Prediction of the Impact of Digitization on the Energy Sector in EU Countries

Predikcia vplyvu digitalizácie na energetický sektor v krajinách EÚ

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Abstract

Digitalization in the transformation of the energy sector in EU countries is a hot topic today and, according to recent studies, it is proving to be a desirable transition to efficient solutions for the future. The paper focuses on the potential impacts of digital technologies on energy efficiency, resource management, and sustainability. The main aim is to predict how digital innovations, such as Information-Communication Technologies (ICT), Smart Grids, Internet of Things (IoT), Artificial Intelligence (AI), and Big Data, can enhance the operational efficiency and environmental performance of the energy sector. The study identifies key challenges, including data security, infrastructure costs, and regulatory frameworks, while highlighting the benefits of digital solutions for energy transition and climate goals. The results provide insights into the future development of the energy sector in the context of the EU's sustainable development agenda.

Keywords:
digitalization, technology impact, energy efficiency, sustainability

Introduction

The energy sector has undergone significant changes in recent decades, primarily driven by digitalization. The introduction of ICT, IoT, AI and Big Data in the production, distribution and consumption of energy is creating a new ecosystem that is more efficient, flexible and sustainable. Digitalization is not only

changing the technical infrastructure of the energy sector, but also fundamentally affecting its economic, social and environmental aspects.

One of the most important benefits of digitalization in the energy sector is increased energy efficiency. Chinie (2019) highlights in his study that ICT significantly contribute to improving energy productivity by enabling more accurate monitoring and management of energy consumption. Smart Grids enable the optimization of energy flows between producers and consumers in real time, thereby reducing energy losses and increasing the efficiency of the entire system.

Similarly, Ha (2022a) points out that digital public services and platforms play a key role in improving energy security. By implementing digital tools for managing energy flows, countries can monitor their energy infrastructure more effectively, respond faster to disruptions, and reduce the risk of outages. This effect is particularly important in the context of the transition to renewable energy sources, which are often dependent on intermittent sources such as wind and solar power. These studies show that digitalization is not just a technological improvement, but also a systemic solution that allows for more dynamic and efficient management of complex energy networks. Without these tools, the transition to decentralized energy sources and renewables would not have been possible to the extent we see today.

Potential of digitalization in the energy sector

The digital transformation contributes to the decarbonization of the energy supply by reducing reliance on fossil fuels and encouraging the adoption and integration of renewable energy sources into the European energy system, enhancing sustainability. Simultaneously, according to Kasianenko et al. (2024), digitalization not only improves operational efficiency but also drives the emergence of new sectors, segments, or professions, unlocks new opportunities for European businesses, and supports the development of secure technologies. Moreover, it empowers citizens, consumers, and communities to actively participate in the energy market. In the energy sector, companies are increasingly adopting digital technologies to optimize operations. For instance, British Petroleum utilizes IoT solutions to monitor the condition of its wells, while Shell employs the Sensabot system—a remotely operated robot capable of functioning in hazardous environments. According to the Ukrainian Future Institute, by 2030, up to 60% of Ukraine's added value will come from high-tech industries such as artificial intelligence, robotics, bioengineering, 3D printing, and nanomedicine.

The impact of digitalization is measured by the added value it generates across economic sectors at the macro level, or for individual products and services at the micro level. The primary outcome of digitalization is the transformation of value chains, reshaping business processes and market dynamics.

This transformation is already underway, with several EU policies addressing key areas of innovation, such as ensuring efficient and secure data exchange and implementing smart meter deployment. Building on these policies, the European Commission's Action Plan will lay the foundation for an integrated energy system that supports increasing market interconnectedness and enhances cooperation between digital and energy value chains. The study by Kwilinski et al. (2023) shows that more efficient energy systems can contribute to reducing social inequalities. Digitalisation can improve access to energy resources even in more remote areas and reduce energy costs for households and small businesses.

An interesting perspective is also offered by the study by Kara et al. (2024), which examines digitalisation in Montenegro. The research shows how digitalisation can contribute to the modernisation of energy infrastructure in smaller countries and thus support economic development. In the case of Montenegro, digitalisation has improved the management of public services, including energy, and enabled more efficient planning and distribution of energy resources.

Digitalisation in energy has the potential to become a significant tool for promoting social inclusion. Thanks to smart solutions, disadvantaged groups can also have better access to energy, which is an important step towards energy justice.

The transition to renewable energy sources is one of the main priorities of the current energy sector. The study by Thanh et al. (2023) analyses how digitalisation affects energy security in Europe and highlights that smart grids enable more efficient integration of renewables such as solar and wind energy into existing distribution systems. Nham et al. (2023) focus on the use of marine resources and the importance of digitalisation in their efficient management. Digital tools enable more accurate monitoring and management of marine energy resources, contributing to the sustainable use of these potentially rich energy areas.

The deployment of smart technologies is essential for the successful integration of renewable energy sources into energy networks. Digital platforms can manage the flow of energy from decentralised sources, monitor supply and demand and optimise distribution to minimise losses and ensure grid stability.

While digitalisation brings many benefits, there are also challenges that need to be addressed. The biggest challenge is cybersecurity. As the number of digital tools and interconnected devices in energy networks increases, so does the risk of cyberattacks that could cause widespread power outages. Ciechanowska (2020) examines how Horizon Europe supports the transformation of the energy sector by funding innovative technologies. The study highlights the importance of digitalisation in the transition to renewable energy, smart grids and energy efficiency. The programme provides opportunities to develop digital solutions for monitoring and optimising energy flows. Another challenge is ensuring equal access to digital technologies. Not all regions have the same infrastructure and access to modern technologies, which can exacerbate disparities between countries and regions.

Methodology

This research utilizes a mixed-methods approach to examine the relationship between digitalization and energy efficiency in EU-27 countries.The analysis is grounded in both quantitative data analysis and a review of relevant literature to provide a comprehensive understanding of the topic. Primary data for the analysis were collected from the Eurostat database (2024), which includes statistics on digitalization rates and energy efficiency indices for EU-27 member states. Additional data sources included reports from the International Energy Agency (IEA) and scholarly articles to validate and complement the findings.

The sample comprises all 27 EU member states to ensure a representative comparison. The period of analysis focuses on the most recent data available for the year 2022. Countries were grouped based on their energy efficiency, as indicated by the dendrogram, into high, medium, and low-efficiency groups. This classification enabled a detailed examination of the variations among the countries. Two primary analytical techniques were applied:

1. Regression Analysis: The relationship between digitalization and energy efficiency was modeled using polynomial regression and Random Forest regression to capture potential non-linearities.
2. Comparative Analysis: A comparative approach was utilized to analyze the socio-economic and policy contexts of the countries in different efficiency categories.

The study acknowledges limitations in data availability and the potential for unobserved variables that could influence the relationship between digitalization and energy efficiency. This mixed-method approach provides a balanced and robust framework for understanding the complex relationship between digitalization and energy efficiency in the EU-27.

Results

The connection of digitalization and energy represents a significant step towards sustainable cities of the future and transformation of energy systems. Smart buildings not only minimize their ecological footprint, but can also become active participants in energy networks, capable of producing energy (e. g. through solar panels) and sharing it with other buildings. The digitalization of the energy sector has not only technical but also significant socio-economic consequences.

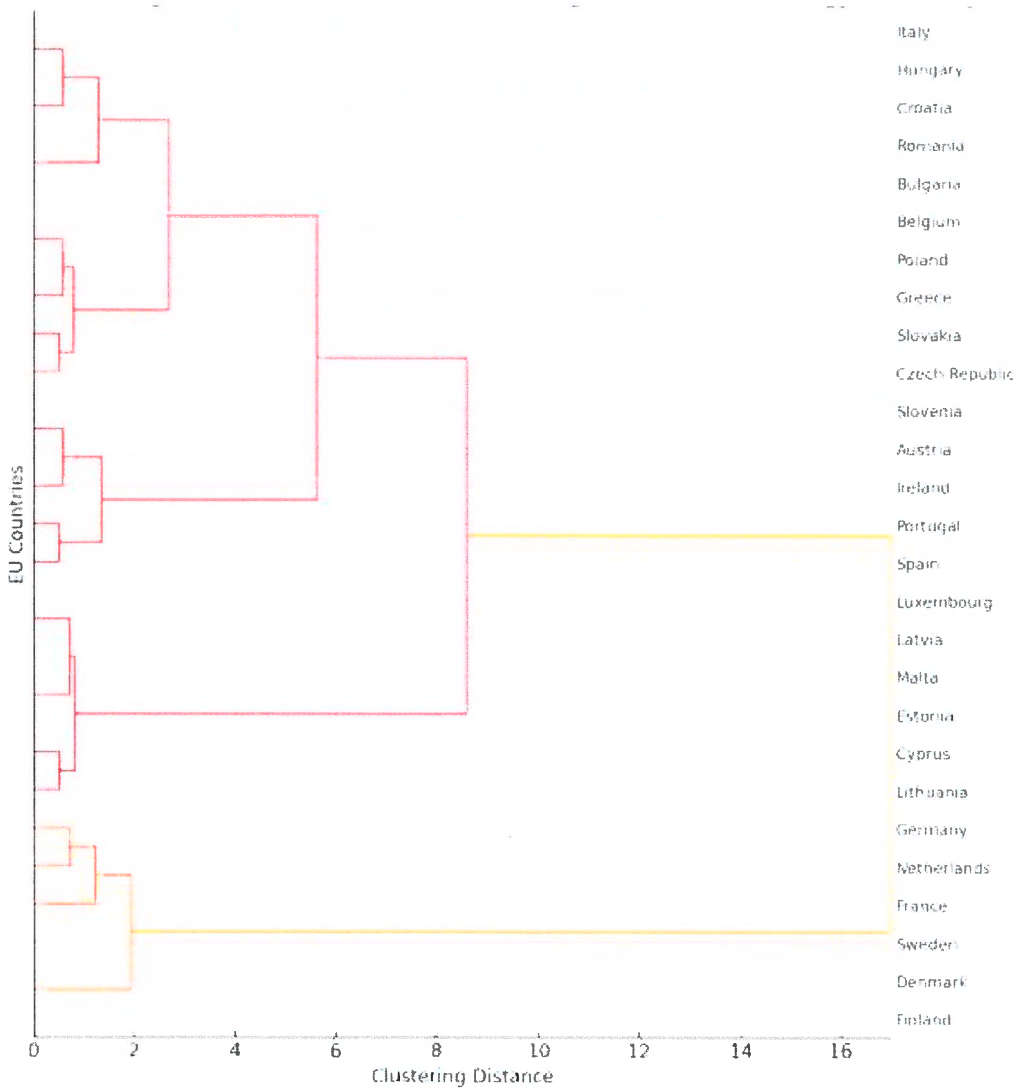


Fig. no. 1 Energy efficiency of EU-27 countries

Source: Own research

The dendrogram of EU-27 countries based on digitalization and energy efficiency (Fig. no. 1) shows that countries can be classified into three main groups based on how efficiently they use energy.

The most efficient countries, which serve as a model for other Member States, include Denmark, the Netherlands (invests in innovative solar technologies), Germany (a European leader in renewables, dominated by wind power plants), France, Sweden and Finland (using large amounts of bioenergy) (Igliński et. al, 2024). Their industries are highly digitalised and efficient, with smart grids and modern technologies playing a significant role in saving energy

and reducing dependence on fossil fuel imports. Strict regulations and extensive investment in research and innovation help them maintain low energy consumption per unit of GDP.

The medium-efficient countries include Spain, Portugal, Austria, Slovenia, Ireland, the Czech Republic, Slovakia, Poland and Hungary. These countries are in a transitional phase, combining traditional energy sources with increasing use of renewable energy. For example, Spain and Portugal already produce a large part of their electricity from solar and wind energy but are still to some extent dependent on fossil fuels. Central European countries such as the Czech Republic, Slovakia, Poland and Hungary have higher energy intensity due to their strong industrial sector and are gradually trying to modernize their infrastructure. They receive funding from EU funds for the transformation of the energy sector, which helps them reduce energy consumption and improve overall efficiency (Crnčec et al., 2023).

Less efficient countries such as Bulgaria, Romania, Croatia and Greece face higher energy intensity, which is due to several factors. Their infrastructure is often outdated, with a high share of coal-fired power plants and insufficient modernization of the energy grid. These countries also have lower investments in renewables and less stringent regulatory measures, which makes them more dependent on traditional fossil fuels. Economic constraints and lower public finances complicate the deployment of energy-efficient technologies, leading to higher energy consumption per unit of GDP. A transition to more sustainable energy sources will be essential for these countries to meet the EU's climate goals while reducing their economic vulnerability to energy price fluctuations (Siksnelyte-Butkiene et al., 2022).

The relationship between digitalization and energy efficiency is complex and controversial. Some studies even report that it is difficult to draw a conclusion due to the different digital impacts on energy consumption (Lin – Zhu, 2021, Bansal et al., 2022).

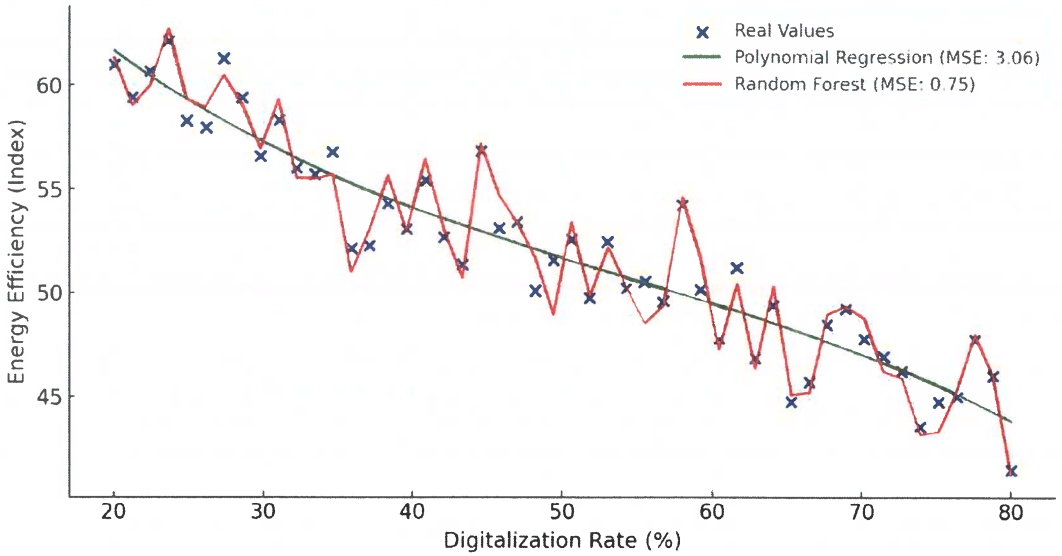


Fig. no. 2 Comparison of regression models: digitalization vs. energy efficiency

Source: Own research according to Eurostat (2024)

Fig. no. 2 compares two regression models – Polynomial Regression and Random Forest – in predicting the relationship between digitalization rate and energy efficiency.

The x-axis shows the Digitalization Rate (%), while the y-axis shows the Energy Efficiency (Index). The blue crosses represent the actual values, while the green curve shows the polynomial regression predictions and the red line shows the Random Forest predictions.

When comparing the accuracy of the models, it can be seen that Random Forest has a lower mean square error (MSE: 0.75) compared to polynomial regression (MSE: 3.06), which indicates that it better captures the variability of the data and is more accurate in prediction. Random Forest adapts better to local fluctuations and can capture the nonlinear relationships between digitalization and energy efficiency, while polynomial regression produces a smoother curve that cannot fully reflect the variability of real data. It is generally assumed that the more companies or countries implement digital technologies, the less efficient they manage energy. However, this hypothesis is not universally valid. As Graph 1 shows, countries such as Denmark, the Netherlands, Germany, France, Sweden and Finland have been able to combine a high level of digitalization with energy efficiency. This success is the result of targeted investments in smart grids,

automated demand management systems, and infrastructure modernization, as confirmed by research by Lin and Huang (2023).

Despite these positive examples, the number of countries with such a balanced combination is still relatively low, which is reflected in theoretical models and statistical results that suggest a negative correlation between digitalization and energy efficiency. Given these ambiguous relationships, the authors analysed a two-way effect model, adding a quadratic term of the main explanatory variable to the model to explore the nonlinear nature of the relationship. This analysis focused on three main aspects: the nature of the national economy, the availability of energy resources, and the level of electrification.

According to Lange et al. (2020), the overall relationship between digitalization and energy consumption is influenced by four key factors: direct impacts of digitalization, changes in energy efficiency, impacts on economic growth, and structural changes in sectors. These factors may explain why digital technologies contribute to reducing energy intensity in some countries, while in others they may lead to its increase.

If there were a negative correlation between digitalization and energy efficiency, it would mean that higher levels of digitalization would not contribute to improving efficiency, but on the contrary would reduce it. This scenario could indicate that digital technologies consume more energy than they can save, which could be a consequence of the high consumption of servers and data centers. Less digitalized countries could use traditional but more efficient energy management methods. The implementation of digital solutions could be inefficient if not properly optimized. However, in practice, we often observe a positive correlation, as digitalization usually increases the efficiency of energy management and allows for the optimization of consumption. For example, a study by Lin and Xie (2023) confirmed that the introduction and use of digitalization elements has a positive impact on the efficiency of enterprises in the energy industry. It is important to note that the perception of digitalization as a tool for improving energy efficiency is supported by many experts and organizations. For example, the International Energy Agency (IEA) highlights in its report that digital technologies can transform energy systems, making them more interconnected, reliable and sustainable. Convenient digital services increase energy demand, while the use of digital technologies can cause a rebound effect, which paradoxically leads to higher total energy consumption (Røpke – Christensen, 2012, Lin – Zhu, 2021).

In summary, although theoretically a negative correlation between digitalization and energy efficiency could indicate that digitalization technologies

consume more energy than they can save, empirical evidence and expert analyses often point to a positive impact of digitalization on energy efficiency.

Conclusion

The future of energy will inevitably be digital. However, the ability to combine technological progress with a focus on sustainability, social justice and security will be key to success. Creating robust and secure digital platforms for energy systems will be a priority, as will educating professionals and the public about the opportunities and risks associated with the digital transformation.

Digitalization is fundamentally changing the energy sector. It enables more efficient management of energy production and consumption, improves energy efficiency, supports the integration of renewable sources and contributes to socio-economic development. However, it also brings new challenges, such as ensuring cybersecurity and equal access to digital technologies. Shared data and digital infrastructure are central to coordinating the entire energy system. They play a crucial role in managing its growing complexity while minimizing consumer costs. Enhanced data quality and seamless data exchange will enable more efficient planning and operation of energy infrastructure, optimizing performance and resource allocation (Kasianenko et al., 2024).

The importance of digitalization as a tool for integrating migrants into the labour market and optimizing work processes in the energy sector is highlighted. Digitalization also enables better planning of labour resources and increasing the efficiency of energy projects (But et al., 2023). The future of energy will be inextricably linked to digitalization. The successful transition to a sustainable, efficient and equitable energy system will depend on the ability to harness the potential of modern technologies, while protecting the interests of society and the environment.

Acknowledgment

This research was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research, and Sport of the Slovak Republic as part of the research project ***VEGA 1/0713/24 Digital economy as a key challenge for the transformation of enterprises in Slovakia.***

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