



## **DIGITALIZATION AND ENERGY INDICATORS IN THE EUROPEAN UNION**

**Rūta Nedzinskienė<sup>1</sup>, Neringa Lušaitė<sup>1</sup>, Egidijus Nedzinskas<sup>2</sup>**

<sup>1</sup>*Kaunas University of Technology*, <sup>2</sup>*Lithuania Business College*

### **Abstract**

Digitalization is increasingly recognized as a key driver of energy efficiency, renewable energy development, and the decarbonization of energy systems. Artificial intelligence, the Internet of Things, big data analytics, smart grids, and digital twins contribute to more efficient energy generation, transmission, and consumption while enhancing resource management and reducing operational costs. Nevertheless, significant differences remain among the EU Member States regarding their levels of digitalization, energy efficiency, renewable energy deployment, and greenhouse gas emissions. Assessing these differences is essential for designing effective policies that support both the digital and green transitions. The aim of this study is to develop the multidimensional measurement framework and to assess the EU Member states according to their digitalization, energy, and emissions performance. The analysis is based on the Eurostat data covering the period from 2010 to 2023. This study examines digitalization, energy and environmental sustainability in the 27 European Union Member States using the Eurostat data for 2010–2023. Principal component analysis was employed to reduce the dimensionality of the selected indicators and identify the key underlying dimensions, while hierarchical cluster analysis was applied to classify countries according to their digital, energy, and environmental characteristics. The four composite indicators were developed: energy intensity, renewable energy, digital innovation capacity, and digital business. EU Member States were classified into four groups with distinct development profiles. The Leaders cluster demonstrates the highest levels of digitalization and innovation capacity, while the Followers are characterized by strong digital business performance and highly developed economies. The Moderate group exhibits intermediate levels of technological and environmental performance, whereas the Modest group consists mainly of countries with comparatively lower digital innovation capacity and digital business development. The main contribution of this study is the development of a multidimensional framework integrating digitalization, energy, and environmental indicators to evaluate country's performance and identify policy priorities. This analysis can help identify areas requiring improvement and support policy decisions aimed at maximizing the benefits of digital transformation for energy efficiency, penetration of renewables and environmental sustainability in separate countries and the whole region. The proposed framework offers a comprehensive approach for benchmarking EU Member States, identifying strengths and weaknesses, and supporting evidence-based policymaking aimed at accelerating digital transformation, improving energy efficiency, expanding renewable energy deployment, and achieving the European Union's climate neutrality and sustainable development objectives.

**KEY WORDS:** Digitalization; Energy efficiency; Renewable energy; Sustainability; Principal component analysis; Cluster analysis; European Union.

**JEL classification:** O33 ; Q40 ; Q53

### **Introduction**

The European Union has established the ambitious objectives of reducing greenhouse gas emissions, improving energy efficiency, increasing the share of renewable energy, and promoting the digital transformation of the economy. These goals are in line with United Nations 2030 Agenda for Sustainable Development, the Paris Agreement, the European Green Deal, and the EU climate and energy framework.

A growing body of literature suggests that digital technologies can contribute significantly to improving energy efficiency and reducing GHG emissions. Intelligent energy management systems, smart grids, predictive maintenance, and data-driven optimization facilitate more efficient energy production, transmission, and consumption while reducing energy losses and operational costs (Pakulska & Poniatowska-Jaksch, 2022; Fu et al., 2024; Jiang et al., 2024). Empirical studies have demonstrated that digitalization can reduce energy consumption and energy intensity while improving energy efficiency and supporting the decarbonization of energy systems (Xu et al., 2022; Huang et al., 2023; Song et al., 2023). Furthermore, digital technologies enhance the integration of renewable energy sources by improving forecasting accuracy, facilitating energy storage solutions, and supporting decentralized energy systems (Olabi et al.,

2023; Wang & Xu, 2022; Kong et al., 2024). Digitalization also plays an important role in reducing greenhouse gas emissions. Higher levels of digitalization have been associated with increased renewable energy deployment, improved energy productivity, and lower carbon intensity of economic activities (Hao et al., 2023; Józwick et al., 2023; Li et al., 2025). However, the use of digital technologies requires substantial energy resources. As a result, efficiency gains may be partly offset by increased energy demand and production (Tang, 2024; Peng et al., 2024; Matthess et al., 2023). Consequently, the overall impact of digitalization on sustainability remains an important area of academic and policy debate.

This issue is particularly relevant within the European Union because Member States differ considerably in their economic structures, technological capabilities, energy systems, innovation potential, and stages of the low-carbon transition. Despite operating within a common EU policy framework, countries demonstrate different levels of energy efficiency, dependence on fossil fuels, renewable energy deployment, digital infrastructure, adoption of digital technologies by businesses, and innovation capacity. As a result, progress in one dimension does not necessarily correspond to similar progress in another. A country with advanced digital capabilities may still exhibit relatively high energy consumption or greenhouse gas emissions, whereas comparatively low emissions in another country may partly reflect differences

in economic development or industrial structure rather than superior environmental performance. This heterogeneity limits the usefulness of evaluating the EU transition solely through individual indicators. Therefore, it is essential to assess the EU member States position and progress within the European Union according to digitalization and energy system.

The multidimensional nature of digital and energy transformations requires an integrated assessment framework. Separate energy and digitalization indicators show fragmented information and make it difficult to identify broader development patterns across Member States. Thus, a multidimensional approach is needed that can provide a more comprehensive understanding of how digital and energy characteristics are related and how countries differ in their transition pathways.

Therefore, the aim of this study is to develop the multidimensional measurement framework and to assess the EU Member states position and progress according to their digitalization, energy, and emissions performance. This analysis can help identify areas requiring improvement and support policy decisions aimed at maximizing the benefits of digital transformation for energy efficiency, penetration of renewables and environmental sustainability in separate countries and the whole region.

To achieve this objective, Principal Component Analysis is applied to identify the key dimensions underlying the selected indicators, while hierarchical cluster analysis is used to classify countries according to their digital, energy, and environmental characteristics. The investigation covers 27 EU Member States and uses Eurostat data for the period 2010 – 2023. The study contributes to the literature by providing a multidimensional assessment of EU countries and by identifying their strengths and weaknesses in the context of digital and sustainable development.

The remainder of the article is structured as follows: 1) Theoretical Background section discusses the relationships between digitalization, energy efficiency, renewable energy development, and greenhouse gas emissions, providing the conceptual basis for the multidimensional assessment applied in this study; 2) Methodology section describes the selection of indicators and data, as well as the application of principal component analysis and hierarchical cluster analysis; 3) Results section presents the construction and interpretation of the composite indicators and examines the classification of EU Member States according to their digitalization, energy, and environmental performance; 4) Conclusions section summarizes the main findings and contributions of the study, discusses its limitations, and outlines directions for future research.

## Theoretical Background

Digitalization has become an important factor in the transition toward more efficient and sustainable energy systems. Artificial intelligence, the Internet of Things, machine learning, big data analytics, smart grids, and Digital Twins improve the monitoring, forecasting, and management of energy systems, enhancing their safety, reliability, and operational efficiency (Pakulska &

Poniatowska-Jaksch, 2022; El Zein & Gebresenbet, 2024; Kong et al., 2024). By enabling real time data collection, analysis, and automated decision making, these technologies can improve energy generation, distribution, and consumption.

Energy efficiency is also crucial for companies as they are increasingly becoming more sustainable and environmentally conscious. To achieve both cost reduction and sustainability digital technologies play a huge role. Andrei & Johnsson (2025) highlight that companies which use technologies for energy efficiency report that advanced digital technologies assist in cost reduction and achieving energy and operational efficiency as collected data gives opportunity to monitor and analyse the processes and make data-based decisions. Thus, the contribution of digitalization to energy efficiency is not limited to the automation of individual processes. Access to detailed information can improve managerial decision making by allowing firms to identify inefficient operations, compare alternative production scenarios, and allocate energy resources more effectively. For example, Internet of Things (IoT), by observing and collecting energy usage and price information in real time, might give insights regarding anomalous facts (Reichardt et al., 2025). This information assists in solving problems and searching for optimal processes. Digital twins also might contribute to large scale in reducing energy consumption for companies in different sectors. Digital twins collect all real time data and reports in real time which helps management to control workflows, which lead to lower energy consumption (Geng et al., 2026). Digital twins collect data by sensors themselves and become more autonomous and advance at each step. By having the digital twin with current date companies can test scenarios and start process optimization. Prompter decisions can be made using renewable energy, enhancing process flexibility (Mandry et al., 2025). Cloud computing, Artificial Intelligence and other digital technologies also assist in energy efficiency for companies. Guan et al. (2025) have found that companies which are using digital technologies can significantly decrease their energy intensity compared to other firms. Lower energy intensity implies that firms can potentially generate greater economic value from a given amount of energy, strengthening both their economic and environmental performance.

Through intelligent energy management, predictive maintenance, fault detection, and optimized resource allocation, digital technologies facilitate more efficient energy generation, transmission, distribution, and consumption while reducing energy losses and operational costs (Jiang et al., 2024; Fu et al., 2024; Lukianenko & Simakhova, 2024). This demonstrates that the influence of digitalization extends across the entire energy value chain. Empirical evidence supports these benefits. An analysis of 109 countries found that a 1% increase in digitalization reduces energy consumption by 0.015%, decreases energy intensity by 0.016%, and improves the energy structure by 0.008% (Xu et al., 2022). Similarly, Huang et al. (2023) reported that a 0.01 increase in the digital economy index reduced energy intensity by 0.5%, while Song et al. (2023)

found that a one-percentage-point increase in the size of the digital economy increased energy efficiency by approximately 14.65 percentage points. Furthermore, a one-unit increase in digitalization within the electricity sector was associated with a reduction of 5.6041 units in the carbon intensity of electricity generation (Huang & Lin, 2023). This finding is particularly important from an environmental perspective because it indicates that digitalization may contribute not only to lower energy consumption but also to cleaner energy production.

Digital technologies also play a crucial role in supporting renewable energy deployment and integration. They improve the forecasting accuracy of wind and solar energy production, facilitate the integration of intermittent renewable energy sources with storage systems, and enhance the efficiency of decentralized energy systems such as microgrids and rooftop solar installations (Olabi et al., 2023; Wang & Xu, 2022; Kong et al., 2024). By reducing generation costs, increasing energy productivity, and optimizing energy flows, digitalization accelerates the transition from fossil fuel-based energy production to cleaner energy sources (Xie & Wang, 2023; Campana et al., 2025). It is to notice that digitalization and renewable energy development may reinforce each other. Digital capabilities facilitate renewable energy integration, while increasing renewable energy penetration creates additional demand for forecasting, monitoring, optimization, and other digital solutions.

Consequently, higher levels of digitalization are generally associated with lower energy intensity, greater renewable energy adoption, reduced greenhouse gas emissions, and more sustainable economic development (Hao et al., 2023; Jóźwik et al., 2023; Li et al., 2025). The nexus between them provides an important theoretical basis for considering digitalization, energy efficiency and GHG emissions within a common analytical framework. However, it cannot be stated as evidence that digitalization automatically improves environmental performance.

The use of digital technologies requires substantial energy and resources. Data centres, communication networks, cloud services, as well as other digital tools increase electricity demand. Also, improvements energy efficiency reduces energy cost and consequently stimulate additional production and consumption. As a result, efficiency gains may be partly offset by increased energy demand and production (Tang, 2024; Peng et al., 2024; Matthess et al., 2023). It is to notice that reductions in energy intensity do not necessarily result in proportional reductions in total energy consumption. These potentially opposing effects make the relationship between digitalization and environmental sustainability more complex.

The multidimensional nature of both digitalization and energy provides a theoretical justification for an integrated assessment of EU Member States. This assessment can help to identify whether countries demonstrating strong digital performance also achieve favourable energy and environmental outcomes. Therefore, it is extremely important to determine appropriate assessment indicators

and evaluate the digitalization and energy efficiency situation across EU Member States. This provides the theoretical foundation for the multidimensional assessment framework applied in the following sections.

## Methodology

Principal component analysis was used to empirically group the indicators according to the area they represent and to reduce the dimensionality of data (Mendoza-Mendoza et al., 2025). The orthogonal Varimax method was used for this purpose as it maximizes the variance of squared loadings across each component, thus facilitating a more straightforward and comprehensible factor configuration where each variable is inclined to exhibit substantial loadings on a singular factor while demonstrating minimal loadings on alternative factors. Before starting the analysis, we have examined the individual Measure of Sampling Adequacy (MSA) for each variable to indicate if a variable is suitable for the factor analysis, i.e. if its measure is greater than 0.5. Next, we have examined the overall Kaiser's Measure of Sampling Adequacy with a threshold of 0.6 to test if the entire data set is appropriate for applying factor analysis. Furthermore, we have calculated the communalities that indicate how much of the variance in each variable is explained by the common factors found in the data. We followed the rule that factors must explain at least half of the variance in individual variables (i.e., the factors obtained explain >50% of the variance in each statement). To determine the number of factors suitable for retention, an assessment of the eigenvalues derived from the correlation matrix was conducted. In accordance with the Kaiser criterion, only those factors exhibiting eigenvalues exceeding 1 were retained for subsequent analysis. Also, the proportion of the total variance of the variables explained by the factors must be at least 50%. The rotated factor loadings (in absolute values) equal or greater than 0.70 were considered very strong, 0.50 – 0.69 moderate, and 0.30 – 0.49 weak but still meaningful (Hair et al., 2019).

Cluster analysis was conducted to classify European Union countries according to their digitalization indicators, energy efficiency, renewable energy and GHG emissions. The categorization of countries into separate groups, along with the comparative assessment of their analysed indicators, can help to conduct the comparisons between the groups and within the group countries and to find out the strong and weak areas of a country, which must be in the major attention of policymakers. Hierarchical cluster analysis method was employed for the investigation as the number of countries' groups was not known in advance. The execution of hierarchical cluster analysis entailed the following principal stages (Nedzinskiene & Streimikiene, 2024): 1) identification of objects for examination, 2) establishment of a variable set, 3) computation of distance metrics, 4) classification of selected objects in accordance with the linkage rule, 5) generation of a dendrogram, 6) evaluation of the findings. Following these steps, the 27 EU countries were investigated. The initial as well as composite indicators developed in PCA analysis were used for cluster analysis. The most recent data provided by Eurostat was employed

for analytical computations, while the min-max normalization technique was applied to standardize the indicators. The Euclidean distance metric and Ward's amalgamation algorithm, which aims to minimize variance within clusters, were chosen for analysis. A dendrogram was created, which delineates the degree of similarity at which any two clusters were merged and illustrates the classification of objects. The classification results were analysed and lead to the comparisons of most important indicators between the counties.

27 EU Member States were selected for the investigation. The period from 2010 to 2023 year was used

as reflecting the most recent situation in EU countries. Data before 2010 were not included in the analysis because digitalization is a rapidly changing phenomenon, and older observations may not accurately reflect current patterns of digital development. The indicators for the investigation were selected according to our previous study (Nedzinskienė et al., 2025) as the created Path model in that study has revealed the most important ones in the nexus between digitalization, energy and emissions. These indicators and their main statistical characteristics for 2023 year are presented in Table 1.

**Table 1.** The main indicators and their statistical characteristics for 2023

| Indicator                                                           | Measure                                    | Mean   | Std Dev | Min   | Max    |
|---------------------------------------------------------------------|--------------------------------------------|--------|---------|-------|--------|
| <b>GHG emissions</b>                                                |                                            |        |         |       |        |
| GHG (Domestic net greenhouse gas emissions per capita)              | Tonnes per capita                          | 6.68   | 2.45    | 1.20  | 11.10  |
| <b>Energy efficiency</b>                                            |                                            |        |         |       |        |
| Energy productivity (the ratio of GDP to total energy consumption). | Euro per kilogram of oil equivalent (KGOE) | 9.01   | 4.89    | 2.94  | 26.16  |
| Primary Energy consumption per capita                               | Tonnes of oil equivalent (TOE) per capita  | 2.82   | 0.96    | 1.57  | 5.61   |
| Gross electricity production / GDP                                  | Kilogram of oil equivalent / Eur           | 0.02   | 0.01    | 0.00  | 0.04   |
| Final electricity consumption / GDP                                 | kWh/Euro                                   | 0.17   | 0.06    | 0.06  | 0.33   |
| Residential electricity consumption / GDP                           | kWh/Euro                                   | 0.05   | 0.02    | 0.01  | 0.13   |
| <b>Renewable Energy</b>                                             |                                            |        |         |       |        |
| Share of renewable energy consumption                               | Percentage                                 | 27.22  | 13.01   | 14.36 | 66.39  |
| Share of fossil fuels in gross available energy                     | Percentage                                 | 68.12  | 15.38   | 30.37 | 96.17  |
| <b>Digitalization</b>                                               |                                            |        |         |       |        |
| Level of internet access by households                              | Percentage of households                   | 93.05  | 3.00    | 86.90 | 99.06  |
| Employed ICT specialists                                            | Percentage of total employment             | 5.09   | 1.49    | 2.40  | 8.70   |
| Total number of people receiving education                          | Persons per capita                         | 0.21   | 0.03    | 0.16  | 0.27   |
| Business enterprise R&D expenditure in high-tech sectors            | Percentage of gross domestic product (GDP) | 1.15   | 0.71    | 0.28  | 2.70   |
| Enterprises with a website                                          | Percentage of enterprises                  | 76.06  | 12.60   | 49.85 | 98.27  |
| Social media                                                        | Percentage of enterprises                  | 63.12  | 14.06   | 38.04 | 87.14  |
| Cloud / Cloud Computing Utilization                                 | Percentage of enterprises                  | 46.81  | 16.46   | 17.50 | 78.29  |
| Enterprises with e-commerce trading activities                      | Percentage of enterprises                  | 24.99  | 7.75    | 12.92 | 38.89  |
| Number of patent applications                                       | Per million inhabitants                    | 147.17 | 168.44  | 2.21  | 513.19 |
| Persons employed in science and technology                          | Persons per capita                         | 0.17   | 0.04    | 0.10  | 0.28   |

## Results

Principal component analysis was performed separately to Energy (energy efficiency and renewable energy) indicators as well as digitalization indicators.

Energy indicators. Before conducting the research, we have examined if a variable is suitable for the factor analysis. The individual MSA for each variable was

calculated and the ones with a measure lower than 0.5. were excluded. In the case of energy indicators only the indicator Primary energy consumption with MSA value 0.413 was excluded as it did not fit well for factor analysis. Therefore, this indicator was left as individual one for further analysis. Principal component analysis was performed using the data of all the rest of the energy indicators.

The obtained the overall MSA value 0.746 exceeded the threshold of 0.6 meaning that the proportion of total variance explained by the variables was greater than 0.6, also the Bartlett's null hypothesis that the indicators are not correlated with each other was rejected ( $p < 0.001$ ). Therefore, this confirmed that the analysed data are suitable for factor analysis. We found that the communalities for all items were much greater than 0.5 meaning that the factors obtained explain >50% of the variance in each statement around its mean.

Using eigenvalues for values greater than one, we found that the indicators form 2 factors that explain 85.68% of the variance in the scale indicators. Table 2 presents the rotated component matrix. The loadings of all indicators are very strong, indicating strong correlations between the observed variables and the extracted components.

**Table 2.** Rotated component matrix for energy indicators

| Indicators                                          | Component |       |
|-----------------------------------------------------|-----------|-------|
|                                                     | 1         | 2     |
| Final electricity consumption / GDP                 | .940      | .269  |
| Residential electricity consumption / GDP           | .902      | .267  |
| Gross electricity production / GDP                  | .890      | .294  |
| Energy productivity (GDP/ total energy consumption. | -.806     | .111  |
| Share of renewable energy consumption               | .072      | .936  |
| Share of fossil fuels in gross available energy     | -.239     | -.906 |

The first factor includes Final energy consumption/GDP, Residential electricity consumption/GDP, Gross electricity consumption/GDP indicators with a positive sign of loadings and Energy productivity (the ratio of GDP to total energy consumption) indicator with a negative sign of loading that have the opposite meaning than the other indicators. Higher values of energy productivity indicate more efficient energy use and lower energy intensity, while higher values of the remaining indicators reflect greater energy consumption relative to economic output. Consequently, this factor may be interpreted as representing energy intensity, where higher factor values indicate a more energy-intensive economic structure and lower overall energy efficiency, therefore, it can be called the factor of Energy intensity.

The second factor includes indicators of the Share of energy consumption (with a positive sign) and the Share of fossil fuels in gross available energy (with a negative sign). The opposite signs of these loadings reflect the inverse relationship between renewable and fossil energy sources. Specifically, higher shares of renewable energy are associated with lower dependence on fossil fuels, therefore it clearly represents the factor of Renewable energy.

Digitalization indicators. All the indicators of digitalization were suitable for factor analysis as the individual MSA for each variable was higher than 0.5. The obtained the overall MSA value 0.841 proved a high proportion of total variance explained by the variables, also the Bartlett's null hypothesis that the indicators are not correlated with each other was rejected ( $p < 0.001$ ). We have also found that the communalities for all items were greater than 0.5. Using eigenvalues for values greater than one, we found that 2 factors can be created that explain 74.44% of the variance in the scale indicators. Although the loadings of all indicators were moderate to strong, the indicator Total number of people receiving education was grouped to the factor of digital business activities. First such grouping was lacking theoretical background and second, it is a very important indicator showing the level of education in the country, so we decided to exclude it from PCA analysis and keep as individual indicator for further comparison of countries performance. The PCA analysis was run with all the rest of digitalization indicators and even better results were obtained as with very similar other measures, the newly created 2 factors explained 77.10% of the variance in the scale indicators. The loadings of all indicators were moderate to very strong (Table 3).

**Table 3.** Rotated component matrix for digitalization indicators

| Indicators                                               | Component |      |
|----------------------------------------------------------|-----------|------|
|                                                          | 1         | 2    |
| Level of internet access by households                   | .826      | .197 |
| Employed ICT specialists                                 | .835      | .348 |
| Business enterprise R&D expenditure in high-tech sectors | .410      | .593 |
| Enterprises with a website                               | .624      | .678 |
| Social media                                             | .536      | .649 |
| Cloud / Cloud Computing Utilization                      | .420      | .736 |
| Enterprises with e-commerce trading activities           | .046      | .914 |
| Number of patent applications                            | .876      | .340 |
| Persons employed in science and technology               | .900      | .271 |

The first factor includes Level of internet access by households, Employed ICT specialists, Number of patent applications, Persons employed in science and technology indicators and can be called Digital innovation capacity. This component reflects the technological and innovation capacity of a country, including digital infrastructure, ICT-related human capital, scientific potential, and innovation output. High factor loadings show that countries with higher values of these indicators tend to demonstrate greater digital innovation capacity. As Business enterprise R&D expenditure in high-tech sectors, has high loadings in both factors it can also be assigned to the first one because of it shows the level of innovation more than the adoption of digital solutions in companies.

The second factor includes business related indicators: Enterprises with a website, Use of social media, Cloud / Cloud Computing Utilization, Enterprises with e-commerce trading activities, thus, it can be named Digital business factor. This component represents the practical adoption and integration of digital technologies in business activities. It captures the extent to which enterprises use digital tools, online platforms, cloud technologies, and e-commerce solutions in their operations.

Final list of indicators. It is to summarize that PCA analysis revealed 2 composite energy and 2 digitalization indicators. These composite indicators together with the initial ones that are also very important for the analysis will be used for further investigation. The indicators and their interpretations are provided in Table 4.

**Table 4.** The final list of indicators

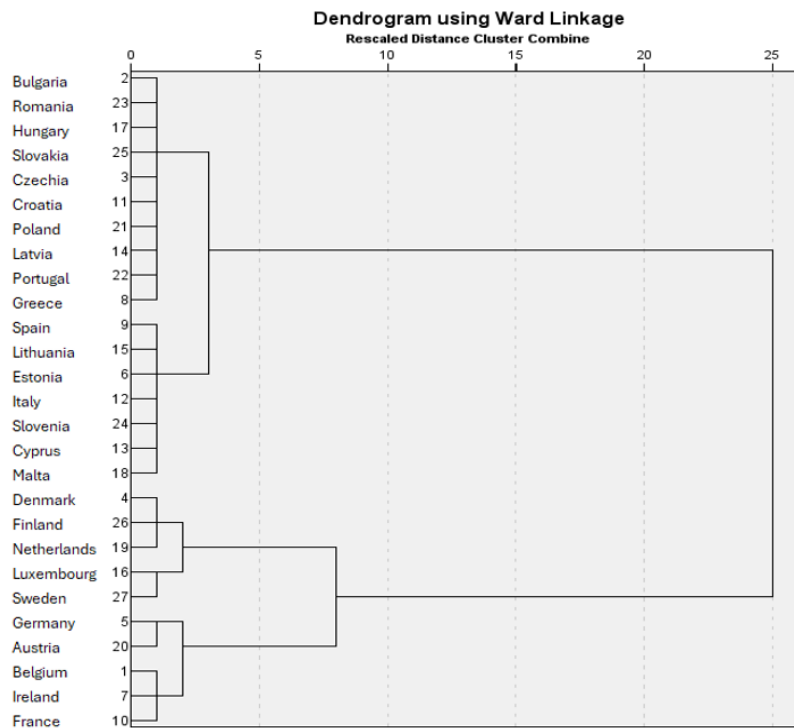
|                       | INDICATOR                                  | SINGLE / COMPOSITE | INTERPRETATION                                                           |
|-----------------------|--------------------------------------------|--------------------|--------------------------------------------------------------------------|
| <b>EMISSIONS</b>      | GHG emissions per capita                   | Single             | The lower - the better, but depends on economic development of a country |
|                       | Primary Energy consumption per capita      | Single             | The lower - the better, but depends on economic development of a country |
| <b>ENERGY</b>         | Energy intensity                           | Composite          | The lower - the better                                                   |
|                       | Renewable energy                           | Composite          | The higher – the better                                                  |
|                       | Digital innovation capacity                | Composite          | The higher – the better, but the rebound effect should be considered     |
| <b>DIGITALIZATION</b> | Total number of people receiving education | Single             | The higher – the better                                                  |
|                       | Digital innovation capacity                | Composite          | The higher – the better, but the rebound effect should be considered     |
|                       | Digital business                           | Composite          | The higher – the better, but the rebound effect should be considered     |

Environmental and energy indicators are generally interpreted according to the principle that lower greenhouse gas emissions, lower primary energy consumption, and lower energy intensity reflect better sustainability performance and more efficient resource use. However, greenhouse gas emissions and primary energy consumption per capita should be interpreted with caution, as lower values may also be associated with lower levels of economic development and industrial activity. In contrast, higher shares of renewable energy indicate a cleaner and more sustainable energy structure, contributing positively to the low-carbon transition.

Regarding digitalization, higher levels of education, digital innovation capacity, and digital business

development are generally considered favourable, as they reflect stronger technological advancement, innovation potential, and digital transformation. Nevertheless, the potential rebound effect should also be considered, since digitalization may simultaneously increase energy consumption and resource use despite efficiency improvements.

The final list of indicators was used for the classification of 27 European Union countries according to their performance in digitalization, energy and emissions areas. The data were normalized using min-max method, the Euclidean distance metric and Ward's amalgamation algorithm were applied and a dendrogram was created (Figure 1):



**Fig. 1.** The dendrogram

It was found that EU countries can be clearly classified into the 4 main groups according to their indicators. The

summarized data of each group and its indicators are presented in Table 5.

**Table 5.** Average normalized indicator values for each group of countries

| Group of countries                                                                       | Indicators               |                                       |                         |                         |                                            |                             |                  |
|------------------------------------------------------------------------------------------|--------------------------|---------------------------------------|-------------------------|-------------------------|--------------------------------------------|-----------------------------|------------------|
|                                                                                          | GHG emissions per capita | Primary Energy consumption per capita | Energy intensity factor | Renewable energy factor | Total number of people receiving education | Digital innovation capacity | Digital business |
| Leaders:                                                                                 |                          |                                       |                         |                         |                                            |                             |                  |
| Denmark, Luxembourg, Netherlands, Finland, Sweden                                        | 0.61                     | 0.63                                  | 0.32                    | 0.57                    | 0.73                                       | 0.66                        | 0.72             |
| Followers:                                                                               |                          |                                       |                         |                         |                                            |                             |                  |
| Belgium, Germany, Ireland, France, Austria                                               | 0.72                     | 0.37                                  | 0.27                    | 0.34                    | 0.65                                       | 0.37                        | 0.72             |
| Moderate countries:                                                                      |                          |                                       |                         |                         |                                            |                             |                  |
| Estonia, Spain, Italy, Cyprus, Lithuania, Malta, Slovenia                                | 0.48                     | 0.21                                  | 0.42                    | 0.28                    | 0.34                                       | 0.24                        | 0.67             |
| Modest countries:                                                                        |                          |                                       |                         |                         |                                            |                             |                  |
| Bulgaria, Czechia, Greece, Croatia, Latvia, Hungary, Poland, Portugal, Romania, Slovakia | 0.49                     | 0.19                                  | 0.56                    | 0.31                    | 0.35                                       | 0.18                        | 0.43             |

Leaders (Denmark, Luxembourg, Netherlands, Finland, and Sweden) demonstrate particularly high values of digital innovation capacity, digital business development, and education indicators. Sweden and Finland also exhibit the strongest renewable energy performance among all groups. However, several countries in this cluster, especially Luxembourg and Finland, show relatively high greenhouse gas emissions and primary energy consumption per capita, reflecting the higher levels of economic activity and consumption characteristic of highly developed economies. Nevertheless, this group generally demonstrates strong

progress toward a low-carbon economy supported by advanced technological and digital capabilities.

Compared to the Leaders, the level of digital innovation capacity is more moderate in the Followers group (Belgium, Germany, Ireland, France, and Austria). France and Austria demonstrate comparatively stronger renewable energy performance and lower greenhouse gas emissions, while Ireland and Germany exhibit higher greenhouse gas emissions per capita. Overall, this cluster reflects economically advanced countries where digitalization is well developed, although progress toward environmental sustainability differs among the countries.

Moderate countries (Estonia, Spain, Italy, Cyprus, Lithuania, Malta, and Slovenia) have relatively low primary energy consumption per capita and moderate greenhouse gas emissions, but it can be related to the lower economic development compared with the Leaders and Followers. Several countries, particularly Lithuania and Malta, show strong digital business development despite comparatively weaker digital innovation capacity. Renewable energy performance within the group remains moderate, indicating an ongoing but uneven transition toward a low-carbon economy.

Modest countries (Bulgaria, Czechia, Greece, Croatia, Latvia, Hungary, Poland, Portugal, Romania, and Slovakia) demonstrate the highest energy intensity values, especially in Bulgaria, indicating lower levels of energy efficiency and greater dependence on energy-intensive economic structures. Although greenhouse gas emissions and primary energy consumption per capita are relatively low in several countries, particularly Romania and Portugal, these results may partly reflect lower levels of economic development and industrial activity rather than higher sustainability performance. Renewable energy development remains moderate or relatively weak in most countries of this cluster, meaning structural changes are still required in these countries.

## Conclusions

The results of this study have revealed substantial differences among EU Member States in terms of digitalization, energy intensity, renewable energy and GHG emissions. Principal component analysis has identified four composite indicators: Energy Intensity, Renewable Energy, Digital Innovation Capacity, and Digital Business that can be used as a framework to assess the countries' performance in terms of digitalization and sustainability.

Cluster analysis distinguished four groups of countries with different development patterns. The Leaders group represents the most advanced cluster in terms of digitalization and innovation. The Followers group is characterized by highly developed economies with strong digital business performance and relatively high educational attainment. The Moderate countries' group have moderate environmental and technological performance, while the modest countries are mainly the countries with lower levels of digital innovation capacity and digital business development.

Limitations and Future Research. The main limitation of this study is that it identifies patterns and similarities among countries but does not establish causal relationships. Future research could apply econometric methods to examine causal relationships. Further studies could also investigate the potential rebound effects of digitalization on energy efficiency and environmental performance.

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**Rūta Nedzinskiene**, PhD of Social Sciences (Economics), is a Senior Lecturer at School of Economics and Business, Kaunas University of Technology. She has participated in scientific projects, including research on circular economy modelling, technological innovation and the competitiveness of the Lithuanian economy. She has also conducted postdoctoral project “Digital technologies impact on energy efficiency improvement, penetration of renewables and GHG emissions reduction.” at Vytautas Magnus University. Her international academic experience includes research and professional internships at Purdue University Northwest in the United States and universities in France, Italy, Hungary and Portugal. She also has extensive practical experience as a financial analyst and data analyst, working with large datasets, key performance indicators, budgeting, forecasting, automated reporting and business intelligence systems. Her research interests include business systems modelling, innovation assessment, enterprise performance assessment and measuring systems, circular economy issues, and the impact of digitalization on energy and sustainability. Email: ruta.nedzinskiene@ktu.lt, Orcid ID: <https://orcid.org/0009-0009-4474-3993>.

**Neringa Lušaitė** is a master's student in Business Big Data Analytics at the Faculty of Mathematics and Natural Sciences, Kaunas University of Technology. Her master's thesis focuses on short-term forecasting of wind and solar energy generation in the Baltic States using machine learning methods. Her research explores the application of data-driven forecasting techniques to renewable energy generation, aiming to improve the accuracy of short-term forecasts and contribute to more effective energy planning and decision-making. Prior to her master's studies, N. Lušaitė received a bachelor's degree in finance from Kaunas University of Technology. Her bachelor's thesis, “The Relationship Between Financial Flexibility and the Performance of Lithuanian Energy Companies,” examined Lithuanian energy sector. She also obtained the Bloomberg Market Concepts (BMC) certificate, wrote several articles and participated in student academic conferences. N. Lušaitė has also gained significant professional experience in the fields of finance and accounting. Currently, she works as a Financial Analyst. Before moving into her current role, she spent three years at EY (Ernst & Young), one of the Big Four international professional services firms. During this time, she worked on both Lithuanian and international projects, gaining experience in a global and multicultural business environment. Her research interests include finance, sustainability, renewable energy, machine learning, and business analytics. Email: neringa.lusaite@ktu.edu, Orcid ID: <https://orcid.org/0009-0006-3388-5310>.

**Egidijus Nedzinskas**, PhD of Social Sciences, is an Associate Professor in the Department of Law, Lithuania Business College. His scientific research areas are in Law (01S) and Education (07S). He published more than 50 scientific articles and has an extensive record of presentations at national and international scientific conferences. The scientific research has been carried out in the fields of legal liability and social responsibility, international compatibility of legislation, domestic violence, legal regulation of migration processes, study process optimisation, student educational traineeships, methods of applied studies, factors of selection of study programmes. E. Nedzinskas has participated in EU funded projects, international academic activities, professional training and public education initiatives. He has undertaken international internships and has delivered public lectures on current legal issues. His recent research addresses emerging legal challenges associated with digital transformation, criminal sanctions, corruption offences, critical competencies of police officers, protection against domestic violence and legal responsibility. Tel.: +37068666880. Email: egidijus.nedzinskas@ltvk.lt, Orcid ID: <https://orcid.org/0009-0000-7495-450X>.