://doi.org/10.1007/s11356-022-18715-z.

Dehghan Shabani, Z. and Shahnazi, R., 2019. Energy consumption, carbon dioxide emissions, information and communications technology, and gross domestic product in Iranian economic sectors: A panel causality analysis. *Energy*, 169, pp.1064–1078. https://doi.org/10.1016/j.energy.2018.11.062.

Dogan, A. and Pata, U.K., 2022. The role of ICT, R&D spending and renewable energy consumption on environmental quality: Testing the LCC hypothesis for G7 countries. *Journal of Cleaner Production*, 380(P1), p.135038. https://doi.org/10.1016/j.jclepro.2022.135038.

European Commission, 2022. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. REPowerEU Plan COM(2022) 230 final*. [online] Available at: < https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230&from=EN > [Accessed 8 April 2025].

European Commission, 2025. *Eurostat*. [online] Available at: < https://ec.europa.eu/eurostat/web/main/data/database > [Accessed 8 April 2025].

European Parliament, 2022. *Resolution of 14 September 2022. Amendments adopted by the European Parliament on 14 September 2022 on the proposal for a directive of the European Parliament and of the Council on energy efficiency (recast) (COM(2021)0558 – C9-0330/2021 – 2021/0203(COD))*. [online] Available at: < https://www.europarl.europa.eu/doceo/document/TA-9-2022-0315_EN.html > [Accessed 8 April 2025].

Geng, J.-B. and Ji, Q., 2016. Technological innovation and renewable energy development: Evidence based on patent counts. *International Journal of Global Environmental Issues*, 15(3), pp.217–234. https://doi.org/10.1504/IJGENVI.2016.076945.

Gerstlberger, W., Knudsen, M.P., Dachs, B. and Schröter, M., 2016. Closing the energy-efficiency technology gap in European firms? Innovation and adoption of energy efficiency technologies. *Journal of Engineering and Technology Management - JET-M*, 40(2016), pp.87–100. https://doi.org/10.1016/j.jengtecman.2016.04.004.

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.

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.

Husaini, D.H. and Lean, H.H., 2022. Digitalization and Energy Sustainability in ASEAN. *Resources, Conservation and Recycling*, 184(April), p.106377. https://doi.org/10.1016/j.resconrec.2022.106377.

Irandoust, M., 2018. Innovations and renewables in the Nordic countries: A panel causality approach. *Technology in Society*, 54, pp.87–92. https://doi.org/10.1016/j.techsoc.2018.03.007.

Ishida, H., 2015. The effect of ICT development on economic growth and energy consumption in Japan. *Telematics and Informatics*, 32(1), pp.79–88. https://doi.org/10.1016/j.tele.2014.04.003.

Khayyat, N.T., Lee, J. and Heo, E., 2016. How ICT investment influences energy demand in South Korea and Japan. *Energy Efficiency*, 9(2), pp.563–589. https://doi.org/10.1007/s12053-015-9384-9.

Khoshnevis Yazdi, S. and Shakouri, B., 2017. Renewable energy, nonrenewable energy consumption, and economic growth. *Energy Sources, Part B: Economics, Planning and Policy*, 12(12), pp.1038–1045. https://doi.org/10.1080/15567249.2017.1316795.

Khurshid, A., Rauf, A., Calin, A.C., Qayyum, S., Mian, A.H., Qayyum, S. and Fatima, T., 2022. Property rights in the carbon mitigation efforts. Evidence from western and Technological innovations for environmental protection : role of intellectual property rights in the carbon mitigation efforts. Evidence from western and southern Europe. *International Journal of Environmental Science and Technology*, 19(5), pp.3919–3934. https://doi.org/10.1007/s13762-021-03491-z.

Kocsis, I. and Kiss, J.T., 2014. Renewable energy consumption, R&D and GDP in European Union countries. *Environmental Engineering and Management Journal*, 13(11), pp.2825–2830. https://doi.org/10.30638/eemj.2014.316.

Komarnicka, A. and Murawska, A., 2021. Comparison of consumption and renewable sources of energy in european union countries—sectoral indicators, economic conditions and environmental impacts. *Energies*, 14(12), pp.1–24. https://doi.org/10.3390/en14123714.

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.

Pejović, B., Karadžić, V., Dragašević, Z. and Backović, T., 2021. Economic growth, energy consumption and CO2 emissions in the countries of the European Union and the Western Balkans. *Energy Reports*, 7, pp.2775–2783. https://doi.org/10.1016/j.egyr.2021.05.011.

Pesaran, M.H. and Shin, Y., 1999. An Autoregressive Distributed-Lag Modelling Approach to Cointegration Analysis. In: S. Strom, ed. *Econometrics and Economic Theory in the 20th Century*. [online] Cambridge: Cambridge University Press. pp.371–413. https://doi.org/10.1017/CCOL521633230.011.

Pesaran, M.H., Shin, Y. and Smith, R., 1997. Pooled Estimation of Long-run Relationships in Dynamic Heterogeneous Panels. *Department of Applied Economics University of Cambridge*. [online] Available at: < https://econpapers.repec.org/RePEc:cam:camdae:9721 > [Accessed 10 March 2025].

Polcyn, J., Us, Y., Lyulyov, O., Pimonenko, T. and Kwilinski, A., 2022. Factors influencing the renewable energy consumption in selected european countries. *Energies*, 15(1), pp.1–27. https://doi.org/10.3390/en15010108.

Ren, S., Hao, Y., Xu, L., Wu, H. and Ba, N., 2021. Digitalization and energy: How does internet development affect China's energy consumption? *Energy Economics*, 98, p.105220. https://doi.org/10.1016/j.eneco.2021.105220.

Salahuddin, M. and Alam, K., 2015. Internet usage, electricity consumption and economic growth in Australia: A time series evidence. *Telematics and Informatics*, 32(4), pp.862–878. https://doi.org/10.1016/j.tele.2015.04.011.

Salahuddin, M. and Alam, K., 2016. Information and Communication Technology, electricity consumption and economic growth in OECD countries: A panel data analysis. *International Journal of Electrical Power and Energy Systems*, 76, pp.185–193. https://doi.org/10.1016/j.ijepes.2015.11.005.

Samargandi, N., Fidrmuc, J. and Ghosh, S., 2014. Is the Relationship Between Financial Development and Economic Growth Monotonic? Evidence from a Sample of Middle-Income Countries. *Cesifo Working Paper No. 4743*. https://doi.org/10.1016/j.worlddev.2014.11.010.

Solarin, S.A., Bello, M.O. and Tiwari, A.K., 2022. The impact of technological innovation on renewable energy production: accounting for the roles of economic and environmental factors using a method of moments quantile regression. *Heliyon*, 8(7), p.e09913. https://doi.org/10.1016/j.heliyon.2022.e09913.

Takase, K. and Murota, Y., 2004. The impact of IT investment on energy: Japan and US comparison in 2010. *Energy Policy*, 32(11), pp.1291–1301. https://doi.org/10.1016/S0301-4215(03)00097-1.

Thanh, T.T., Ha, L.T., Dung, H.P. and Huong, T.T.L., 2023. 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.

Wang, H. and Wang, M., 2020. Science of the Total Environment Effects of technological innovation on energy efficiency in China : Evidence from dynamic panel of 284 cities. *Science of the Total Environment*, 709(360), p.136172. https://doi.org/10.1016/j.scitotenv.2019.136172.

Wang, L., Huang, Y., Ghafoor, A., Hafeez, M. and Salahodjaev, R., 2023. Asymmetric macroeconomic determinants of renewable energy consumption: do financial institutions and ICT trade matter? *Environmental Science and Pollution Research*, 30(4), pp.9841–9851. https://doi.org/10.1007/s11356-022-22816-0.

Wang, Z., Le Hoa Pham, T., Wang, B., Hashemizadeh, A., Bui, Q. and Nawarathna, C.L.K., 2022. The simultaneous impact of education and financial development on renewable energy consumption: an investigation of Next-11 countries. *Environmental Science and Pollution Research*, 29(56), pp.85492–85509. https://doi.org/10.1007/s11356-022-21330-7.

Wiebe, K.S., 2016. The impact of renewable energy diffusion on European consumption-based emissions†. *Economic Systems Research*, 28(2), pp.133–150. https://doi.org/10.1080/09535314.2015.1113936.

World Bank, 2025. *WDI, World Development Indicators*. [online] Available at: < https://databank.worldbank.org/source/world-development-indicators > [Accessed 11 March 2025].

Wu, D. and Song, W., 2023. Does green finance and ICT matter for sustainable development: role of government expenditure and renewable energy investment. *Environmental Science and Pollution Research*, 30(13), pp.36422–36438. https://doi.org/10.1007/s11356-022-24649-3.

Xu, Q., Zhong, M. and Li, X., 2022. How does digitalization affect energy? International evidence. *Energy Economics*, 107(March), p.105879. https://doi.org/10.1016/j.eneco.2022.105879.

Zhou, Y., Liu, Z., Wang, M., Dong, R.K. and Yue, X.G., 2023. Evaluating the impacts of education and digitalization on renewable energy demand behaviour: new evidence from Japan. *Economic Research-Ekonomska Istrazivanja*, 36(3), p.2164033. https://doi.org/10.1080/1331677X.2022.2164033.