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THE ENABLING IMPACT OF DIGITAL TECHNOLOGIES ON PENETRATION OF RENEWABLE ENERGY

Ruta Nedzinskiene[1]*, Dalia Streimikiene[2]
[1]Dr., Vytautas Magnus University, LITHUANIA, ruta.nedzinskiene@ktu.lt
[2] Prof. Dr., Vytautas Magnus University, LITHUANIA, dalia.streimikiene@vdu.lt
*Corresponding author

Abstract

World leaders have emphasized that to avoid dramatic consequences of climate change by the end of this century, global warming must be limited to 1.5°C. Achieving this goal requires a substantial reduction in greenhouse gas emissions, particularly carbon dioxide. The adoption of renewable energy presents numerous significant benefits over conventional fossil fuels, including environmental friendliness, sustainability, and safety. The digital age offers opportunities for energy system transition. This paper aims to address the main question: what is the enabling impact of digital technologies on penetration of renewable energy sources in the transition to climate-neutral society? The findings underscore the critical role of digital technologies in promoting the integration of renewable technologies and facilitating climate change mitigation efforts, as these technologies help to reduce information asymmetry, decrease production costs, and optimize resource allocation within the renewable energy sector. The results obtained may serve for formulating policies aimed at improving energy systems for reducing carbon emissions, mitigation of climate change and protecting the environment.

Keywords: Digital Technologies; Renewable Energy; Digital Economy

1. INTRODUCTION

There is an urgent imperative to decarbonize the energy sector, which can be accomplished by shifting from fossil fuels to clean energy alternatives, such as renewable resources. The European Union has proposed an increase in the share of renewable energy production to at least 42.5% by 2030. Digitalization, under the framework of Industry 4.0, transforms industrial value chains, making production systems more efficient, adaptable, and automated; this transformation is particularly relevant in energy management, where digital technologies enhance operational efficiency and sustainability (Khan et al., 2025). Digital transformation is highlighted as a strategic approach to improving energy efficiency, which is essential for stakeholders interested in sustainability and renewable energy adoption (Alofaysan et al., 2024). Technologies such as AI, IoT, machine learning, big data, blockchain, Digital Twins facilitate the integration and optimization of renewable energy systems, supporting energy security and resilience.

Most researchers highlight the positive effects of digitalization to renewable energy as the interconnection between digitalization and smart grid optimization enhances the efficiency and sustainability of renewable energy integration in the global power system (Campana et al., 2025), digitalization in renewable energy is associated with reduced transmission losses and costs (Pakulska & Poniatowska-Jaksch, 2022), digital technologies enhance performance management and cost optimization in renewable energy systems by providing timely maintenance services and improving energy efficiency (Majidi Nezhad et al., 2024). Moreover, digitalization facilitates green economic growth by promoting green technology innovation, which is crucial for the development of renewable energy. This integration supports the expansion and efficiency of renewable energy sources (Hao et al., 2023). However, other researchers also highlight the negative points of the impact as digitalization can lead to increased energy demand and electronic waste, which may offset some of its positive impacts on renewable energy and environmental quality (Jóźwik et al., 2023).

This paper aims to address the main question: what is the enabling impact of digital technologies on penetration of renewable energy sources in the transition to climate-neutral society?

Systematic literature review as well as statistical data analysis were used for the investigation. The results obtained may serve for formulating policies aimed at supporting the penetration of renewable energy and reducing carbon emissions towards sustainable development goals.

2. SYSTEMATIC LITERATURE REVIEW

The most recent articles from Web of Science database containing the keywords of the topic were selected for the systematic literature review. Systematic literature review was revealed the main enabling effects of digital technologies on renewable energy as well as some challenges and barriers.

2.1 The enabling impact of digital technologies

The enabling impact of digital technologies on renewable energy covers the 4 main areas of energy efficiency, improved data management, optimization of energy structure and save and sustainable energy systems that all lead to the environmental benefits and mitigation of climate change (Fig. 1).

2.1.1 Energy efficiency

Technologies like IoT, AI, machine learning, and big data are considered key drivers for digital development in the energy industry (Pakulska & Poniatowska-Jaksch, 2022). The digitalization of energy systems, powered by AI and computational intelligence, allows for advanced controls and performance predictions, leading to unprecedented levels of energy efficiency and sustainability (Kong et al., 2024). Digital technologies (DTs) support intelligent monitoring, predictive maintenance, fault diagnosis, and condition monitoring in renewable energy systems, enhancing operational efficiency and reliability (Majidi Nezhad et al., 2024). Digitalization positively impacts energy efficiency by integrating digital technologies and green innovations, which include renewable energy sources. This integration optimizes energy use and supports the efficient management of resources (Alofaysan et al., 2024). Digital technology improves the matching efficiency of supply and demand, increases energy efficiency, and boosts the proportion of clean energy used, thereby supporting renewable energy initiatives (Hao et al., 2023). Artificial Intelligence (AI) is the most widely adopted digital technology within the energy sector, playing a crucial role in improving safety, efficiency, and reliability while reducing costs (El Zein & Gebresenbet, 2024). The reductions in energy intensity and consumption correlated with increased digitalization highlight the capacity of digitalization to facilitate more efficient energy utilization, aligning with the European Union's focus on enhancing energy productivity and sustainability via technological innovations.

2.1.2 Improved data management

Big data analytics play a crucial role in optimizing energy systems by forecasting renewable energy generation, managing energy storage systems, and coordinating energy dispatch, thus maximizing the adoption of renewable energy sources while ensuring grid stability. Digital platforms and software solutions facilitate the integration and optimization of multi-energy systems, enabling real-time data-based decision-making for energy forecasting, scheduling, and optimization (Kong et al., 2024). Recent advances in AI, particularly machine learning (ML) and deep learning (DL), offer new insights into solving complex challenges in renewable energy systems (Majidi Nezhad et al., 2024), digital technologies, such as AI and IoT, improve energy management by enabling dynamic performance predictions and advanced model predictive controls, optimizing the integration and operation of renewable energy systems like PVs and heat pumps (Zhou & Liu, 2024). Digitalization enhances the efficiency, manageability, and adaptability of energy systems, making them more effective in integrating renewable energy sources (Olabi et al., 2023). Digital platforms facilitate the swift transfer of data, improving energy management structures and markets, which supports renewable energy prospects (Ozturk et al., 2025). Digital technologies facilitate proficient collection, organization, and examination of data, thereby promoting a transition from traditional to digital business frameworks within the energy sector.

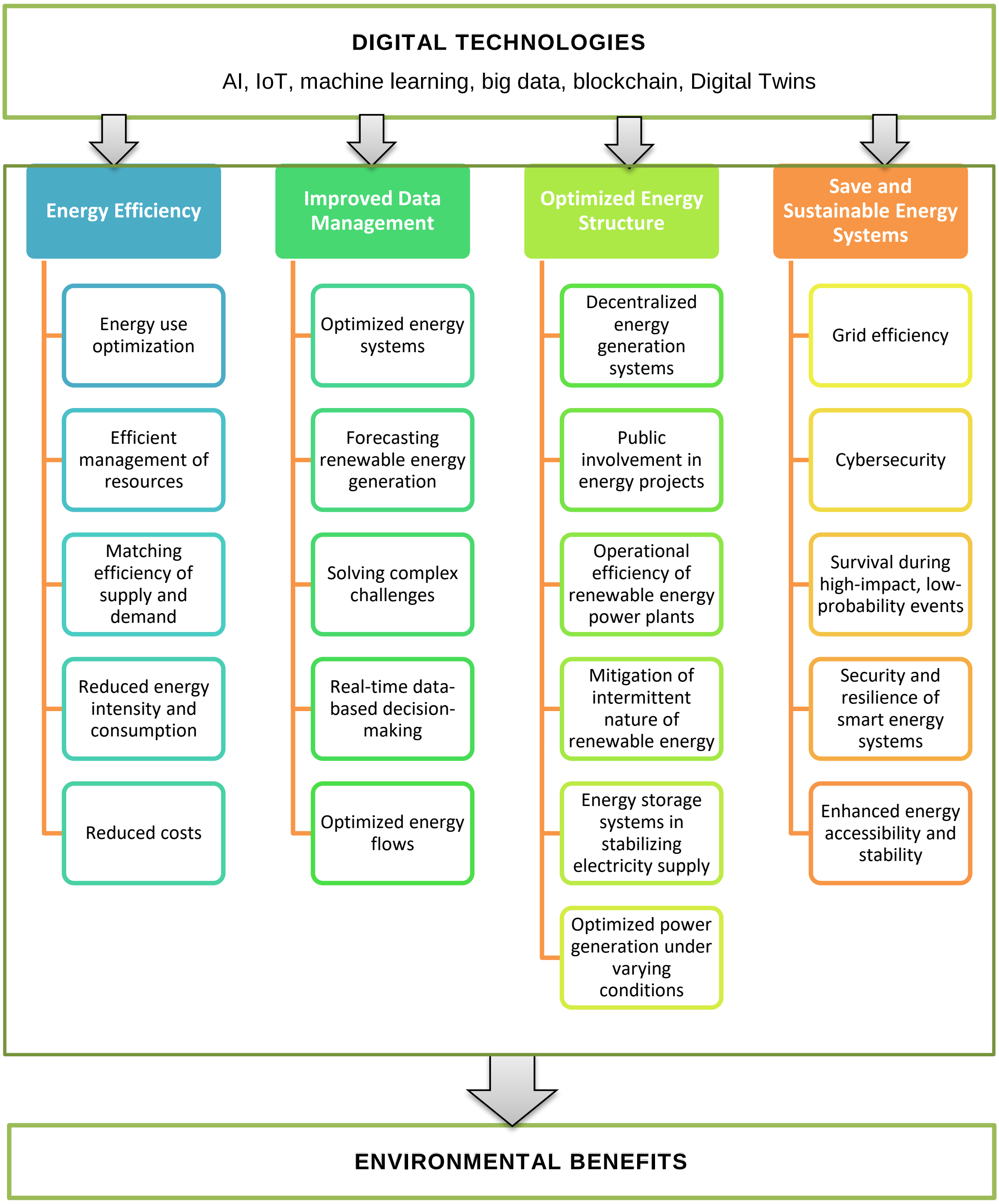

Fig 1. The enabling impact of digital technologies

2.1.3 Optimized energy structure

Digital technologies significantly contribute to the efficiency and diffusion of renewable energy systems, particularly in solar and wind power sector (El Zein & Gebresenbet, 2024). Digitalization supports the development of decentralized energy generation systems, such as rooftop solar panels and microgrids, which increase energy resilience, reduce transmission losses, and empower communities to generate clean energy independently (Kong et al., 2024). It significantly enhances renewable energy generation, by improving resource efficiency and fostering sustainable innovation (Jóźwik et al., 2023). Digitalization has a positive impact on renewable energy production by encouraging innovation and enhancing public involvement in energy projects, such as smart grids and sophisticated technologies crucial for renewable energy growth (Ozturk et al., 2025). The intermittent nature of renewable energy sources like wind and solar can be mitigated through digital technologies that facilitate integration with energy storage systems, optimizing energy production and consumption (Olabi et al., 2023). Digitalization integrates with solar photovoltaic systems through technologies like maximum power point tracking, which optimizes power generation under varying conditions (Wang & Xu, 2022). DTs aid in modeling and optimizing solar energy systems, addressing challenges posed by meteorological factors and enhancing prediction accuracy (Majidi Nezhad et al., 2024), it aids energy storage systems in stabilizing electricity supply, supporting renewable energy consumption by balancing power flow and smoothing output fluctuations (Wang & Xu, 2022). Digital technologies, particularly Digital Twins (DTs), enhance the operational efficiency of renewable energy power plants by enabling real-time monitoring, predictive maintenance, and operational simulations. This leads to optimized plant efficiency and reduces environmental impacts (Khan et al., 2025). Digital technologies, including AI and IoT, are crucial for optimizing energy flows, which is essential for integrating renewable energy sources effectively (Campana et al., 2025). The strategic implementation of digitalization within European Union member states maximizes energy usage efficiency and improves the energy framework through the incorporation of renewable energy sources, thereby advancing the EU's progression towards its sustainability goals.

2.1.4 Save and sustainable energy systems

Digitalization acts as a key enabler for building more sustainable and reliable energy systems, aligning with the objectives of the European Union and the United Nations 2030 Agenda. Digitalization facilitates the better integration of renewable energy into grids, plays a crucial role in supporting the transition towards sustainable practices in the energy sector, helps in proactive management through tools like demand forecasting and system health monitoring, which are essential for enhancing the resilience of renewable energy systems (Khan et al., 2025). Digital transformation through DTs is essential for achieving sustainability in renewable energy, facilitating simulation, physical implementation, and the development of cyber design tools (Majidi Nezhad et al., 2024). Digitalization enhances energy flexibility and resilience, crucial for managing intermittent renewable energy and adapting to climate change. This includes capabilities for power management and survival during high-impact, low-probability events (Zhou & Liu, 2024). Digitalization addresses the instability and collection challenges of renewable energy sources like solar and wind, enhancing their accessibility and stability (Wang & Xu, 2022). The implementation of digital technologies, encompassing cybersecurity measures, guarantees the operational efficacy, security, and resilience of the grid, which are essential for the seamless incorporation of renewable energy sources.

2.1.5 Environmental benefits

Digital solutions optimize resource use and reduce greenhouse gas emissions, contributing to sustainability goals (Campana et al., 2025). In the long term, digitalization promotes sustainable economic development by increasing non-fossil and renewable energy consumption and reducing $CO2$ emissions (Jóźwik et al., 2023). The integration of digitalization with renewable energy enhances the efficiency of digital activities in reducing carbon emissions. This synergy is crucial for advancing environmental sustainability within global value chains (Li et al., 2025). By reducing downtime and minimizing energy waste, DTs support cost-effective operations and help in lowering greenhouse gas emissions, thereby reinforcing their role in sustainable energy generation (Khan et al., 2025). Thus, the importance of digitalization impact on renewable energy is crucial and it leads to reduced GHG emissions, helps to mitigate climate change and is aligned with sustainable development goals.

2.2 Challenges and Barriers

Despite the benefits, digitalization faces challenges such as high costs and security risks, which are significant barriers to its adoption in the renewable energy sector (El Zein & Gebresenbet, 2024). Despite their potential, the integration of DTs in the energy sector faces challenges such as data acquisition, interoperability, and the need for standardization. Addressing these issues is critical for unlocking the full potential of digitalization in renewable energy (Khan et al., 2025). Digitalization can negatively impact renewable energy consumption if not aligned with sustainable standards. The energy-intensive nature of digital infrastructures, such as data centers and telecommunication systems, can increase energy demand, often relying on fossil fuels (Li et al., 2025). While digitalization generally supports renewable energy, the impact can vary across different regions and contexts, highlighting the need for tailored approaches to maximize benefits (Ozturk et al., 2025). The obstacles encompassing data integration, real-time data processing, and interoperability with legacy systems must be resolved to optimally exploit the capabilities of digitalization within the renewable energy sector.

3. EMPIRICAL INVESTIGATION

To evaluate relations between digital technologies and penetration of renewables the following steps were performed: 1) selection of indicators presenting digital technologies and renewable energy; 2) correlation analysis for the assessment of relations between selected indicators.

The digital economy and society indicators group from Eurostat database was selected for digital technologies indicators. This indicators group includes the following indicators' subgroups: 1) ICT usage in households and individuals; 2) ICT usage in enterprises; 3) Digital skills; 4) ICT sector; 5) Additional indicators of digitalization. The following most representative indicators, covering all areas of digital economy and society, were selected for further investigation (Table1).

Table 1. Digitalization indicators

Indicator	Description from Eurostat
Level of internet access – households	Percentage of households who have internet access at home. All forms of internet use are included. The population considered is aged 16 to 74.
Employed ICT specialists – total	Percentage of total employment
Share of enterprises' turnover on e-commerce	Within the last calendar year before the survey. Enterprises' receipts from sales through electronic networks as percentage from total turnover. Enterprises with at least 10 persons employed in NACE sectors C-N and S95.1, by size class.
Enterprises having received orders online (at least 1%) - % of enterprises	Within the last calendar year before the survey. Enterprises with at least 10 persons employed in NACE sectors C-N and S95.1, by size class.
Percentage of the ICT sector in Gross value added	Information and Communication Technology - total
Percentage of the ICT sector personnel in total employment	Information and Communication Technology - total

Data source: Eurostat

As for penetration of renewable energy, the indicator Share of renewable energy in gross final energy consumption (%) was selected as it represents Eurostat Sustainable development indicators and is related to the Goal 7 Affordable and clean energy. The current situation in European Union is presented in Figure 2. It is to notice that Sweden (66,39%), Finland (50,75%) and Denmark (44,40%) are the EU leaders of renewable energy share. Lithuania (31,93 %) performs above the EU average (24,55%), while Malta (15,08%), Belgium (14,74%) and Luxembourg (14,36%) are lagging in terms of renewable energy share in gross final energy consumption.

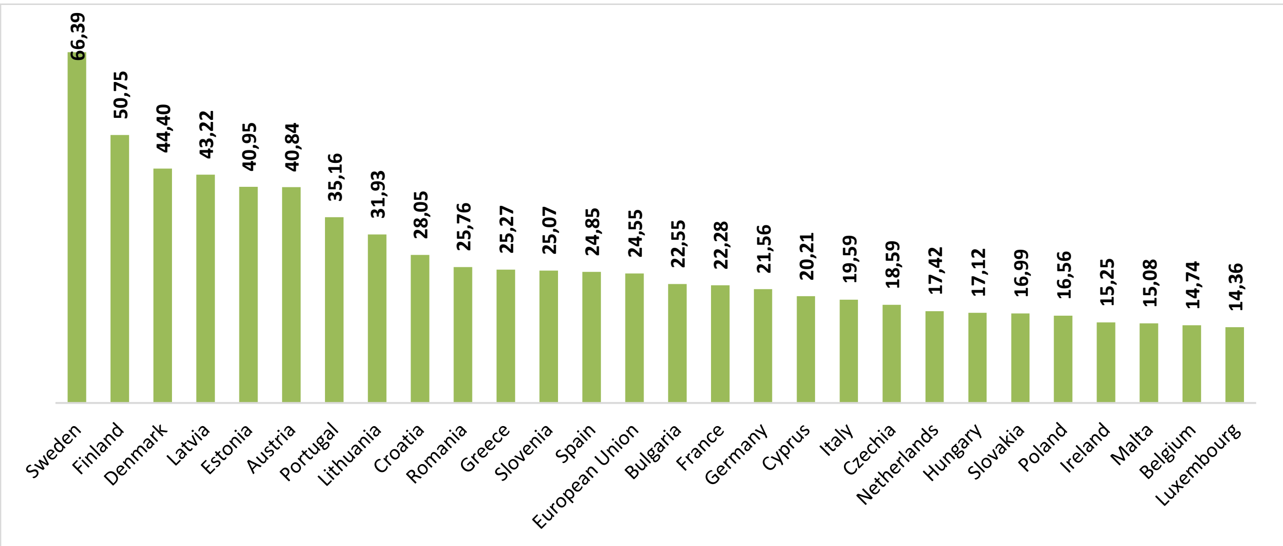

Fig.2. Share of renewable energy in gross final energy consumption in 2023, %.

Data source: Eurostat

The data of digitalization and energy efficiency indicators were collected from Eurostat for the 27 EU Member States over the period 2004–2023 (where available).

Correlation Analysis Correlation analysis was performed to test if there are significant relations between digitalization and penetration of renewables and what is the strength of these relations. Pearson correlation coefficients were calculated for testing linear relations and Spearman correlations were calculated for nonlinear relations (Table 2).

Table 2. Correlation analysis results

Indicators		Level of internet access	Employed ICT specialists	Share of enterprises' turnover on e-commerce	Enterprises having received orders online	Percentage of the ICT sector in Gross value added	Percentage of the ICT sector personnel in total employment
Pearson	Correlation	0.155**	0.339**	-0.005	0.284**	0.079	0.287**
	Sig. (2-tailed)	0.008	<0.001	0.938	<0.001	0.224	<0.001
Spearman	Correlation	0.086	0.109*	-0.075	0.184**	0.059	0.142*
	Sig. (2-tailed)	0.140	0.012	0.209	0.002	0.361	0.013

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

If was found that *Share of renewable energy* has weak but significant correlations with these indicators: *Level of internet access, Employed ICT specialists, Enterprises having received orders online, Percentage of the ICT sector personnel in total employment*. However no significant correlation was detected between the *Share of renewable energy* and *Share of enterprises' turnover on e-commerce, Percentage of the ICT sector in Gross value added.*

4. CONCLUSIONS

The use of digital technologies such as AI, IoT and blockchain is key to developing resilient, efficient, and sustainable energy systems, facilitating the energy transition towards sustainable development goals. Digital technologies have the enabling impact on penetration of renewables by enhancing energy efficiency, improving data management and optimization of energy systems, optimizing the energy structure by integrating energy from renewable sources, building more sustainable and reliable energy systems, aligning with the objectives of the European Union and the United Nations 2030 Agenda. The adoption of digital technologies, including cybersecurity solutions, ensures grid efficiency, security, and resilience. The penetration of renewables ensures a better energy mix and the use of cleaner energy that contributes to reduced GHG emissions and supports the sustainable development goals.

The share of renewable energy in gross final energy consumption was selected to measure the penetration of renewables as this indicator is part of the EU Sustainable Development Goals' indicators set. The EU leaders are Sweden, Finland and Denmark while Malta, Belgium and Luxembourg are lagging in terms of renewable energy share among EU countries. The indicators from Eurostat digital economy and society indicators group were chosen to measure digitalization. It was found that the share of renewable energy has weak but significant correlations with most selected digitalization indicators: Level of internet access, Employed ICT specialists, Enterprises having received orders online, Percentage of the ICT sector personnel in total employment. The empirical investigation has limitations as the data of all EU countries were selected for the research, while correlations between the indicators in developed and developing countries may be different.

The positive correlations between digitalization and renewable energy suggest that policymakers should focus on integrating digital technologies into energy strategies to maximize the benefits for all energy system. There is a need for policies that support the integration of digitalization and renewable energy to mitigate rebound effects and ensure equitable access to clean technologies. This integration is vital for achieving sustainability and net zero goals.

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