Journal of Infrastructure, Policy and Development 2024, 8(9), 6682.
https://doi.org/10.24294/jipd.v8i9.6682

Article

Exploring the interconnected dynamics of energy efficiency and socioeconomic factors in European economic development using SOM

Sonja Brlečić Valčić*, **Ana Markuz**

Department of Economics, University of Zadar, 23000 Zadar, Croatia
* **Corresponding author:** Sonja Brlečić Valčić, sbrlecicv@unizd.hr

CITATION

Valčić SB, Markuz A. (2024). Exploring the interconnected dynamics of energy efficiency and socioeconomic factors in European economic development using SOM. Journal of Infrastructure, Policy and Development. 8(9): 6682. https://doi.org/10.24294/jipd.v8i9.6682

ARTICLE INFO

Received: 27 May 2024
Accepted: 24 June 2024
Available online: 5 September 2024

Abstract: Purpose: Today's challenges underscore the importance of energy across all segments of life. This scientific paper investigates the multifaceted relationship between energy efficiency, energy import reliance, population heating access, renewable energy integration, electricity production capacities, internet utilization, structural EU funds, and education/training within the framework of economic development. **Methodology:** Using data from selected European countries and employing self-organizing neural networks (SOM) and linear regression, this research explores how these interconnected factors influence the journey toward a sustainable and prosperous economic future. **Results:** The analysis revealed a strong connection between energy efficiency and numerous socioeconomic factors of modern times, with most of these connections being non-linear in nature. **Conclusion:** As countries work toward sustainable development goals, prioritizing energy efficiency can contribute to improved quality of life, economic growth, and environmental sustainability.

Keywords: energy efficiency; energy imports; renewable energy sources; economic development; structural EU funds
JEL: O13; 033; M2

1. Introduction

Energy use and economic development are intricately linked. Access to reliable and affordable energy sources facilitates economic growth by powering industries, transportation systems, businesses, and households. However, over-reliance on energy imports can negatively impact a country's balance of payments and energy security. Additionally, increased energy consumption from economic expansion often comes with environmental and social costs.

In the increasingly complex world trade network, the content and structure of exports have evolved, necessitating the introduction of new determinants in empirical models of environmental pollution (Isik et al., 2024). Concurrently, there is a critical need to control the adverse effects of industrialization and traditional economic growth models. By focusing on these areas, the top ecologically pollutant economies can better align with the global sustainability paradigm and effectively mitigate climate change (Yu et al., 2023).

Thus, there is a complex interplay between a country's energy system, economic policies, and broader sustainable development objectives.

This paper examines these dynamics by analysing the socioeconomic impacts of energy efficiency improvements and changing energy import dependence in the context of economic growth and human development. Energy efficiency enhancements that reduce energy intensity can both moderate energy demand and make growth more sustainable. However, the macroeconomic outcomes also depend on whether efficiency reduces domestic energy production or the reliance on imported fuels. Moreover, distributional impacts across income groups and sectors influence whether efficiency improvements ultimately support or hinder development indicators such as poverty reduction, employment, education, health, and gender equality (Markuz, 2022).

The analysis employs a computable general equilibrium modelling approach to quantify direct and indirect macroeconomic, sectoral, and distributional effects under varying scenarios. The model captures the linkages between energy and socioeconomic systems, based on the specific economic and demographic characteristics of EU. The results aim to inform policymakers on designing and prioritizing energy and economic policies that maximize domestic growth and social welfare. By elucidating trade-offs and synergies, the findings can support strategic decisions for sustainable and inclusive development.

The hypotheses of this research are:

1) Energy efficiency is interconnected with numerous socioeconomic factors like heating access, renewable energy use, electricity production, internet use, structural funds, and education.

2) The connections between energy efficiency and these socioeconomic factors are often nonlinear in nature.

3) Prioritizing energy efficiency can support countries in achieving sustainable development goals related to quality of life, economic growth, and environmental sustainability.

The significance of the paper can be highlighted by investigating the complex, multifaceted relationship between energy efficiency, energy imports, access to heating, renewables, electricity capacity, internet use, EU funding, education, and economic development. Research uses an innovative methodology (self-organizing neural networks and regression) to model these nonlinear relationships.

The rest of the paper is structured as follows: Section 2 reviews relevant literature connecting energy systems and socioeconomics; Section 3 describes the methodology; Section 4 presents results; and Section 5 concludes with policy implications.

The conducted analysis demonstrates a significant relationship between energy efficiency and various socioeconomic factors, emphasizing their interconnected nature in the context of economic development. Most connections between energy efficiency and socioeconomic variables are non-linear, indicating complex interactions that cannot be fully explained by simple linear models.

Reliance on energy imports is a critical factor influencing energy efficiency and economic development. Countries with higher energy import reliance tend to exhibit different energy efficiency patterns compared to those with greater energy self-sufficiency. The integration of renewable energy sources plays a vital role in enhancing energy efficiency and reducing dependency on imported energy, thereby contributing to sustainable economic growth.

Structural EU funds are instrumental in supporting initiatives aimed at improving energy efficiency, fostering economic development and sustainability. Furthermore, education and training programs are essential for promoting energy efficiency. A well-informed and skilled workforce is better equipped to implement and maintain energy-efficient practices, underscoring the importance of investment in human capital alongside technological and infrastructural advancements.

These findings underscore the importance of a holistic approach to energy policy, where multiple factors are considered to achieve sustainable economic development. Prioritizing energy efficiency can lead to significant improvements in quality of life, economic growth, and environmental sustainability.

2. Literature review

The increasing global emphasis on sustainable development necessitates an in-depth understanding of the intricate interactions among diverse energy-related and socio-economic components. This paper aims to offer a distinctive perspective on the vital connections between energy efficiency, energy import dependency, population's heating accessibility, renewable energy incorporation, electricity production capabilities, internet penetration, utilization of structural EU funds, and education/training initiatives. By focusing on the context of selected countries, this study seeks to unravel the dynamics through which these elements collectively influence economic development.

Energy efficiency is pivotal in the complex interplay between energy consumption, environmental sustainability, and economic development. As societies strive for both growth and sustainability, understanding the intricate dynamics between energy efficiency and economic progress becomes increasingly crucial (Markuz, 2022).

Firstly, the link between energy efficiency and economic development should address energy efficiency's role in reducing energy consumption and greenhouse gas emissions, as well as the economic benefits derived from enhanced energy efficiency practices (Markuz, 2022). Additionally, economic growth, income inequalities, and energy poverty have increased environmental pressure (Hassan et al., 2022).

If socioeconomic effects are observed, a connection emerges between energy imports and their implications for energy security, particularly the effect of energy imports on the affordability and accessibility of domestic energy. Related to this, the link between renewable energy integration and electricity production capacities is very important, considering the valuable contribution of renewable energy sources to the energy mix and their alignment with renewable energy goals (Markuz, 2022). Additionally, energy security helps reduce poverty (Taghizadeh-Hesary, 2023).

In socio-economic progress based on energy efficiency, it is inevitable to mention internet penetration and address potential disparities in internet access and its effects on development.

In the European context, EU structural funds play a crucial role in promoting sustainable energy and economic projects. Therefore, it is imperative to assess how the distribution of funding impacts regional development disparities (Markuz, 2022).

Lastly, emphasizing the education and training of the population is essential for facilitating a sustainable energy transition. This underscores the need to identify effective strategies for educating and training individuals in renewable energy technologies (Markuz, 2022).

Following above mentioned, to determine the complexity of the connection between energy efficiency and economic development, it is first important to examine how enhancing energy efficiency contributes to economic development by reducing energy costs, mitigating environmental impacts, and fostering innovation. Increasing the trilemma energy balance (clean energy transitions, and clean energy improve while natural resources depletion deteriorates environmental sustainability) by 1% boosts economic growth by 0.3874223% (Khan et al., 2022).

Previous studies have already linked the economic implications to energy efficiency. Based on that, it is emphasized that not only energy costs are important in this link, but also their significance for industries and households and that the potential for energy savings is achieved through efficiency improvements and the cost-effectiveness of energy-efficient technologies and practices (Markuz, 2022).

For example, Fizain and Court (2016) point out that establishing a steadfast economic policy is crucial not only for enhancing energy efficiency and yielding a 'double dividend,' characterized by an augmented social return on energy invested through reduced energy intensity in capital investments but also for mitigating sensitivity to energy price volatility.

Energy efficiency in the European Union should be achieved through the transition to clean energy with the aim of a safer, more competitive, and sustainable energy system that will respond to the existential challenge of our time (Iarmenco et al., 2020).

When emphasizing the importance of preventing energy poverty (Eurobarometer, 2019), the research linking regenerative energy sources to the development of the countries of the European Union (Papież et al., 2018) and the importance of discovering causality between RES and economic growth (Xu, 2016) are highlighted.

Enhancing energy efficiency not only reduces operational costs and environmental impacts but also drives innovation, strengthens industrial competitiveness, and supports the transition to a sustainable energy future (Markuz, 2022).

Countries with modest sources of fossil fuels more often develop renewable energy (Papież et al., 2018) and turn it to innovation (Dincer and Acar, 2017).

Investments through the wider application of innovative technical solutions can significantly influence the interest in sustainable energy practices, especially in alternative energy sources, through various entrepreneurial endeavours (Lins, 2013; Wyns et al., 2014). The conditions for sustainable development and development of companies in the modern context in recent times depend on the impact of technological innovations (Duspara et al., 2018) and the recognition of the importance of research and development in the process of innovation (Lopez-Rodriguez and Martinez, 2014).

Policy frameworks, technological advancements, and collaborative efforts are essential in harnessing the full potential of energy efficiency as a catalyst for economic growth while ensuring a greener and more prosperous future (Markuz, 2022).

In this context, the conclusions of previous research should be highlighted as follows:

- The European Green Plan leads the construction of a harmonized financial system to support advanced solutions under climate neutrality (European Green Deal, 2019).

- The further enhancement and digitization of the interconnectedness of the EU energy market are imperative, particularly within the broader scope of the European Union's long-term strategic directives. These directives underscore the pivotal role of total factor productivity in fostering future growth and bolstering competitiveness (Jakšić et al., 2020).
- Support for convergence, despite certain successful actions, does not necessarily mean that new members realize economic benefits. Such support generally has stronger economic effects in more developed environments and is conditioned by other policies, influencing the competence of the country receiving the support (Cappelen et al., 2003).
- Complex guidelines often lead to slow decision-making and make it difficult to achieve set goals (Ringler and Knodt, 2017).
- Improvements are needed in another extremely important segment: the implementation of EU funds' goals and their absorption. This pertains to institutional capital, which manages projects. Proficient project management is a cornerstone for virtually every contemporary organization, encompassing private enterprises and public administration (Brlečić Valčić et al., 2016).
- The influence of regional assistance on the convergence dynamics in growth patterns (Cappelen et al., 2003).
- Efficient government administration is crucial for achieving better absorption and management of energy efficiency measures. Government policies directly linked to these initiatives can significantly reduce energy productivity by increasing support for efficiency-enhancing measures (Chang et al., 2018).
- Advocacy for elevating the proportion of renewable energy in electricity generation across all tiers, with outcomes poised to address the existential challenges of the current era (Haas et al., 2011; Iarmenco et al., 2020).
- Recommendations for improving education around sustainable ICT in developing countries to mitigate environmental harm (Zhang et al., 2022).
- Developing an interdisciplinary analytical perspective to inform energy policymaking, aiming to achieve multiple economic, social, and environmental objectives simultaneously (Khan et al., 2022).
- Enhancing the competitive strengths of small and medium enterprises to foster resilience and adaptability amidst changes. This involves leveraging the impact of regionally allocated funds and ensuring their effective absorption to fortify these advantages (Kadocsa and Borbás, 2010; Kersan-Škabić and Tijanić, 2017; Peša et al., 2017).
- More ambitious policies and significant turnarounds in policies related to environmentally friendly energy sources are needed in all EU member states (Strunz et al., 2021), especially concerning factor productivity. The possibility of measuring their impact through the inclusion of companies in the digital economy, proper debt ratio, staff quality, and management efficiency is also crucial (Tian and Liu, 2020).

3. Data and methodology

To examine the influence of the selected observed variables (shown in **Table 1**) the analysis was performed by clustering using self-organizing neural networks (SOM) and using linear regression.

Table 1. Selected variables observed.

Input	Variables	Input	Variables
Input 1	Energy Efficiency	Input 2	Energy intensity
Input 3	Energy Productivity	Input 4	Energy imports dependency
Input 5	Population unable to keep home adequately warm by poverty status	Input 6	Share of fuels in final energy consumption
Input 7	Share of renewable energy in gross final energy consumption	Input 8	Electricity production capacities by main fuel groups and operator
Input 9	Electricity production capacities for renewables and wastes	Input 10	Resource productivity and domestic material consumption
Input 11	Circular material use rate	Input 12	GERD by sector of performance
Input 13	Research and development personnel, by sectors of performance	Input 14	Share of government budget appropriations or outlays on research and development
Input 15	Employment in high-and medium-high technology	Input 16	Human resources in science and technology
Input 17	Individuals - internet use	Input 18	E government activities of individuals via websites
Input 19	Digital single market - promoting e-commerce for businesses	Input 20	Gross domestic product at market prices
Input 21	GDP per capita in PPS	Input 22	Nominal labor productivity per person employed
Input 23	ESIF spent (2014-2020)	Input 24	Gross value added at basic prices
Input 25	Government revenue, expenditure and main aggregates	Input 26	General government expenditure by function
Input 27	Government deficit/surplus	Input 28	Long-term unemployment rate
Input 29	At risk of poverty rate of unemployed persons	Input 30	Population by educational attainment level
Input 31	Participation rate in education and training	Input 32	Housing deprivation rate by number of item

Source: Created by the authors according to Markuz (2022).

The data were sourced from the Eurostat statistical database. For the analysis, it was necessary to determine relevant, publicly available data related to the connection between total invested funds and relevant indicators, as well as to select member states suitable for the analysis. Care was taken to ensure that the sample selection was based on data availability, comparability, and structure. In this regard, it was concluded that 18 EU member states could be considered for further analysis. The most significant criterion was the selection of countries with a total population not exceeding 11 million inhabitants. Larger member states, due to their data structure, which is difficult to compare and would cause difficulties in modelling, could not be included in the sample. Additionally, considering the availability of data for the variable "esif spent" and the observed period of the EU financial perspective 2014–2020, it was assessed that the most appropriate period to observe would be from 2015 to 2019. This conclusion is based on the fact that the effects of the spent funds need to be observed at least one year after their utilization. Furthermore, the period after 2019 was affected by global business disruptions, first caused by the pandemic and then by the energy crisis, which would undoubtedly significantly impact the relevant, relatively stable, and reliable effects in the observed period. There was no need for extensive modifications to the downloaded data as very few data points were missing. In cases where data were missing for a particular country, the data from the previous or following year were used. SOM does not require data to be normalized beforehand, so data normalization was not performed for the purpose of this analysis.

Observation of 32 previously selected variables showed that 14 of them have a strong connection with energy efficiency, as an outcome indicator for measuring the progress of Strategy 2020 indicators on EE to 2020 and accepted goals to be achieved by 2030 (reduction of at least 32.5 percent, i.e. primary energy consumption of a maximum of 1273 Mtoe and final energy consumption of a maximum of 956 Mtoe in 2030):

- Energy import dependency (Input 4) indicates the percentage of a nation’s overall energy requirements satisfied by imports from external sources. This metric is derived from energy balances by dividing net imports by the total gross available energy (Eurostat according to Markuz, 2022).
- The population unable to keep home adequately warm because of poverty status (Input 5) is derived from the EU Sustainable Development Goals (SDG) framework. This metric serves to track advancements toward achieving SDG 7, focusing on affordable and clean energy, and SDG 1, aiming to eradicate poverty in all its manifestations globally (Eurostat according to Markuz, 2022).
- Share of renewable energy in gross final energy consumption (Input 7) constitutes a component of the Sustainable Development Goals (SDG) indicator set. This measure is instrumental in assessing advancements towards SDG 7, which centres on affordable and clean energy, as well as SDG 13, focusing on climate action (Eurostat according to Markuz, 2022).
- Electricity production capacities by main fuel groups and operator (Input 8) encompasses comprehensive data, including overall capacity, capacity categorized by the source of electricity production (in MWe), capacity segmented by the type of generation in power plants utilizing combustible fuels (in MWe), and capacity differentiated by the firing type and the fuel used in power plants employing combustible fuels (in MWe) (Eurostat according to Markuz, 2022).
- GERD by sector of performance (Input 12). This breakdown encompasses government (GOV), business enterprise (BES), higher education (HES), private non-profit (PNP), and the overall aggregate across all sectors (Eurostat according to Markuz, 2022).
- Research and development personnel, by sectors of performance (Input 13) involves tracking the total R&D personnel in full-time equivalents as a proportion of the economically active population. This breakdown includes the percentage of the total labor force and total employment, further segmented by gender (Eurostat according to Markuz, 2022).

- Share of government budget appropriations or outlays on research and development (Input 14) quantifies the extent of government budget allocations specifically earmarked for R&D endeavors (Eurostat according to Markuz, 2022).
- Employment in high-and medium-high technology (Input 15) encapsulates a fusion of economic, employment, and science, technology, and innovation (STI) metrics. These metrics delineate manufacturing and service industries or products traded, segmented by technological intensity. This breakdown is achieved primarily through both sectoral and product-oriented approaches (Eurostat according to Markuz, 2022).
- Individuals - Internet use (Input 17) breaks down numbers of individuals' usage of the internet in households on a yearly basis data gathering (Eurostat according to Markuz, 2022).
- E-government activities of individuals via websites (Input 18) serve as an indicator of the information society. This metric reflects the proportion of the population utilizing the internet for various forms of interaction with public authorities (Eurostat according to Markuz, 2022).
- Digital single market - promoting e-commerce for businesses (Input 19) serves to measure indicators of digital Europe through 66 different ways such as by companies, without the financial sector, by classification of companies, etc (Eurostat according to Markuz, 2022).
- ESIF spent (2014-2021) (Input 23) shows data on European structural and European funds absorption in the perspective of 2014-2020 (Eurostat according to Markuz, 2022).
- Gross value added in basic prices (Input 24) signifies the outcome of the production endeavors undertaken by resident production units. In regional accounts, this value can be computed using the output approach, wherein the GDP is derived by summing up the gross value added across diverse institutional sectors or industries. This summation also includes taxes and excludes subsidies on products, which are not specifically allocated to sectors and industries (Eurostat according to Markuz, 2022).
- Participation rate in education and training (Input 31) encompasses involvement in both formal and non-formal educational and training activities (Eurostat according to Markuz, 2022).

Clustering, as defined by Brlečić Valčić (2014), involves organizing data into clusters based on their similarity or specific properties. In this study, clustering was employed to organize parameters into groups conducive to modelling, facilitating further analysis, particularly in connection with energy efficiency.

Kohonen's self-organizing neural network, also known as Self-Organizing Map (SOM), was initially designed to visualize the arrangement of metric vectors like structured sets of measurement values or statistical attributes. This neural network stands out as a highly utilized tool for addressing clustering challenges. Its widespread application is attributed not only to its remarkable clustering capabilities but also to its exceptional visualization tools. These tools facilitate a straightforward and efficient analysis of the resultant clusters, as emphasized by Brlečić Valčić (2014).

Furthermore, several important features of this network should be highlighted (Beal et al., 2010; Brlečić Valčić, 2014; Kiang and Fisher, 2008):

- The learning property of the network takes place on the data that is fed into its input layer. In this way, the analysed data is modelled without the previously known phenomenon that the data describes, because the SOM learns the data and how to analyse it by itself during the training process.
- Reduction of the dimensionality of the analysed data enables an easier understanding of the interrelationship of data attributes.
- SOM functions as an unsupervised neural network, meaning it operates without a teacher or a predefined target vector. The clustering process involves categorizing the set of input vectors into several classes equivalent to the neurons in the competitive layer.
- The clustering process is executed based on the sample distance criterion, meaning that samples with parameters closer by the specified distance metric are grouped into the same cluster.
- The network's characteristics are tuned to attain optimal clustering, ensuring that the distances between samples within the same cluster are minimized, while the distances between different clusters are maximized.

The relevance of using this methodology is proven by the fact that in the initial phase of this research, there were 5794 papers in the Web of Science database in which SOM was used for analysis, of which 424 papers were related to environmental research, 176 papers in the operational research and management category, 19 papers in the category of business and 6 papers in the category of social sciences in general (Markuz, 2022).

4. Results and discussion

The rectangular 2D topology of the analysed data is self-organized during 200 iterations, with the help of 20 neurons in the hidden layer, i.e., the visualization of weight planes, and is shown in **Figure 1**.

The connection of individual observed parameters is manifested in similar patterns of weight planes, i.e., common patterns of colors and shapes cluster the data into certain groups.

The analysis of the relationship between energy efficiency (**Figure 1**, Input 1) and dependence on energy imports (**Figure 1**, Input 4) yields significant insights into their interconnected dynamics. The statistical indicators, with an R-squared value of 0.135 and an Adjusted R-squared value of 0.125, suggest that approximately 13.5% of the variability in energy efficiency can be explained by the dependence on energy imports. This indicates a moderate level of explanatory power, pointing to other influential factors that also contribute to variations in energy efficiency.

The *p*-value of 0.000253 strongly indicates that the relationship between energy efficiency and dependence on energy imports is statistically significant. Given this low p-value, we can reject the null hypothesis that there is no relationship between these variables, affirming that a significant association exists.

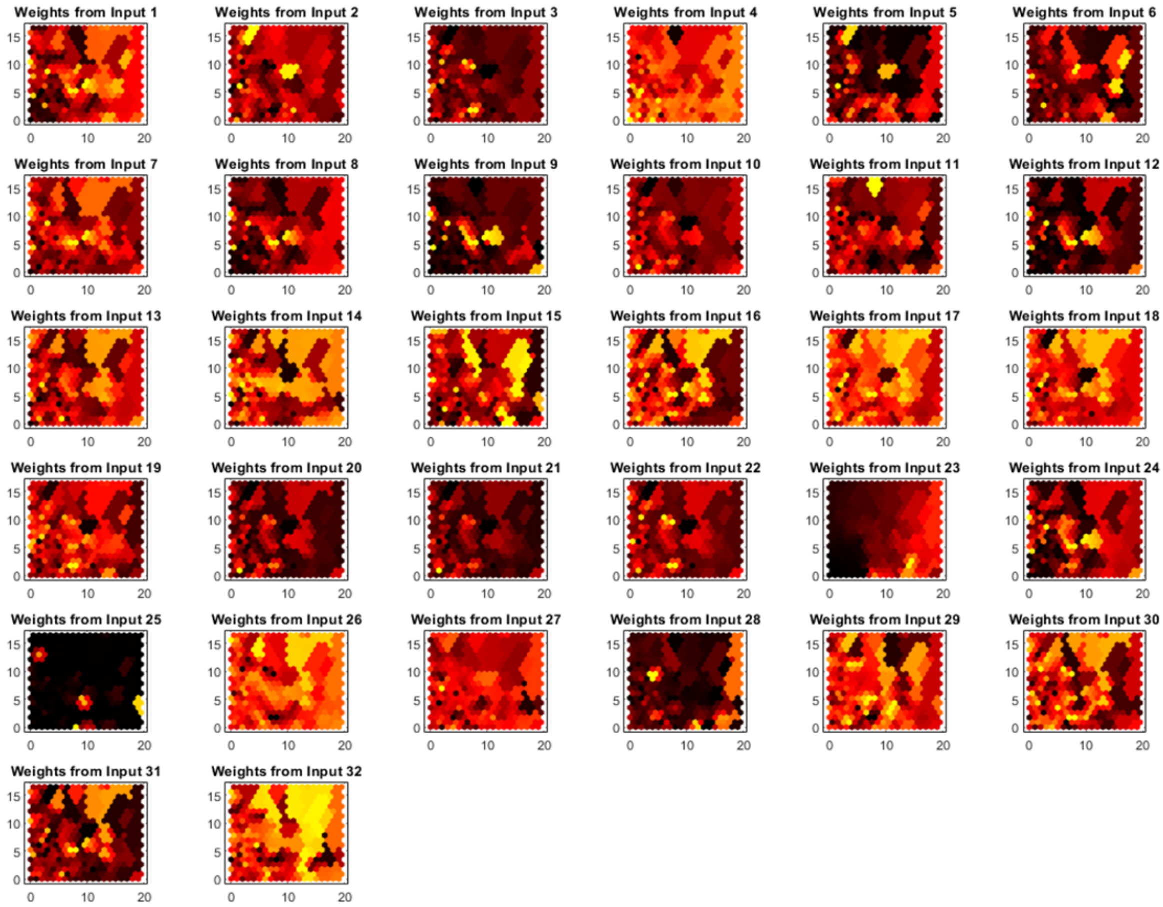

Figure 1. Selected variables on energy efficiency and energy productivity impact analyses through SOM.

Source: Created by the authors in the MATLAB software package according to Markuz (2022).

Furthermore, the relatively modest R-squared and Adjusted R-squared values suggest that this relationship is not purely linear. The connection between energy efficiency and dependence on energy imports likely involves more complex, non-linear interactions. This complexity might stem from various factors such as the types of imported energy, the efficiency of energy use within different sectors, and the policies governing energy imports and efficiency measures.

Many countries rely on energy imports to meet their domestic energy demand. Energy imports can include various sources such as oil, natural gas, coal, and even electricity. The cost of energy imports and, lately, its availability can significantly impact a country's energy security and economic stability. Countries that heavily depend on energy imports are vulnerable to geopolitical disruptions, supply interruptions, and price fluctuations in the global energy markets (Markuz, 2022).

The analysis of the relationship between energy efficiency (**Figure 1**, Input 1) and the population that cannot heat their home due to their poverty status (**Figure 1**, Input 5) reveals important insights into the socio-economic implications of energy efficiency.

The statistical indicators, with an R-squared value of 0.0468 and an Adjusted R-squared value of 0.0365, indicate that only about 4.7% of the variability in energy efficiency can be explained by the proportion of the population unable to heat their homes due to poverty. This suggests a weak explanatory power, implying that numerous other factors influence energy efficiency beyond the poverty-related heating issues.

The p-value of 0.0353 is statistically significant at the 5% level, indicating that the relationship between energy efficiency and the population's ability to heat their homes is not due to random chance. However, the strength of this relationship is quite modest, as reflected by the low R-squared values.

The relatively low R-squared and Adjusted R-squared values, coupled with the significant p-value, imply that the connection between these variables is likely non-linear. This non-linearity could arise from various complex interactions, such as the efficiency of heating systems, regional variations in climate, energy prices, the effectiveness of social support programs, and other socio-economic factors that impact both energy efficiency and the ability of populations to afford heating.

An important socio-economic component can be concluded from such results, i.e., domestic heating is a critical component of residential energy consumption and if there is import overdependency, as it is i.e. in natural gas, this might trigger issues on energy security (Miklošević et al., 2022). It can be overcome primarily by using various energy sources, including natural gas, electricity, heating oil, biomass, and even renewable sources such as solar thermal systems. The choice of heating source can have implications for energy efficiency, greenhouse gas emissions, air quality, and affordability for households (Markuz, 2022).

The third pair of indicators examined in this research investigates the relationship between energy efficiency (**Figure 1**, Input 1) and the share of renewable energy sources (**Figure 1**, Input 7). The statistical analysis reveals significant findings that underscore the strength of this connection.

The statistical indicators show an R-squared value of 0.209 and an Adjusted R-squared value of 0.2, indicating that approximately 20.9% of the variability in energy efficiency can be explained by the share of renewable energy sources. This suggests a substantial explanatory power, especially compared to other factors analysed in this study.

The p-value of 3.24×10^{-6} (or 0.00000324) indicates a highly statistically significant relationship between energy efficiency and the share of renewable energy sources. Given this extremely low p-value, we can confidently reject the null hypothesis that there is no relationship between these variables, affirming that the connection is both strong and significant.

These findings imply that increasing the share of renewable energy sources has a notable positive impact on energy efficiency. Renewable energy sources such as solar, wind, hydro, or geothermal power provide environmentally friendly alternatives for electricity generation in contrast to conventional fossil fuels. Therefore, it is essential in a way to reduce gas emissions to integrate renewable energy into the power mix, as well as to mitigate climate change and achieve energy security. To ensure a reliable power supply, production capacities must be sufficient to cover periods of low renewable generation. This might involve having backup sources (such as natural gas or energy storage systems) that can quickly ramp up when renewables are unavailable. However, renewables have unique characteristics, such as intermittency (solar and wind availability varies) and location-specific feasibility (hydro and geothermal resources) (Markuz, 2022).

The analysis of the relationship between energy efficiency (**Figure 1**, Input 1) and power production capacities (**Figure 1**, Input 8) reveals an exceptionally strong connection, as demonstrated by the statistical indicators.

The R-squared value of 0.844 and the Adjusted R-squared value of 0.843 indicate that approximately 84.4% of the variability in energy efficiency can be explained by power production capacities. This high level of explanatory power suggests a very strong correlation between these two parameters, meaning that changes in power production capacities are closely associated with changes in energy efficiency.

The p-value of 2.57×10^{-39} is exceedingly low, indicating a highly statistically significant relationship between energy efficiency and power production capacities. Given this extremely low p-value, we can reject the null hypothesis with utmost confidence, affirming that the connection is both strong and significant beyond any reasonable doubt. These results imply that power production capacities have a profound impact on energy efficiency. It can be interpreted through the fact that adequate production capacities are necessary to meet electricity demand, maintain grid stability, and prevent power shortages. Countries aiming to reduce their reliance on energy imports might invest in domestic energy production and distribution infrastructure. This could involve expanding renewable energy capacity or improving energy efficiency (Markuz, 2022).

The relationship between internet penetration, socioeconomic progress, and energy efficiency is multifaceted and interconnected. Socioeconomic progress encompasses a range of indicators that reflect improvements in the well-being and quality of life of a society. These indicators can include income levels, education, healthcare access, employment opportunities, and overall living standards. Higher socioeconomic progress indicates a society's ability to provide its citizens with better opportunities and a higher quality of life (Markuz, 2022). Let's explore how these factors relate to each other, especially regarding economic development.

In this context, the conducted analysis established an exceptional connection between the parameter Energy efficiency (Input 1) and research and development (GERD by performance sector) (Input 12). The R-squared and adjusted R-squared values (0.575 and 0.57, respectively) indicate that a substantial amount of the variability in Energy efficiency can be explained by variations in GERD by performance sector. The very low p-value (5.7×10^{-19}) confirms that the relationship between Energy efficiency and GERD by performance sector is statistically significant.

Education institutions contribute to research and innovation in energy efficiency technologies and practices. Through research initiatives and academic programs, they explore new ways to improve energy efficiency, develop cutting-edge technologies, and address challenges in the field.

Therefore, the link between Energy Efficiency (Input 1) and Personnel for Research and Development (Input 13) is important. The R-squared and adjusted R-squared values (0.243 and 0.235, respectively) suggest that while there is a significant relationship between Energy Efficiency and Personnel for Research and Development, the explanatory power of Personnel for Research and Development alone is moderate.

The low p-value (4.45×10^{-7}) indicates that the observed relationship between these variables is unlikely to be due to random chance.

While the connection between Energy Efficiency and Personnel for Research and Development is statistically significant, the explanatory power of Personnel for Research and Development alone is moderate (as indicated by the R-squared values). The non-linear nature suggests that the relationship may require further exploration to understand how changes in Personnel for Research and Development affect Energy Efficiency in different contexts or scenarios.

Likewise, in this context, the importance of the connection between Energy Efficiency (Input 1) and Share of approved state budget funds or expenditures for research and development (Input 14) should be highlighted. Statistical indicators of the connection between these two variables: R-squared: 0.151, Adjusted R-squared: 0.142, and p-value = 9.75×10^{-5} also indicate the fact that their connection is more non-linear. While the R-squared values (both raw and adjusted) indicate a statistically significant relationship, the percentages (0.151 and 0.142) suggest that the share of approved state budget funds or expenditures for research and development explains a smaller proportion of the variability in Energy Efficiency compared to other variables analysed previously.

The significant p-value (9.75×10^{-5}) strengthens the conclusion that there is indeed a meaningful relationship between Energy Efficiency and the share of approved state budget funds or expenditures for research and development.

The analysis highlights a statistically significant but relatively modest and potentially non-linear relationship between Energy Efficiency and the share of approved state budget funds or expenditures for research and development. Further investigation could explore how this relationship manifests under different conditions or contexts, which might reveal insights into optimizing both Energy Efficiency initiatives and research and development funding strategies.

If, on the other hand, the established connection between *Energy Efficiency* (Input 1) and Employment in high and medium-high technology (Input 15) is observed, it should be noted that knowledge and skills gained through education and training have a lasting impact. Trained professionals can continue to drive energy efficiency initiatives throughout their careers, contributing to sustained economic benefits and environmental improvements (Markuz, 2022). Statistical indicators of the connection between these two variables: R-squared: 0.17, Adjusted R-squared: 0.161, and p-value = 3.56×10^{-5} also indicate the fact that their connection is more non-linear. The R-squared values (both raw and adjusted) indicate a statistically significant relationship, with Employment in high and medium-high technology explaining a notable but not dominant portion of the variability in Energy Efficiency. The significant p-value reinforces the conclusion that there is indeed a meaningful relationship between Energy Efficiency and Employment in high and medium-high technology. The statement about the lasting impact of knowledge and skills gained through education and training aligns with the broader understanding that trained professionals can drive sustainable energy efficiency practices over their careers. This contextual insight enhances the understanding of why Employment in high and medium-high technology might influence Energy Efficiency outcomes.

Education helps raise awareness about the importance of energy efficiency and the role education plays in sustainable development. By providing valid and timely information on good energy-saving practices, technologies, and their benefits education empowers individuals, businesses, and policymakers in a way that they could be able to make well-informed decisions, which would eventually lead to a greater contribution towards energy efficiency (Markuz, 2022).

In addition to the relationship established by SOM shown in **Figure 1**, the statistical characteristics of the relationship between the parameters Energy efficiency (Input 1) and Participation in education and training (Input 31) are: R-squared: 0.156, Adjusted R-squared: 0.147, *p*-value = 7. The R-squared values (both raw and adjusted) indicate a statistically significant relationship, with Participation in education and training explaining a notable but not dominant portion of the variability. The significant *p*-value reinforces the conclusion that there is indeed a meaningful relationship between Energy efficiency and Participation in education and training in Energy efficiency 0.59×10^{-5} and indicate a more non-linear type of connection.

Participation in education and training likely enhances the knowledge and skills necessary for implementing and improving energy efficiency measures. This aligns with the understanding that educated and trained individuals may contribute more effectively to energy efficiency initiatives, potentially explaining the observed relationship.

As a socioeconomic effect, the connection between the parameters of Energy efficiency (Input 1) and Individuals - use of the Internet (Input 17) can be singled out. Statistical indicators of the connection between these two variables: R-squared: 0.0412, Adjusted R-squared: 0.0309 and *p*-value = 0.0485 also suggests that the relationship between energy efficiency and internet usage is likely non-linear. In linear regression, such low R-squared values imply that a simple linear model does not adequately capture the complexity of the relationship.

Namely, the internet can play a significant role in driving socioeconomic progress. It enables access to educational resources, online job opportunities, e-commerce, telemedicine, and financial services. Increased internet penetration can lead to skill development, better employment prospects, and improved access to vital services, thereby contributing to higher socioeconomic progress (Markuz, 2022).

The connection of the above is also reflected in the closeness of the parameters Energy efficiency (Input 1) and E-government activities of individuals through websites (Input 18) whose characteristics of statistical connection are R-squared: 0.0463, Adjusted R-squared: 0.036, *p*-value = 0.0363 and indicate that while there is a statistically significant relationship between energy efficiency and e-government activities, the low R-squared values indicate that this relationship is not straightforward and is likely non-linear.

It should be added to the closeness of the parameters Energy efficiency (Input 1) and Single digital market-promotion of e-commerce for companies (Input 19) whose characteristics of statistical connection are R-squared: 0.121, Adjusted R-squared: 0.112, *p*-value = 0.000549 and point that relationship between energy efficiency and the promotion of e-commerce for companies shows a statistically significant and stronger connection compared to previous variables. However, the modest R-squared value suggests a non-linear nature to this relationship. To gain a more comprehensive understanding, it is essential to explore non-linear models and incorporate additional variables that might influence energy efficiency.

The analysis also indicated the connection between Energy Efficiency (Input 1) and ESIF spent (2014-2021) (Input 23). The statistical characteristics of this association are R-squared: 0.159, Adjusted R-squared: 0.15, p-value = 6.99×10^{-5}. It should be concluded that they indicate an exceptional connection of a non-linear character. The p-value is significantly below the 0.05 threshold, indicating a highly statistically significant relationship between energy efficiency and the ESIF spent. This strong significance underscores a robust association. The significant impact of ESIF spending on energy efficiency highlights the importance of financial investments and funding in driving energy efficiency improvements.

Structural EU Funds offer a valuable opportunity to accelerate sustainable development and energy efficiency initiatives within EU member states. By strategically investing in projects that prioritize energy efficiency, countries can drive economic growth, reduce environmental impact, and ensure a more equitable and prosperous future for all regions (Markuz, 2022).

Finally, as a conclusion of all links highlighted in this analysis, the connection between Energy efficiency (Input 1) and Gross added value in basic prices (Input 24) is emphasized.

The statistical characteristics of this association are R-squared: 0.635, Adjusted R-squared: 0.631, p-value =4.84×10^{-22}. Unlike other variables explored, the connection between energy efficiency and gross added value in basic prices is exceptionally strong and linear. The high R-squared value indicates that this economic measure is a critical determinant of energy efficiency. Gross added value in basic prices reflects the overall economic output and productivity. Its strong relationship with energy efficiency suggests that regions or sectors with higher economic productivity tend to have better energy efficiency. This could be due to investments in efficient technologies, better management practices, and economies of scale.

Several key points were gathered from this comprehensive analysis:

- There is a connection between energy efficiency and dependence on energy imports, though it is more nonlinear. Countries that rely heavily on imports are vulnerable to supply disruptions and price fluctuations.
- There is a socio-economic link between energy efficiency and the ability of households to afford heating - critical for well-being. This highlights the need for diverse and affordable energy sources.
- Renewable energy sources are imperative for reducing emissions and progressing energy security. However, their integration poses grid reliability challenges due to intermittency that must be managed.
- Adequate energy production and distribution capacities are vital to meet electricity demand and prevent shortages. This is reflected in the strong correlation between energy efficiency and power production capacities.
- Research, development, innovation, and skilled professionals in the energy sector enable advancements in efficiency technologies and sustainable practices. Educational institutions play a key role here.
- Internet access and e-governance services also correlate with efficiency, indicative of their socio-economic benefits.

- Structural EU funds that prioritize energy efficiency can stimulate sustainable growth across member states.
- Integrating energy efficiency into economic development strategies can reduce costs, and spur productivity and growth-reflected in its correlation with gross value added.

The interlinkages highlight how energy efficiency ties into environmental protection, social welfare, technological progress, and fiscal growth. A concerted, multi-dimensional approach is needed to harness its benefits.

5. Conclusion

This paper elucidates the complex interconnections between energy efficiency, energy import reliance, domestic heating infrastructure, renewable energy integration, electricity production capacity, internet penetration, EU structural funds, education and training programs, and economic development. By thoroughly investigating these interdependent factors within a specific European Union member state, this study provides valuable insights into how strategic policy decisions can guide the nation toward a more sustainable and prosperous future. Given the ongoing global challenges at the intersection of economic growth, energy security, and climate change mitigation, this analysis underscores the importance of holistic approaches that account for the multifaceted nature of sustainable development. The paper argues that rapidly transitioning to cleaner technologies will require immediate and sustained action across all sectors of the economy, supported by mobilized financing. Notably, the paper posits that improving energy efficiency and deploying renewable energy sources could catalyze green job creation while simultaneously promoting sustainable economic growth and reducing climate risk. The paper concludes by emphasizing the need for further in-depth exploration of member state-specific objectives, as targeted efforts will be essential for meeting European Union-wide strategic goals related to energy efficiency and renewable energy adoption. Additional country-level analyses of this nature could further clarify the critical role of energy efficiency and renewable in achieving the bloc’s sustainability targets.

Key findings:

- Strong connection found between energy efficiency and numerous socioeconomic factors related to sustainable development and prosperity.
- Relationships are highly complex and frequently nonlinear in nature.

Implications:

- Prioritizing energy efficiency can substantially contribute to economic growth, improved quality of life, and environmental sustainability.
- Provides data and models to help inform policymaking to simultaneously address economic, social, and environmental objectives.

It is possible to distinguish several limitations of this research as follows:

- Data is limited to selected European countries, reducing generalizability to other regions,
- Inability to establish causal relationships due to the correlational nature of the analysis,
- Many complex socioeconomic factors are difficult to fully account for.

The following can be mentioned as recommendations for future research:

- Expand analysis to include more countries globally for better generalizability,
- Collect longitudinal data and use techniques like panel data analysis to better assess causal impacts over time,
- Incorporate qualitative data through surveys or interviews to capture nuanced socioeconomic factors,
- Examine specific policies and interventions more closely through case studies.

While the analysis provides valuable insights into the factors influencing energy efficiency, several limitations should be acknowledged:

- Many variables do not fully capture the complexity of factors influencing energy efficiency;
- The analysis is constrained by the quality and availability of data for the selected variables;
- The study does not account for geographical or sectoral variations. Energy efficiency dynamics can vary significantly across different regions and economic sectors due to differences in infrastructure, industrial composition, and policy environments.

Recommendations for future research refer to incorporation of non-linear models, including additional variables related to regulatory frameworks, energy prices, technological advancements, and other relevant factors, and using of experimental or quasi-experimental designs to establish causal relationships between the variables and energy efficiency.

Author contributions: Conceptualization, AM and SBV; methodology, SBV; software, SBV; validation, AM and SBV; formal analysis, SBV; investigation, AM; resources, AM; data curation, SBV; writing-original draft preparation, AM; writing-review and editing, SBV; visualization, AM; supervision, SBV; project administration, SBV; funding acquisition, SBV. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

Beale, M. H., Hagan, M. T., Demuth, H. B. (2010). Neural network toolbox. User’s Guide, MathWorks, 2, 77-81.

Brlečić Valčić, S. (2014). A modern approach to the valuation of companies in the oil and gas industry based on computer intelligence [PhD thesis]. University of Rijeka.

Brlečić Valčić, S., Dimitrić, M., & Dalsaso, M. (2016). Effective Project Management Tools for Modern Organizational Structures. Journal of Maritime & Transportation Science, 51(1), 131–145. Internet Archive. https://doi.org/10.18048/2016.51.09

Cappelen, A., Castellacci, F., Fagerberg, J., et al. (2003). The Impact of EU Regional Support on Growth and Convergence in the European Union. JCMS: Journal of Common Market Studies, 41(4), 621–644. Portico. https://doi.org/10.1111/1468-5965.00438

Chang, C.-P., Wen, J., Zheng, M., et al. (2018). Is higher government efficiency conducive to improving energy use efficiency? Evidence from OECD countries. Economic Modelling, 72, 65–77. https://doi.org/10.1016/j.econmod.2018.01.006

Dincer, I., & Acar, C. (2017). Innovation in hydrogen production. International Journal of Hydrogen Energy, 42(22), 14843–14864. https://doi.org/10.1016/j.ijhydene.2017.04.107

Duspara, L., Knežević, S., Šošić, R. (2018). Impact of technological innovation on Enterprise., In: Lalić, B., Tasić, N., Gračanin, D. (editors), Proceedings of the 9th International Scientific and Expert Conference TEAM; 2018. pp. 338-342.

EUR-Lex. (2019). European Green Deal. Available online: https://eur-lex.europa.eu/EN/legal-content/summary/european-green-deal.html (accessed on 2 March 2024).

European Commission. (n.d.). Eurostat. Available online: https://ec.europa.eu/eurostat (accessed on 2 March 2024).

European Commission. Directorate General for Energy., & Kantar. (2019). Europeans' attitudes on EU energy policy. Publications Office. https://doi.org/10.2833/500568

Fizaine, F., & Court, V. (2016). Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy, 95, 172–186. https://doi.org/10.1016/j.enpol.2016.04.039

Gruenbichler, R. (2023). Implementation Barriers of Artificial Intelligence in Companies. In: Proceedings of FEB Zagreb International Odyssey Conference on Economics and Business, 5(1). https://doi.org/10.22598/odyssey/2023.5

Haas, R., Resch, G., Panzer, C., et al. (2011). Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources – Lessons from EU countries. Energy, 36(4), 2186–2193. https://doi.org/10.1016/j.energy.2010.06.028

Hassan, S. T., Batool, B., Zhu, B., et al. (2022). Environmental complexity of globalization, education, and income inequalities: New insights of energy poverty. Journal of Cleaner Production, 340, 130735. https://doi.org/10.1016/j.jclepro.2022.130735

Hinrichs-Rahlwes, B. (2013). Sustainable Energy Policies for Europe, 1st ed. CRC Press. pp. 163–170. https://doi.org/10.1201/b15934-22

Iarmenco, M., Donos, E., Plotnic, O. (2020). Promotion of renewable energy in the European Union. In: Tofan, M., Bilan, I., Cigu, E. (editors). Proceedings of the EUFIRE 2020 International Conference on European Finance, Business and Regulation. pp. 709-716.

Işık, C., Ongan, S., Ozdemir, D., et al. (2024). Renewable energy, climate policy uncertainty, industrial production, domestic exports/re-exports, and CO_2 emissions in the USA: A SVAR approach. Gondwana Research, 127, 156–164. https://doi.org/10.1016/j.gr.2023.08.019

Jaksic, S., Erjavec, N., & Cota, B. (2020). Export and total factor productivity of EU new member states. Croatian Operational Research Review, 11(2), 263–273. https://doi.org/10.17535/crorr.2020.0021

Kadocsa, G., Borbás, L. (2010). Possible ways for improving the competitiveness of SMEs. A Central-European approach. In: Fehér-Polgár, P. (editors). Proceedings of the 8th International Conference on Management, Enterprise and Benchmarking MEB 2010. pp. 103-121.

Kersan-Škabić, I., & Tijanić, L. (2017). Regional absorption capacity of EU funds. Economic Research-Ekonomska Istraživanja, 30(1), 1191–1208. https://doi.org/10.1080/1331677x.2017.1340174

Khan, I., Zakari, A., Dagar, V., et al. (2022). World energy trilemma and transformative energy developments as determinants of economic growth amid environmental sustainability. Energy Economics, 108, 105884. https://doi.org/10.1016/j.eneco.2022.105884

Khan, I., Zakari, A., Zhang, J., et al. (2022). A study of trilemma energy balance, clean energy transitions, and economic expansion in the midst of environmental sustainability: New insights from three trilemma leadership. Energy, 248, 123619. https://doi.org/10.1016/j.energy.2022.123619

Kiang, M. Y., & Fisher, D. M. (2008). Selecting the right MBA schools – An application of self-organizing map networks. Expert Systems with Applications, 35(3), 946–955. https://doi.org/10.1016/j.eswa.2007.08.053

Markuz, A., Mustajbegović, S., & Hrvatin, S. (2022). Obnovljivi izvori energije u kontekstu dobre prakse projekta FIRESPOL. Zbornik Sveučilišta Libertas, 7(8), 39–49. https://doi.org/10.46672/zsl.7.8.3

Papież, M., Śmiech, S., & Frodyma, K. (2018). Determinants of renewable energy development in the EU countries. A 20-year perspective. Renewable and Sustainable Energy Reviews, 91, 918–934. https://doi.org/10.1016/j.rser.2018.04.075

Peša, A., Bosna, J., Perović, E. (2017). Economic indicators of the Croatian integration in the European Union. In: Mašek Tonković, A. (editor). Proceedings of the 6th International Scientific Symposium Economy of Eastern Europe - Vision and Growth. pp. 918-926.

Ringel, M., & Knodt, M. (2018). The governance of the European Energy Union: Efficiency, effectiveness and acceptance of the Winter Package 2016. Energy Policy, 112, 209–220. https://doi.org/10.1016/j.enpol.2017.09.047

Strunz, S., Lehmann, P., & Gawel, E. (2021). Analyzing the ambitions of renewable energy policy in the EU and its Member States. Energy Policy, 156, 112447. https://doi.org/10.1016/j.enpol.2021.112447

Taghizadeh-Hesary, F., Zakari, A., Yoshino, N., et al. (2022). Leveraging on energy security to alleviate poverty in asian economies. The Singapore Economic Review, 68(04), 1063–1090. https://doi.org/10.1142/s0217590822440015

Tian, J., & Liu, Y. (2021). Research on Total Factor Productivity Measurement and Influencing Factors of Digital Economy Enterprises. Procedia Computer Science, 187, 390–395. https://doi.org/10.1016/j.procs.2021.04.077

Wyns, T., Khatchadourian, A., Oberthur, S. (2014). EU Governance of Renewable Energy post 2020 - Risks and Options. Available online: https://eu.boell.org/sites/default/files/eu_renewable_energy_governance_post_2020.pdf (accessed on 2 March 2024).

Xu, H. (2016). Linear and nonlinear causality between renewable energy consumption and economic growth in the USA. Zbornik Radova Ekonomskog Fakulteta u Rijeci: Časopis Za Ekonomsku Teoriju i Praksu, 34(2), 309–332. https://doi.org/10.18045/zbefri.2016.2.309

Yu, Z., Kamran, H. W., Amin, A., et al. (2023). Sustainable synergy via clean energy technologies and efficiency dynamics. Renewable and Sustainable Energy Reviews, 187, 113744. https://doi.org/10.1016/j.rser.2023.113744

Zhang, C., Khan, I., Dagar, V., et al. (2022). Environmental impact of information and communication technology: Unveiling the role of education in developing countries. Technological Forecasting and Social Change, 178, 121570. https://doi.org/10.1016/j.techfore.2022.121570