DIGITALISATION AND SUSTAINABLE ENERGY SECTOR TRANSFORMATION: ANALYSIS OF KEY TRENDS

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Abstract. The digitalisation of the energy sector and investment in modern digital solutions aim to optimise the use of energy resources, reduce the burden on the environment, increase the rate of decarbonisation of the economy, ensure the decentralisation of energy supply and more efficiently use the existing energy infrastructure. In the paper, a study of digitalisation processes and their impact on the sustainable development of the energy sector was carried out to form a system of coordinated actions within the framework of the development and promotion of the concept of smart transformations in the energy sector for the transition to a model of sustainable and environmentally responsible development. The authors conducted a structural analysis to study digitalisation trends in the energy industry and their impact on the decarbonisation of the economy. Features, trends, and potential for the digitalisation of the energy sector are analysed based on reports from the International Energy Association. The authors emphasised that the global energy industry was the first to actively implement digital technologies and information systems to optimise energy supply and implement transformational processes. In recent years, there has been a significant increase, more than 20%, in energy companies' investment in digital technologies. The work found that implementing digital technologies can optimise energy costs, and the total savings from these digital measures can amount to about 80 billion US dollars annually by 2040. The paper defines the effects of the digitalisation of the energy system: ensuring carbon neutrality with the lowest consumer costs, forming a fair system of interaction between consumers and stakeholders, stimulating economic growth in all sectors due to the development of new types of economic activity, creating jobs, changing the range of goods and services of enterprises. The paper concluded that stimulating digitisation and investing in digital solutions, such as network optimisation at the distribution level, will help reduce further capital costs and allow faster development of electric transport, decentralised renewable energy sources, heat pumps and other technologies, thanks to more efficient use of existing infrastructure.
Keywords: sustainable development, energy sector, energy transformation, digitalisation, carbon neutrality.

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1. Introduction. The digital transformation contributes to the decarbonisation of the energy supply, removes dependence on fossil fuels and promotes the use and integration of renewable energy sources in the European energy system while increasing its sustainability. At the same time, fostering digitalisation in the energy sector creates jobs, opens up new opportunities for European businesses, and contributes to developing environmentally safe technologies. Implementing technologies and practices related to the decarbonisation of the energy sector will contribute to creating a toolkit that will allow citizens, consumers and communities to play an active role in the energy market. Globally, relevant processes are already underway, and many EU policies target specific areas of innovation, such as ensuring efficient and secure data exchange and measures to deploy smart grids. The implementation and implementation of the European Commission's Action Plan lays the foundation for building an integrated energy system that will support the growing interconnectedness of the market and its stakeholders to collaborate effectively and enable digital and energy value chains to interact more closely.

Today, digitisation is essential to achieve the EU's climate goals for 2030 and 2050. The russian invasion of Ukraine and high energy prices have increased the EU's need to gain independence from russian fossil fuel imports, strategic sovereignty and security, in particular, through creating a digital energy system. Over 50% of all EU households and small and medium-sized enterprises are equipped with "smart" electricity meters.

According to the European action plan (Official Website of the EU, 2024) "digitalisation of the energy system", in particular, provides: helping consumers gain control over energy consumption and bills with new digital tools and services; control over energy consumption and energy intensity, including through an environmental labelling scheme for data centres, energy labelling for computers and measures to increase the transparency of energy consumption in telecom services, energy efficiency labelling for cryptocurrency mining; strengthening the cyber security of energy networks, in particular, through the new Network Code on cyber security of cross-border exchanges of electricity following Regulation 2019/943 on the internal electricity market and the draft Recommendation of the Council of the EU on increasing the resilience of critical infrastructure; promotion of investments in digital infrastructure in the power industry (Henke et al., 2024; Icaza et al., 2024). At the same time, properly implementing security, privacy, and consumer protection issues is essential. The purpose of the paper is to conduct a comprehensive study of digitisation processes and their impact on the sustainable growth of the energy sector to form a system of coordinated actions regarding the formation of the concept of smart transformations in energy for the transition to a model of sustainable and environmentally responsible development.

2. Materials and Methods.

The document will use structural analysis to study digitalisation trends in the energy industry and their impact on the economy's decarbonisation process. The features, trends, and potential of the energy sector's digitalisation were analysed based on the reports International Energy Association (IEA, 2024).

3. Results and discussions.

The global development trends of the digitisation industry are influential. Internet traffic is growing exponentially, almost tripling in the last five years. At the same time, about 90% of global information flows were created during the previous two years. The corresponding exponential growth has led to the use of ever-larger units of measurement. For example, global annual internet traffic exceeded the exabyte threshold in 2001 and the zettabyte threshold in 2022 (WifiTalents, 2024; Internet, 2024). Table 1 presents the dynamics of global Internet traffic, characterised by a steady growth trend.

Table 1. Global Internet traffic: annual dynamic

	1997	2007	2017	2022
Global Internet traffic: annual dynamic	60 petabyte (10^{15} bytes)	54 exabyte (10^{18} bytes)	1,1 zettabyte (10^{21} bytes)	4,2 zettabyte (10^{21} bytes)

Sources: created by authors based on (WifiTalents, 2024)

On the level of national economies, digitalisation is not only an end but a tool for achieving strategic goals and a vision of economic processes. In particular, the digitalisation of the Ukrainian economy is defined within the framework of the following key strategic goals until 2030: increasing nominal GDP, ensuring influence, independence, independence in making economic and geopolitical decisions, providing a higher than average level of income and quality of life of Ukrainians in Europe and neighbouring countries, creation of conditions for the growth of capitalisation of Ukrainian business.

In digitalisation, traditional industries and sectors of the economy are radically changing. Classic business models are changing, analogue processes and operations are flowing into the Internet, and creating personal offers for each client is possible. Automation and robotics minimise the need for human resources, and the efficiency and productivity of labour increase rapidly. Radical changes are also taking place in sectors considered essential for industry development, such as metallurgy, oil and gas production, energy, agro-industrial complex, etc. For example, in the energy industry, oil and gas production company British Petroleum actively uses IoT to monitor the condition of its wells. Shell operates the Sensabot system, which is a remotely controlled robot capable of operating in locations that are dangerous for humans.

Digitalization creates new sectors and segments, as well as new professions. In particular, according to the estimates of the Ukrainian Future Institute, up to 60% of added value in Ukraine in 2030 will be created in new high-tech sectors of the economy, such as artificial intelligence, robotics, bioengineering, 3D printing, nanomedicine and others. The impact of digitisation is determined by the added value it creates for each sector of the economy or sphere of life at the macro-economic level or for a specific product or service at the micro-level (Ukrainian Institute of the Future, 2023). The main effect of digitalisation is a change in value chains. Technologies and digitalisation will displace a person from the processes he is used to — production, service, entertainment, trade, education, and even medicine. Digital Spillover (Converge, 2017) estimates that the ROI for digital technologies is 6.7 times higher than traditional technologies and that every dollar invested in digital technologies generates $20 in GDP growth. According to the estimates of the Association of Industrial Automation of Ukraine (Henke et al., 2024), the effects of digitisation for Ukrainian business include the growth of industrial production, the growth of high-tech segments, the growth of production capacity, an increase in the number of orders fulfilled on time, a reduction in stocks, an increase in the efficiency of installed equipment, reduction of equipment downtime, savings on procurement costs, an additional attraction to the country of investments in developing Industry 4.0 (Table 2).

Table 2. The effects of digitalization for Ukrainian business: annual trends

The effects of digitalization	Annual growth, %
Growth of industrial production	7-10
Growth of high-tech segments	2
Increase in production throughput	60
Increase in the number of orders fulfilled on time	95
Stock reduction	20
Savings on purchase costs	30
Reduction of equipment downtime	22
Increase in efficiency of installed equipment	15

Sources: created by authors based on (Association of Industrial Automation of Ukraine, 2023)

The global energy industry was the first to actively implement digital technologies and information systems to optimise energy supply and implement transformational processes. In the early 1980s, large energy companies were the flagships of digitalisation, which used information technologies to optimise management processes and transform energy networks. In particular, oil and gas companies actively used digital technologies to improve their management system, implement environmental management systems, implement renewable energy technologies, and make decisions about exploration and resource extraction (Janicke et al., 2023; Kojonsaari et al., 2023).

In recent years, investments by energy companies in digital technologies have increased dramatically. In particular, global investment in digital electricity infrastructure and software has grown by more than 20% since 2014. At the same time, investments in the electric power industry were almost 40% higher than in the gas industry. In addition, digital technologies are widely used in the final energy consumption sectors, the transport sector, and individual smart systems that monitor and control energy consumption by private consumers (Liao et al., 2024).

Transformational processes and digitalisation will increase the level of energy security of national economies and increase productivity simultaneously with the destruction of costs for oil, gas, coal and electricity. The functioning of the oil and gas extraction industry, as a component of the energy sector, is characterized by a strong history and experience in using digital technologies, especially in resource exploration and production efficiency monitoring. At the same time, there is significant reserve potential for developing and implementing digitalization technologies to optimize operational activity and resource conservation and prevent economic losses from pollution and unauthorized mining. The future promotion of smart technologies and digitalization in the oil and gas industry should focus on expanding, scaling, and improving digital tools and their application possibilities at all stages of the economic cycle.

Widespread use of digital technologies can reduce production costs by 10-20%, including improved processing of satellite data and sensors and improved modelling of resource deposits. Technically recoverable oil and gas resources could be increased by approximately 5% worldwide, with the largest increase expected in shale gas. Figure 2 shows the scale of the potential impact of digitisation processes on the volumes of technically extracted oil and gas resources.

Implementing digitisation of technologies and analytical findings can ensure cost optimisation in the energy sector. Reducing costs and increasing the efficiency of operations can be achieved by reducing the costs of operation and maintenance, increasing the efficiency of the operation of power plants and electrical networks, reducing the number of unplanned shutdowns and downtimes, and increasing the useful life of the assets of energy companies and network infrastructure.

The total savings from these digital measures could amount to about $80 billion annually from 2016-2040, or about 5% of total annual electricity generation costs.

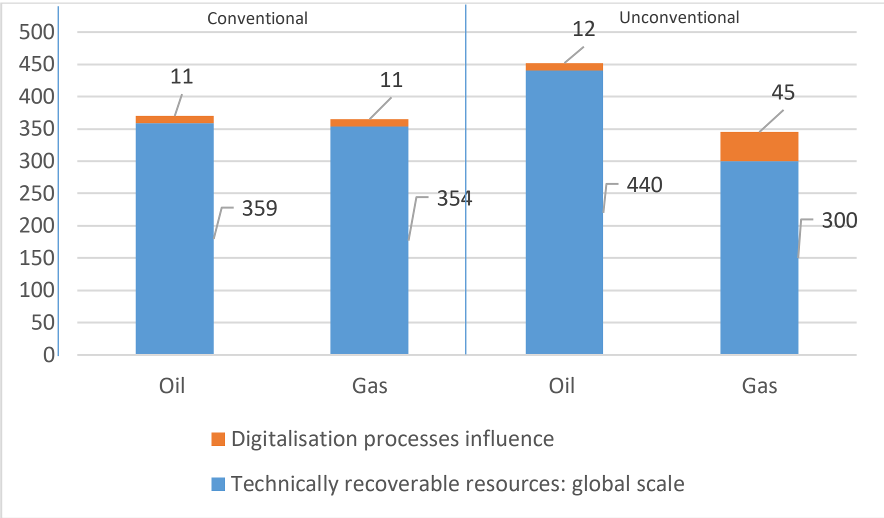

Figure 1. The scale of the potential impact of digitisation processes on the volumes of technically extracted oil and gas resources, billion ton
Sources: created by authors based on (IEA, 2024)

A review of various energy sectors highlights the diverse ways digital technologies can influence jobs and skills within the industry. While digitalization is expected to enhance efficiencies throughout the supply chain, it is unlikely to entirely replace the significant labour requirements for major engineering and construction tasks linked to physical infrastructure.

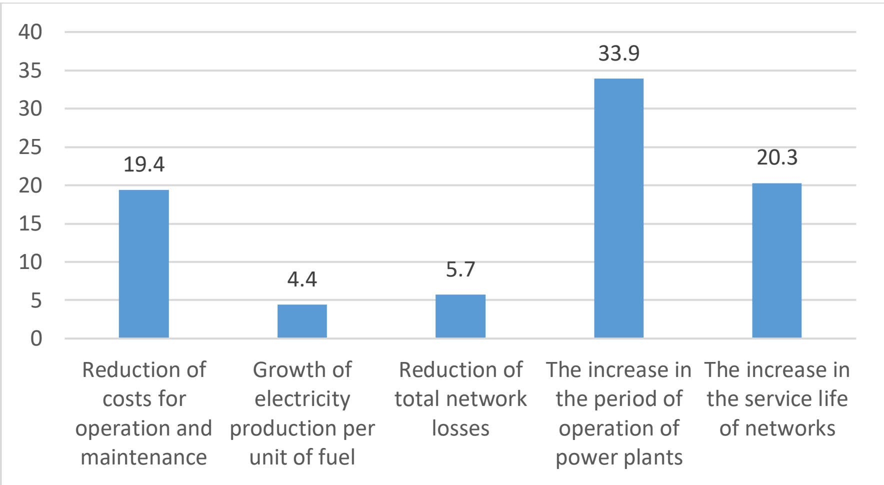

Figure 2. Cost optimization as a result of the implementation of digitalization technologies at power plants and electric networks during 2016-2040, billion USD
Sources: created by authors based on (IEA, 2024)

Occupations heavily reliant on tasks that can be automated, such as those centred on predictable, repetitive physical activities and data management, may face a higher risk of automation compared to roles involving less routine functions. Individuals supporting digital infrastructure will need specialized ICT competencies like coding and cybersecurity. Additionally, workers across the entire energy sector will require fundamental ICT skills to operate digital tools effectively. Soft skills like leadership, communication, and teamwork will also gain prominence due to the rise of collaborative ICT-enabled work opportunities. The speed and scope of digitalization and its effects on energy sector employment are surrounded by significant uncertainty (Norouzi et al., 2023). These outcomes will be influenced by several factors that differ based on regional and sector-specific circumstances. Policymakers in the energy field should engage in broader discussions within the government to address these impacts effectively.

Digitalization has the most significant potential for transformation in breaking down barriers between different energy sectors, enhancing adaptability, and facilitating integration across complete systems. This transformation is prominently seen in the electricity sector, where digitalization erases distinctions between energy generation and consumption.

This phenomenon gives rise to four interconnected opportunities:
1) smart demand response;
2) the incorporation of fluctuating renewable energy sources;
3) the adoption of intelligent charging systems for electric vehicles;
4) the growth of small-scale decentralized electricity resources like residential solar photovoltaic systems. These opportunities are intertwined; for instance, the critical role of demand response in delivering the flexibility necessary for incorporating more renewable energy generation.

The implementation of smart demand response has the potential to offer 185 gigawatts of system flexibility, which is approximately equal to the total installed electricity capacity of both Australia and Italy. This could lead to savings of USD 270 billion that would have otherwise been required for new electricity infrastructure. Around 1 billion households and 11 billion smart appliances could actively engage in interconnected electricity systems in the residential domain alone (Lee. et al., 2023; Stermieri et al., 2024). This participation would enable these households and devices to adjust the timing of their grid electricity usage.

Implementing smart charging technologies for electric vehicles can shift charging times to periods of low electricity demand and high supply. This approach offers increased grid flexibility and could save between USD 100 billion and USD 280 billion in avoided investment in new electricity infrastructure from 2016 to 2040, depending on the number of EVs deployed (Pantaleo et al., 2022).

Emerging digital tools can significantly enhance sustainability efforts, with innovations such as satellites for verifying greenhouse gas emissions and technologies that monitor air pollution at the neighbourhood level. Accurate accounting is essential for verification schemes and maintaining integrity in carbon certification systems like carbon markets. Although the technology is complex and satellite launches are costly and challenging to schedule, a coordinated fleet of monitoring satellites, shared by several space agencies, is expected to be operational by 2030 (Żuk, 2023).

Digitalization can also advance specific clean energy technologies like carbon capture and storage. Applications of digital technology in CO2 capture offer benefits similar to those seen in industry and power generation, including process optimization through automation and improved data collection and analytics, which can lower overall costs (You & Kim, 2020). Many digital innovations from the oil and gas sector are also applicable to assessing and developing CO2 storage solutions (Figure 3, 4).

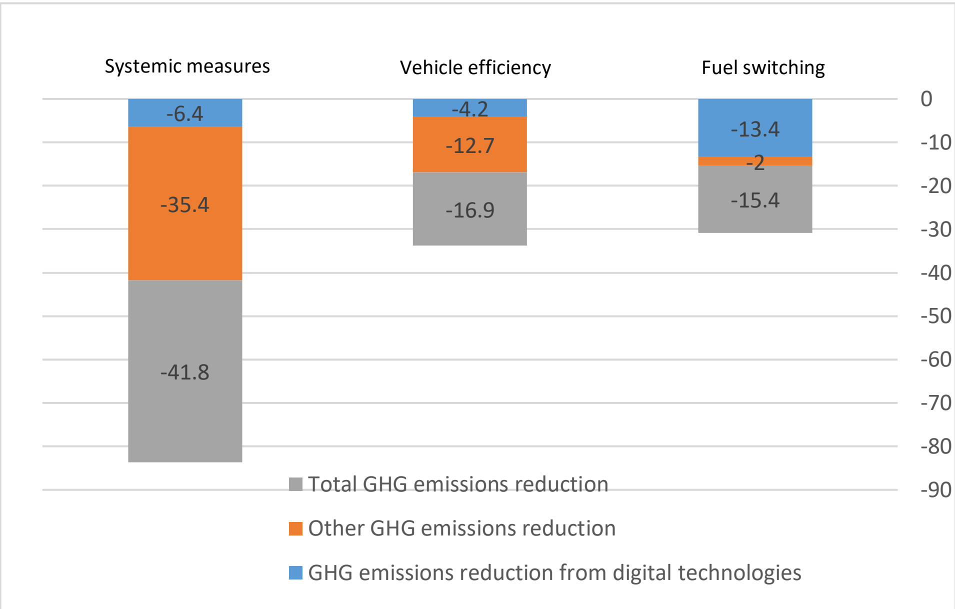

Figure 3. Impact of digitalisation on CO2 emissions: trends of transport branch, %
Sources: created by authors based on (IEA, 2024)

Digital innovations can deliver significant reductions in greenhouse gas emissions. At the same time, optimising energy efficiency in transport is also an important component, and switching to ecologically safe fuel types due to the introduction of digital technologies will ensure the decarbonisation of the industry (Liang et al., 2024; Rao et al., 2024).

Policy-making can be enhanced through more timely and sophisticated energy data collection and publication, facilitated by greater access to digital data. For instance, digital data can revolutionize "data fusion", whereby combined datasets offer insights far beyond the sum of their parts. An example from the

United Kingdom involves integrating local data on annual electricity and/or gas consumption with information on building types, floor areas, building ages, energy audits, and socio-economic indicators.

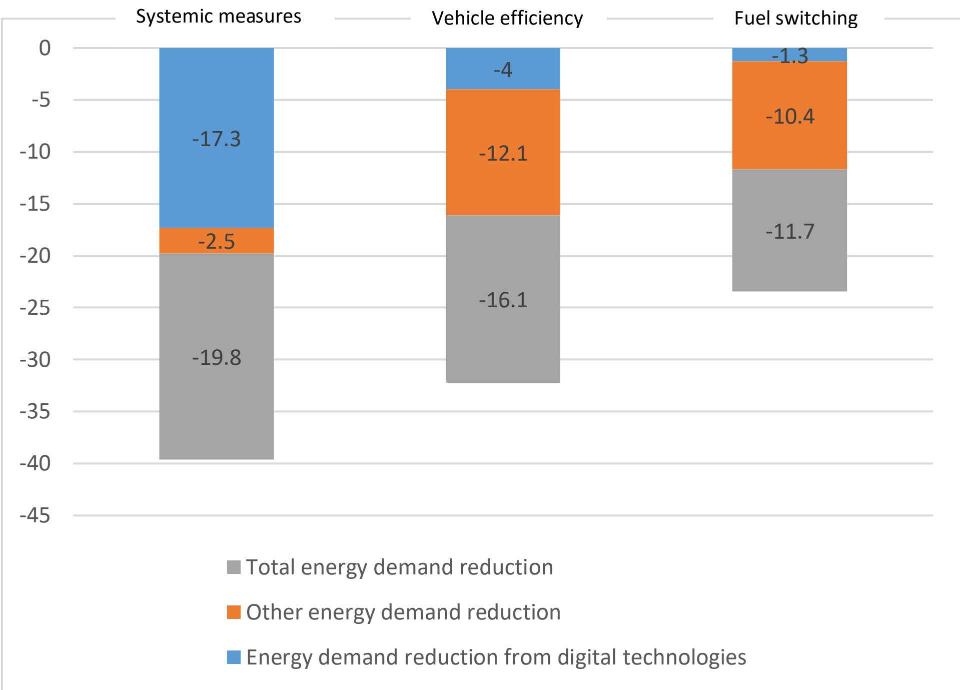

Figure 4. Impact of digitalisation on CO2 emissions: trends in demand reduction, %
Sources: created by authors based on (IEA, 2024)

Promoting digital innovations will ensure a reduction in demand for energy resources by a total of 20%. Further technological progress in this area, combined with lower prices for renewable energy sources and batteries, could increase demand for renewable energy sources by up to 100%. In this way, new digital technologies can help transform energy sources: two-thirds of electricity is currently produced from fossil fuels, and by 2050, wind and solar energy should replace this, providing two-thirds of electricity naturally (Lee et al., 2024; Lund et al., 2021).

Noted, EU energy trends include the development of "green" technologies and decarbonising the economy (Chygryn et al., 2020). The implementation of such projects in European countries is currently possible thanks to the fact that in the last 20-30 years, there has been a gradual renewal of the energy infrastructure and the introduction of Smart Grid elements. By 2024, 40% of the bloc's members' planned energy investments will fall on such networks (in Ukraine, this indicator barely reaches 5%). "Smart" networks are, in addition to the latest equipment, also a complex of automated systems and software that allow remote and real-time monitoring of network parameters, the state of equipment and all processes in the network, monitoring its weak points and notifying of any -what changes in her work. In particular, OSR uses a "digital double" for modelling and forecasting network development, testing the effectiveness of applied technical solutions and innovations even when planning the construction or reconstruction of networks.

4. Discussion and conclusion.

Stimulating digitization and investing in digital solutions, such as network optimization at the distribution level, will help reduce further capital costs and allow faster development of electric transport, decentralized renewable energy sources, heat pumps and other technologies, thanks to more efficient use of existing infrastructure.

The digital energy system will significantly benefit decarbonization, the economy, and consumers.

1. Achieving carbon neutrality of the energy system with the lowest consumer costs. Digitization will provide better visibility of renewable energy sources for system operators and help markets signal to users when to use the system, for example, by rewarding consumers who reduce consumption at certain times of the day. Common data and digital infrastructure are at the heart of the coordination of the entire system. They are the key to overcoming its increasing complexity with the lowest consumer costs. Improved data quality and data exchange will also allow much better planning and operation of the energy infrastructure.

2. Creating a fair system of interaction for consumers. Digital data will be fundamental to helping and encouraging consumers to participate in managing the energy system, leading them to better economic outcomes after the transition to carbon-neutral energy by providing more specialized services, including for those who have low income or are vulnerable. Analytical services will identify consumer problems and advise them on appropriate solutions, such as tariffs and services.

3. Stimulation of economic growth in all sectors. Digital technologies and the standards underlying them will stimulate future economic growth. New economic activity, jobs, enterprises, products, services and trade benefits will become possible thanks to the opening of access to the digital energy system and its data for the rest of the economy.

The digital transformation helps decarbonise the energy supply, eliminating dependence on fossil fuels and promoting the use and integration of renewable energy sources in the European energy system while increasing sustainability. At the same time, digitalization will create jobs, open new opportunities for European businesses, and promote the development of safe technologies. Finally, it provides tools that enable citizens, consumers and communities to play an active role in the energy market. This digitization is already underway, and many EU policies target specific areas of innovation, such as ensuring efficient and secure data exchange and measures to deploy smart meters. Building on existing policies, the European Commission's Action Plan will lay the groundwork for building an integrated energy system that can support growing market interconnectedness and enable digital and energy value chains to work more closely together.

Conflicts of Interest: Authors declare no conflict of interest.

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ЦИФРОВА ТА СТАЛА ТРАНСФОРМАЦІЯ ЕНЕРГЕТИЧНОГО СЕКТОРУ: АНАЛІЗ ОСНОВНИХ ТЕНДЕНЦІЙ

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Цифровізація енергетичного сектору та інвестиції в сучасні цифрові рішення мають на меті оптимізувати використання енергетичних ресурсів, зменшити навантаження на навколишнє середовище, підвищити темпи декарбонізації економіки, забезпечити децентралізацію енергопостачання та більш ефективно використовувати існуючу енергетичну інфраструктуру. У роботі проведено дослідження процесів цифровізації та їх впливу на сталий розвиток енергетичного сектору з метою формування системи скоординованих дій в рамках розробки та просування концепції смарт-трансформацій в енергетиці для переходу до моделі сталого та екологічно відповідального розвитку. Авторами проведено структурний аналіз з метою дослідження тенденцій діджиталізації в енергетиці та їх впливу на декарбонізацію економіки. Особливості, тенденції та потенціал цифровізації енергетичного сектору проаналізовано на основі звітів Міжнародної енергетичної асоціації. Автори підкреслюють, що світова енергетика першою почала активно впроваджувати цифрові технології та інформаційні системи для оптимізації енергопостачання та реалізації трансформаційних процесів. За останні роки спостерігається значне зростання інвестицій енергетичних компаній у цифрові технології - більш ніж на 20%. Дослідження показало, що впровадження цифрових технологій може оптимізувати витрати на енергію, а загальна економія від цих цифрових заходів може становити близько 80 мільярдів доларів США щорічно до 2040 року. У роботі визначено ефекти від цифровізації енергетичної системи: забезпечення вуглецевої нейтральності з найменшими витратами споживачів, формування справедливої системи взаємодії між споживачами та стейкхолдерами, стимулювання економічного зростання в усіх секторах за рахунок розвитку нових видів економічної діяльності, створення робочих місць, зміна асортименту товарів та послуг підприємств. У документі зроблено висновок, що стимулювання оцифрування та інвестування в цифрові рішення, такі як оптимізація мережі на рівні розподілу, допоможе скоротити подальші капітальні витрати та дозволить швидше розвивати електротранспорт, децентралізовані відновлювані джерела енергії, теплові насоси та інші технології завдяки більш ефективним використання наявної інфраструктури.
Ключові слова: сталий розвиток, енергетичний сектор, енергетична трансформація, цифровізація, вуглецева нейтральність.