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THE ROLE OF DIGITALIZATION IN ENERGY EFFICIENCY MANAGEMENT AND TRANSITION TO A CARBON-NEUTRAL ECONOMY[1]

The article aims to investigate the impact of digital technologies on increasing energy efficiency and reducing carbon emissions in modern conditions. **The scientific novelty** of the article lies in the identification and quantitative analysis of the relationship between the level of digitalization and indicators of energy efficiency and decarbonization. For the first time, the DESI index has been used for a comprehensive assessment of digitalization in the context of energy security and sustainable development, establishing a statistically significant correlation between digital transformations and energy efficiency indicators. Additionally, recommendations have been proposed for adapting the international digitalization experience in the energy sector to Ukraine's national conditions, which is crucial for transitioning to a carbon-neutral economy. The article employs the following **scientific methods**: data analysis – to examine trends in digitalization and energy efficiency; cluster analysis – to systematize and classify information sources; correlation-regression analysis – to evaluate the relationship between the DESI (Digital Economy and Society Index) and WETI (World Energy Trilemma Index); synthesis and generalization of international experience – to develop recommendations for adapting leading international digitalization practices in the energy sector to the national conditions of Ukraine. The article analyzes the impact of digital technologies on increasing energy efficiency and reducing carbon emissions in the modern world. For this, the Google Trends tool was used, which made it possible to analyze the popularity of queries related to digitization and digital transformation over the past five years. Based on data from Scopus® and VOSviewer, the study identified five key clusters: decarbonization and digitalization, energy, energy efficiency, energy investment, and sustainable development. Correlation-regression analysis between digitalization and decarbonization was carried out. For this, the Digital Economy and Society Index (DESI) was chosen, which allows a comprehensive assessment of the digitalization process in different countries through such indicators as the level of Internet connection, digital skills of the population, the integration of digital technologies in business and the development of electronic services. The study results indicate a moderate correlation between the DESI and the World Energy Trilemma Index (WETI), which assesses energy security, equity, and environmental sustainability. A statistically significant positive relationship between these indices was also established, which indicates the relationship between the level of digitalization and energy efficiency indicators. **The practical significance** of the article lies in developing recommendations for implementing digital technologies to increase energy efficiency and reduce carbon emissions at the national level. The proposed strategies can be used to improve energy system management, integrate renewable energy sources, reduce costs, and enhance the resilience of energy systems to external threats, including cybersecurity. This article can be helpful for scientists, students, politicians, representatives of government organizations, and enterprises working in the field of energy and ecology. It will be a valuable source of information for those interested in sustainable development, the digitalization of energy systems, and the implementation of innovative technologies to improve energy efficiency.

Keywords: digitalization, energy efficiency, decarbonization, digitization, digital transformation, renewable sources, energy innovations, digital management, blockchain in energy.

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Problem statement. Digitization significantly influences core aspects of life and work organization in a postmodern society that is becoming more globalized and digitized. In this regard, it becomes crucial for organizations to plan digital transformation quickly, efficiently, and adequately to remain flexible and competitive in the market. In this context, understanding digitalization and related concepts becomes crucial [2]. Our research focuses on digitalization in the energy context, looking at its impact on improving energy efficiency, optimizing resources, and reducing carbon emissions.

Using the Google Trends toolkit [4], we researched and analysed the popularity of such queries as digitization, digitalization, and digital transformation among the world public – the study results are represented in Fig. 1.

Figure 1 represents the highest level of public interest in digital transformation. The level of interest in digitization and digitization is determined at approximately the same level.

In today's world, where the fight against climate change and decarbonization are becoming vital global challenges, digitization is gaining critical importance. The integration of digital technologies into the decarbonization strategy opens up new horizons for effective resource management, emissions monitoring, and the implementation of innovative solutions. Digitalization helps optimize the management of energy resources and increase energy use efficiency.

Analysis of recent research and publications. Digital technologies allow adequate energy supply and demand management, which helps reduce losses and make for a more rational use of energy resources. By integrating them into the overall grid, digitalization makes it easier to manage decentralized renewable energy systems, such as solar and wind farms. Smart technologies and data analytics help energy companies track and reduce their carbon footprint, helping to achieve decarbonization goals. Automated systems and the Internet of Things (IoT) control and optimize energy consumption at all levels. Digitalization stimulates the development of carbon-neutral business models and promotes the implementation of innovative solutions for the sustainable development of energy.

Thus, digital technologies are critical in implementing decarbonization in the energy sector. In particular, the results of the analysis of scientific works in the Scopus database using the search keywords "digitalization AND decarbonization" made it possible to substantiate the relevance of this topic. So, the database for 2016–2024 contains 266 documents. The most significant number of them falls in 2023, fig. 2. It should be noted that many works on the topic have also been formed in the current year, even though the year has not yet ended.

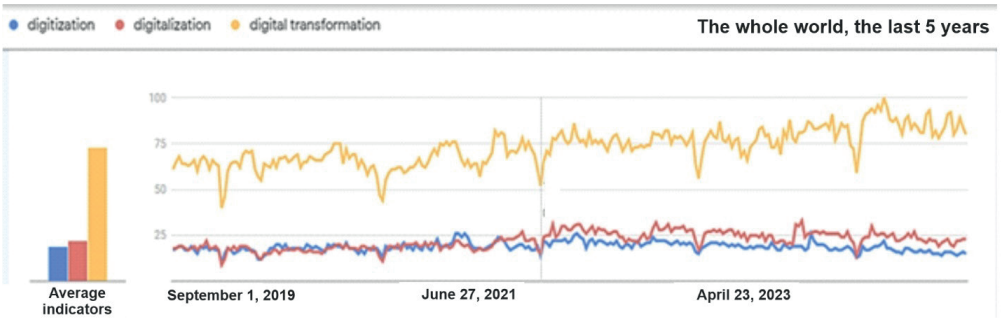

Figure 1. The level of popularity of requests digitization, digitalization and digital transformation among the world public over the past 5 years

Source: created by the authors on the basis of Google trends software tools [4]

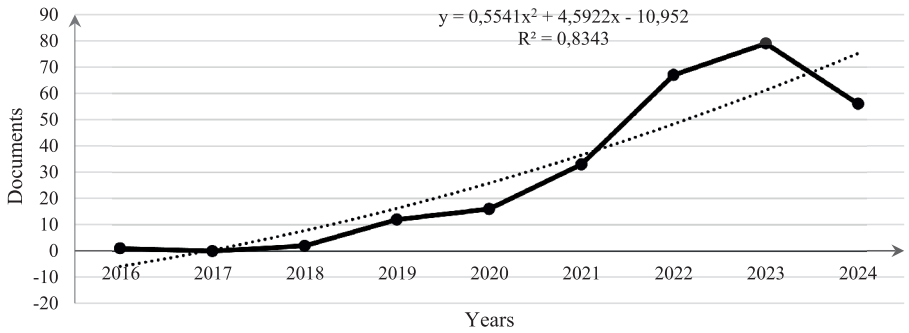

Figure 2. Dynamics of the number of scientific works for 2016–2024 based on the analysis of search results TITLE-ABS-KEY (digitalization AND decarbonization)

Source: created by the authors based on the Scopus database [13]

According to the Scopus database, the following domestic scientists devoted themselves to the problems of digitalization in decarbonization: Sakun L, Vedenina Yu., Khomenko M., Reznik D., Kovalenko M. [11], Maksimova I. ([11], [8]), Saveliev Ye. , I. Zvarych, V. Kurylyak, M. Lyzun, S. Sachenko, I. Lishchynskyi [8], G. Rudko [5] The results of the Scopus database became the basis for building a map of the network connection between the main concepts of "digitalization" and "decarbonization" using the VOSviewer software, fig. 3.

The purpose of the article to analyze and develop recommendations for the use of digitalization as a tool for increasing energy efficiency and decarbonization at the national level.

Summary of the main research material. The essence of digital energy efficiency management tools, digital tools in energy, and their main functions are represented in Fig. 4.

Digitalization helps optimize the management of energy resources and increase energy use efficiency. There are several digitalization indices related to energy, namely DESI (Digital Economy and Society Index), Smart Grid Index (SGI), ICT Development Index (IDI), Energy Digitalization Index, and Fostering Effective Energy Transition.

We chose the DESI (Digital Economy and Society Index) coefficient for the study because it describes the digitalization process through the analysis of critical aspects of the development of the digital economy and society. DESI covers indicators such as the level of Internet connectivity, the population's digital skills, the integration of digital technologies in business, and the development of e-services and innovation. This index allows a comprehensive assessment of the current state and progress of digital transformation in different countries, which is essential for analyzing the impact of digitalization on energy

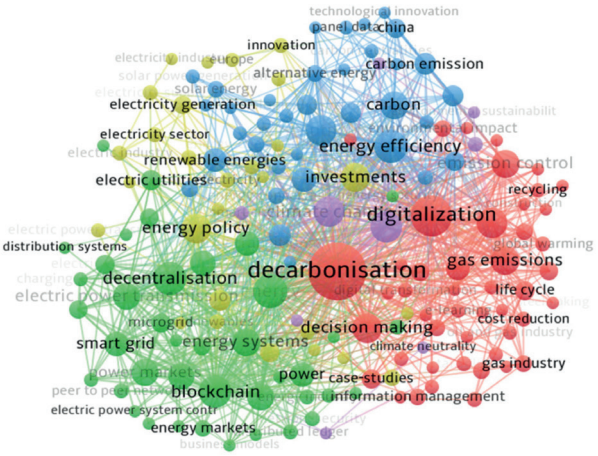

Figure 3. Map of the network connection between the main concepts TITLE-ABS-KEY (digitalization AND decarbonization) using software VOSviwer.

Source: created by the authors based on the Scopus database [13] and software VOSviwer version 1.6.16

Digital energy efficiency management tools are a set of software solutions and technologies used to monitor, analyze, control and optimize energy consumption in various industries, including industry, commerce and residential sectors. These tools allow you to increase energy efficiency, reduce energy consumption and reduce greenhouse gas emissions.

The main functions of digital energy efficiency management tools

Monitoring — Real-time energy consumption data collection and tracking.

Tools: *smart meters, energy management software (EEMS), and platforms using Internet of Things (IoT) technologies to integrate and manage energy systems.*

Analysis — Data processing and analysis to identify inefficient energy use and opportunities for savings.

Tools: *Building Automation Systems (BAS); Schneider Electric EcoStruxure*

Automation — Automatic regulation of energy supply and consumption systems to ensure optimal use of resources.

Tools: *Building Automation Systems (BAS); Schneider Electric EcoStruxure*

Prognostication — Using analytical models to predict future energy consumption and identify potential problems.

Tools: *Simuwatt; Planon Energy Management*

Figure 4. The concept of digital energy efficiency management tools and their main functions

Source: generated by the author based on [17]

efficiency and decarbonization. This index evaluates the digital progress of EU countries in various areas, including implementing digital technologies in energy to improve energy efficiency [12].

The values of the DESI Digital Economy and Society Index (Digital Economy and Society Index) for EU countries over the last three years are shown in Fig. 5.

Data analysis in Figure 5 allows us to draw the following conclusions. In 2023, EU countries will continue to show progress in the digital economy and society. Finland, Denmark, and Sweden are leading the way, with high DESI scores, indicating their advanced level in digital technology. Most countries, including the Netherlands, Ireland, and Estonia, show gradual growth. However, some countries, such as Romania and Bulgaria, remain in low positions, although their indicators also increase. EU countries are taking significant steps forward in developing digital infrastructures and services.

It is necessary to characterize the dynamics of the DESI index for Ukraine separately. In 2021, Ukraine's Digital Economy and Society Index (DESI) was 37.5. This indicates that Ukraine was at a low level of digitization compared to many European countries. 2022 Ukraine saw a moderate improvement; the DESI increased to 39. This indicates gradual progress in digital technologies, although the level remains low. In 2023, the Index rose to 41.2. This shows further, but small, progress in digitization. Ukraine still lags behind most European countries but continues to implement digital solutions and infrastructures gradually. Ukraine is showing slow but steady progress in digitization, with a gradual increase in the DESI index over recent years. The low level of digitization indicates the need for further development of digital infrastructure, improved access to digital services and technologies, and investment in education and training. Ukraine needs to accelerate the implementation of digital solutions to enhance its competitiveness in the international arena and support economic development.

One of the parameters reflecting the level of energy efficiency is the World Energy Trilemma Index, which evaluates three critical aspects of the energy system: energy security, energy justice, and environmental sustainability. Using this index allows you to analyze how countries balance the need for reliable energy supply, the

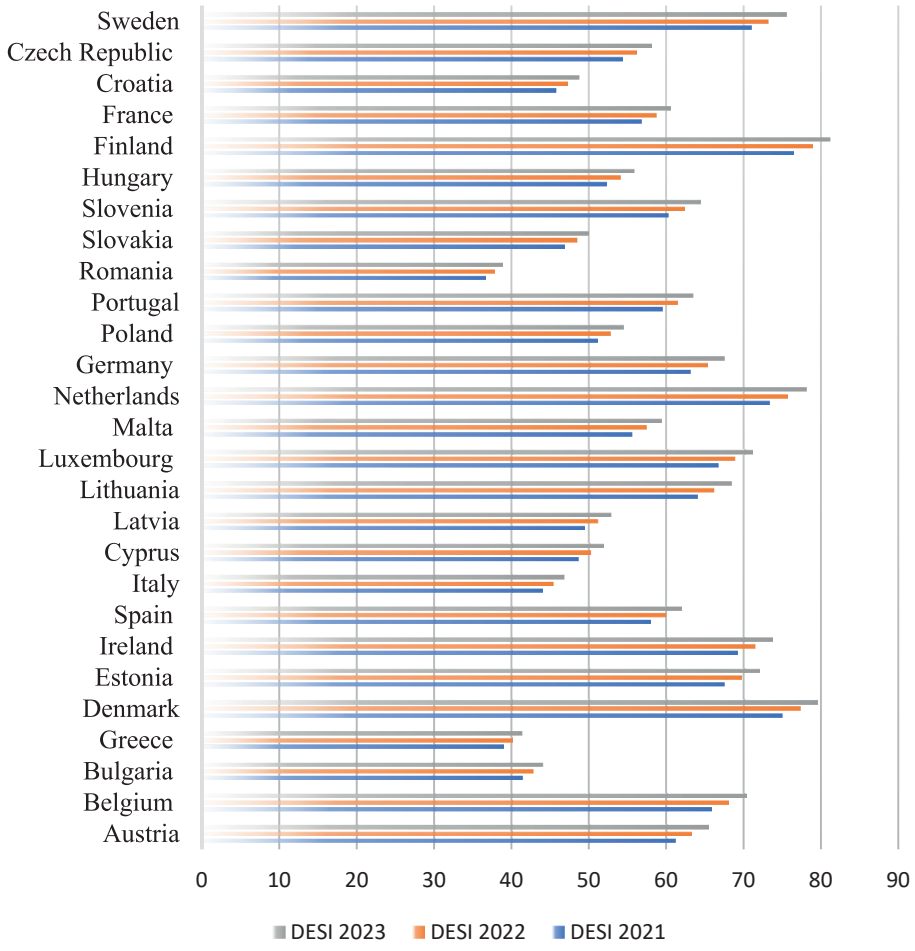

Figure 5. Value of the Digital Economy and Society Index for EU countries for 2021–2023

Source: generated by the author based on [18]

availability of energy resources for the population, and reducing the environmental impact. In digitalization, integrating digital technologies can significantly increase energy efficiency, which will positively affect the indicators of this index, contributing to the achievement of decarbonization goals and the transition to a carbon-neutral economy, fig. 6.

Thus, the Index highlights a country's challenges in balancing the world's energy trilemma and opportunities to improve the achievement of energy goals now and in the future. Index rankings compare countries on the three dimensions, while historical index scores offer insights into each country's performance trends over time [8]. The World Energy Trilemma Index (WETI) acts as a metric of progress, helping energy leaders effectively manage competing demands. The trilemma index monitors and measures the performance of the integrated energy system in 120 countries [9].

In today's world, where the fight against climate change and decarbonization are becoming vital global challenges, digitization is gaining critical importance. The integration of digital technologies into the decarbonization strategy opens up new horizons for effective resource management, emissions monitoring, and the implementation of innovative solutions. To better understand how digitalization affects the processes of decarbonization, we investigated the correlations between the Digital Economy Index (DESI) and the Energy Trilemma Index. Analysis of these relationships will help identify modern approaches and practices that contribute to the effective combination of digital technologies and sustainable development.

Between the Digital Economy Index (DESI) and the Energy Trilemma Index, it is necessary to distinguish the following interrelationships that may affect the processes of decarbonization:

1) Effectiveness of management and innovation. Countries with high DESI scores often demonstrate better resource management and an innovative approach to solving energy and environmental challenges. Digital technologies enable effective monitoring, optimization, and management systems to be implemented, which can help improve performance in all three aspects of the Energy Trilemma Index: affordability, sustainability, and acceptability.

2) Monitoring and data. Advanced digital infrastructures provide better data collection and analytics capabilities, allowing countries to monitor and manage their energy systems. This can affect all three aspects of the trilemma, making it easier to achieve a balance between energy security, sustainability, and affordability.

3) Investments and innovations. Countries with a high level of digitalization usually attract more investment in new technologies, including those related to renewable energy sources and reducing emissions. This can positively impact the sustainability of energy systems and reduce their carbon footprint while supporting affordability and energy security.

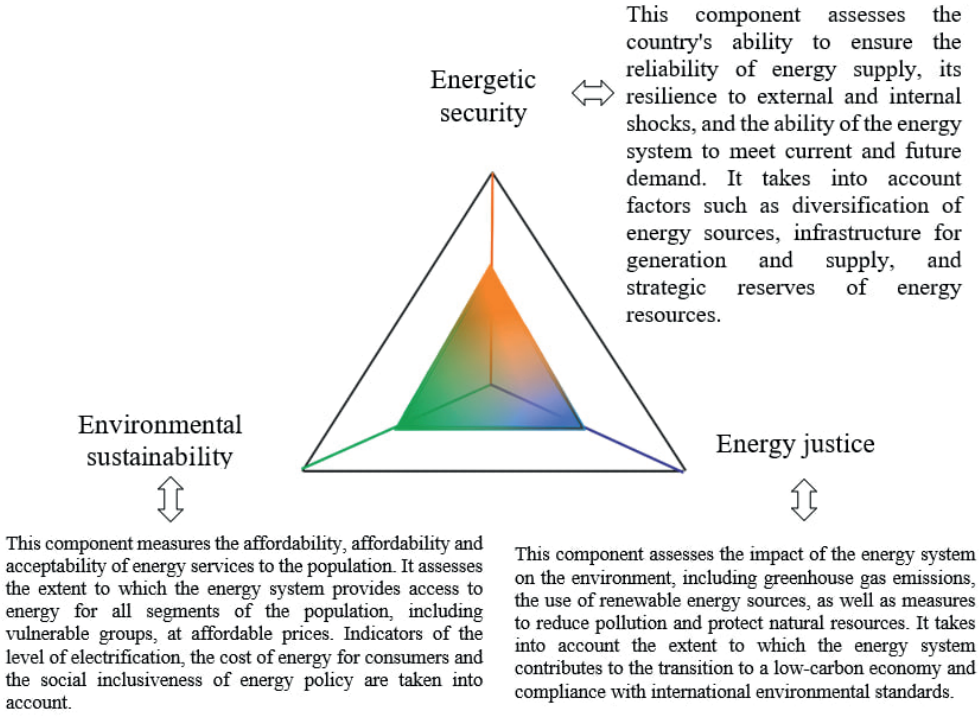

Figure 6. Methodology of the World Energy Trilemma Index

Source: represented by the author based on data [1; 2]

4) Lower costs and increased availability: Digitization can help reduce the cost of energy services by automating and optimizing processes. This can improve energy availability for consumers and reduce the financial burden, thereby improving the scores in the affordability aspect of the Energy Trilemma Index.

5) Energy security. A high level of digitalization can provide better visualization and management of energy resources, which helps reduce dependence on imported energy resources and increases the country's overall energy security.

6) Social and economic integration. Digitalization can also contribute to better social and economic integration, influencing the acceptability of energy policies and decisions and making them more adaptable to society's needs.

Correlation results between the DESI 2023 index and the trilemma score show a moderate positive relationship. This means countries with higher DESI scores also tend to score higher in the trilemma score, although not in all cases. For example, Denmark and Sweden, which have the highest DESIs, also receive high trilemma scores, confirming their leadership positions in digital technology. Countries with high DESIs, such as Germany and Finland, also have high trilemma scores. However, there are some outliers, such as Bulgaria, where the DESI is high but the trilemma score is relatively low.

To assess the statistical significance of the obtained correlation coefficient, the Student's t-test was calculated. For the computed t-tests, significance levels were found using the STUDRASP standard function. Thus, t = 4.38, and (t) = 0.000185849. The following confidence probabilities p =1 – a: p ≈ 1 corresponds to the calculated significance levels. Therefore, the correlation coefficient yx can be considered statistically significant with a high confidence probability p 1. It follows that the Digital Economy Index (DESI) and the Energy Trilemma Index have a high correlation in communication.

Conclusions. Integrating digital technologies into Ukraine's national energy policy is essential for increasing energy security, efficiency, and decarbonization. In the energy challenges, mainly due to the war and aggression on the part of Russia, digitalization is becoming a vital tool for strengthening energy sustainability and the transition to «green» energy.

World experience shows that the digitalization of energy can significantly increase resource management efficiency, integrate renewable energy sources, reduce costs, and improve the resilience of energy systems to external threats, including cyber security. The use of artificial intelligence, big data, «smart» energy networks, and automated control systems has become an integral part of the energy strategies of many developed countries.

Table 1

Correlation study between the Digital Economy Index (DESI) and the Energy Trilemma Index.

	Country	DESI^{2023} y	WETI ^{2023} x		Country	DESI^{2023} y	WETI ^{2023} x
1	Austria	65,5	80,9	15	Netherlands	78,1	77,6
2	Belgium	70,4	77,1	16	Germany	67,5	80,2
3	Bulgaria	44,1	69,2	17	Poland	54,5	70,7
4	Greece	41,4	70,5	18	Portugal	63,5	76,7
5	Denmark	79,6	83,2	19	Romania	38,9	75,1
6	Estonia	72,1	80,2	20	Slovakia	50	76,6
7	Ireland	73,8	76,3	21	Slovenia	64,5	78,4
8	Spain	62	77,8	22	Hungary	55,9	77,3
9	Italy	46,8	74,3	23	Finland	81,2	82,7
10	Cyprus	51,9	65,8	24	France	60,6	80,6
11	Latvia	52,9	76,3	25	Croatia	48,8	77,3
12	Lithuania	68,4	75	26	Czech Republic	58,1	78
13	Luxembourg	71,2	77,3	27	Sweden	75,5	83,1
14	Malta	59,4	70,4				
	Correlation coefficient		0,658637082				
	Calculation of the level of significance p = 1 – a						
	t		4,38				
	a		0,000185849				
	p = 1 – a		0,999814151				

Source: represented by the author based on data [1; 12]

Integrating digital technologies is particularly important for Ukraine, which is on the way to transforming its energy system. A successful transition to a modern, ecologically clean, and flexible energy model requires adapting the international experience to national realities. In this context, recommendations on the practical implementation of digital technologies in the energy field are a necessary step for the development of the energy sector of Ukraine in the face of global challenges, fig. 7.

For the successful development of a Smart Grid, it is necessary to ensure effective coordination between various participants of the energy market – the state, the private sector, and regulators. This requires the creation of interdepartmental commissions that deal with the development of policies, coordination of funding, and regulation of innovative approaches in legislation. Infrastructure investments must be managed centrally, considering national interests and private investors' capabilities.

As AI and Big Data are introduced to the energy sector, managers must ensure proper data management and privacy. The creation of particular departments or the involvement of consulting companies to develop forecasting models will help ensure the effective integration of these

Areas of improvement	World experience	Recommendations for Ukraine
1) Development Smart Grid	In the countries of the EU, the USA and China, "smart" networks are actively developing, which provide effective monitoring and management of energy supply in real time.	Invest in the development of Smart Grid infrastructure to integrate different energy sources, which will help reduce energy losses and improve demand management.
2) Using artificial intelligence and Big Data	Companies such as Google and Siemens use artificial intelligence to analyse energy consumption and optimize the operation of energy systems. This allows you to predict load peaks and reduce operating costs.	Implement Big Data analysis systems for demand forecasting, risk assessment and improved energy resource planning. This will help make the energy system more flexible and adaptable.
3) Digitization of management of energy facilities	In Germany, SCADA systems are widely used for remote monitoring and management of energy facilities. This allows you to quickly respond to emergency situations and minimize downtime and operational costs.	Implement automated monitoring and control systems for energy facilities (SCADA, IoT) to improve the efficiency of infrastructure management.
4) Integration of renewable energy sources with digital technologies	Denmark and the Netherlands are leading the way in integrating renewable energy into their energy systems thanks to digital platforms for balancing supply and demand.	Implement platforms for managing the production and consumption of renewable energy, which will increase the share of renewable sources in the overall energy balance and reduce dependence on fossil fuels.
5) Cyber security of energy infrastructure	In the US, standards have been created for the cyber security of energy facilities, such as the NERC CIP, which are aimed at protecting energy systems from cyber threats.	Create cybersecurity standards for the energy industry, in particular for the protection of infrastructure that operates on the basis of digital technologies. Provide regular audits and training of staff on cyber security issues.
6) Development of the market of flexible energy services	The UK has flexible energy markets where consumers can sell excess energy produced or reduce consumption during peak times.	Create regulatory conditions for the development of the market for flexible energy services, where consumers and small producers can interact with the energy system through digital platforms.
7) Support of innovative start-ups in the field of energy	In the EU and Israel, incubators and accelerators for startups in the field of energy, which are engaged in the development of digital solutions for the energy sector, are actively operating.	Support start-ups and research in the field of digital energy solutions through government grants and cooperation programs with international institutions.
8) Education and training of specialists	In Germany and the Scandinavian countries, programs for training engineers in digital technologies for energy are actively developing, which contributes to the formation of qualified personnel.	To implement educational programs in universities and enterprises, focused on the training of specialists in digital technologies in the energy sector.

Figure 7. Recommendations for the effective implementation of digital technologies in the energy sector of Ukraine based on foreign experience

Source: generated by the author

technologies. In addition, strategic leadership must be provided to coordinate the use of data between government agencies, energy providers, and academic institutions.

To successfully implement SCADA and IoT systems, it is necessary to create new management structures or modernize existing ones that are responsible for monitoring energy facilities. It is essential to develop development and modernization plans for each energy facility. Training personnel capable of managing the new digital systems is also necessary. Managers must ensure management's flexibility, considering the rapid development of technologies and their scaling.

Successful implementation of digital platforms for renewable energy management requires managers to focus on planning and coordination between energy providers. Creating a unified national strategy to integrate renewable sources with traditional ones is necessary. Managers must ensure communication between market regulators, energy companies, and end users to optimize processes.

Managing cybersecurity requires a centralized approach, including creating a national cybersecurity strategy for the energy sector. Developing security protocols, regular audits, and quick responses to potential threats play an important role. It is necessary to create management structures responsible for compliance with cyber security standards at energy facilities and ensure continuous personnel training.

To implement flexible energy services, managers must facilitate the creation of regulatory mechanisms that allow consumers to sell excess energy or adapt their consumption in real-time. Creating a transparent and efficient platform that will enable interaction between suppliers and consumers is crucial. This requires interaction between government structures, market regulators, and energy companies.

Creating special incubators, providing financial support, and promoting access to international grants are necessary to support startups. Managers should develop mechanisms for public and private financing of startups and create partnership programs with foreign investors. In addition, it is vital to establish a network of accelerators specializing in digital solutions in the energy field.

Practical training of specialists in digital technologies in energy requires the creation of national educational programs and advanced training courses for current industry employees. Managers must ensure the development of partnerships between higher education institutions, businesses, and governments to create training programs that meet the modern needs of the energy industry. It is also essential to increase the motivation of young professionals through internships and scholarships.

Implementing digital technologies in the energy field in Ukraine requires a systematic approach, investments, and adaptation of global practices to local conditions. This will improve the energy system's efficiency, integrate renewable energy sources, and make the energy sector more resilient to the challenges of the modern world.

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РОЛЬ ДІДЖИТАЛІЗАЦІЇ В УПРАВЛІННІ ЕНЕРГЕТИЧНОЮ ЕФЕКТИВНІСТЮ ТА ПЕРЕХОДІ ДО ВУГЛЕЦЕВО-НЕЙТРАЛЬНОЇ ЕКОНОМІКИ

Мета статті – дослідити вплив цифрових технологій на підвищення енергоефективності та зменшення викидів вуглецю в сучасних умовах. **Наукова новизна** статті полягає у виявленні та кількісному аналізі взаємозв'язку між рівнем цифровізації та показниками енергоефективності і декарбонізації. Вперше для всебічної оцінки цифровізації в контексті енергетичної безпеки та сталого розвитку було використано індекс DESI, що дозволило встановити статистично значущу кореляцію між цифровими перетвореннями та показниками енергоефективності. Крім того, було запропоновано рекомендації щодо адаптації міжнародного досвіду цифровізації в енергетичному секторі до національних умов України, що є вирішальним для переходу до вуглецево-нейтральної економіки. У статті застосовано такі наукові **методи:** аналіз даних – для вивчення тенденцій цифровізації та енергоефективності; кластерний аналіз – для систематизації та класифікації інформаційних джерел; кореляційно-регресійний аналіз – для оцінки взаємозв'язку між індексом DESI (Digital Economy and Society Index) та індексом WETI (World Energy Trilemma Index); синтез та узагальнення міжнародного досвіду – для розробки рекомендацій щодо адаптації провідних міжнародних практик цифровізації в енергетичному секторі до національних умов України. **Практичне значення** статті полягає в розробці рекомендацій для впровадження цифрових технологій з метою підвищення енергоефективності та зменшення викидів вуглецю на національному рівні. Запропоновані стратегії можуть бути використані для покращення управління енергетичними системами, інтеграції відновлювальних джерел енергії, зменшення витрат та підвищення стійкості енергетичних систем до зовнішніх загроз, включаючи кібербезпеку. Ця стаття може бути корисною для науковців, студентів, політиків, представників державних організацій та підприємств, що працюють у сфері енергетики та екології. Вона стане цінним джерелом інформації для тих, хто цікавиться сталим розвитком, цифровізацією енергетичних систем та впровадженням інноваційних технологій для покращення енергоефективності.

Ключові слова: цифровізація, енергоефективність, декарбонізація, діджиталізація, цифрова трансформація, відновлювані джерела, енергетичні інновації, цифрове управління, блокчейн в енергетиці.