Digital Transformation of Energy Infrastructure in the Conditions of Global Changes: Bibliometric Analysis

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Abstract: At the current stage of transformational transformations, the problems of energy infrastructure transformation are extremely important. And these issues are especially relevant in the conditions of rapid development of the digital economy. According to the calculations of The Boston Consulting Group experts, the volume of the digital economy by 2035 will amount to 16 trillion dollars. USA. At the same time, it is worth noting that the digital transformation observed in the energy sector as a critically important branch of the national economy has led to the emergence of new challenges and risks of information and cybersecurity, which should be given special attention in order to increase competitiveness and achieve sustainable development. In view of this, the purpose of this study is to determine the trends and key areas of research on the transformation of energy infrastructure in the era of digitalization based on bibliometric analysis using the VOSviewer software. The article specifies the meaning of the concepts “energy infrastructure”, “transformation”, "digital transformation". A bibliometric analysis of the relationship between the terms “energy infrastructure”, “energy system”, “energy network”, “digital transformation”, “digitalization”, “information technologies” was performed. The author's approach to the interpretation of the concept of “digital transformation of the energy infrastructure in the conditions of global changes” is proposed. It has been established that the use of information systems and digital technologies in recent years has been recognized as a strategic direction for the transformation of energy infrastructure in many European countries. A comparative analysis of existing international methods for evaluating the development of energy systems, taking into account the information component, was performed. It has been proven that the priority direction of research in the future should be the substantiation of the theoretical and methodological provisions of the formation of the digital energy ecosystem.

1 INTRODUCTION

Currently, the development of the energy system in the global world takes place in the conditions of constant natural disasters, climate changes, terrorist acts, and cyber threats. Therefore, the strategic directions of ensuring national security in the international security system of the countries of the world are the protection and security of energy infrastructure as an important element of critical infrastructure [1]; application of digital technologies to achieve sustainable development of energy infrastructure, taking into account adaptation to climate change; implementation of the concept of public-private partnership of protection strategies in ensuring the stability of the energy infrastructure in crisis situations, etc.

It is worth noting that the transformation of the energy infrastructure should be considered from the point of view of digitalization [2]. According to estimates by Forbes experts, 67% of the leaders of companies from the Global 2000 list chose digital transformation as a priority goal of their corporate strategy in 2018.

According to a study by analysts of the International Data Corporation, the total global spending on digital technologies will grow by 16.8% annually and reach 2.1 trillion dollars in 2019. According to forecasts of The Boston Consulting Group, the volume of the digital economy by 2035 will amount to 16 trillion dollars. Research by

Huawei and Oxford Economics showed that intelligent network interaction will trigger the growth of the digital economy, which will reach 23 trillion dollars by 2025. This increase will be 78.3% compared to 2017 (12.9 trillion dollars). By 2025, it is planned to increase the share of the digital economy by 7.2 percentage points, or from 17.1 to 24.3% of global GDP.

Therefore, the digital transformation observed in many sectors of the national economy (including the energy sector) has led to the emergence of new challenges and risks of information and cybersecurity, which should be given special attention in order to increase competitiveness and achieve sustainable development.

2 LITERATURE REVIEW

The process of changes and transformations is defined by the concept of "transformation", which is quite complex and multifaceted. It is believed that the concept of "transformation" became widely used in the social sciences in the second half of the 20th century, to characterize the latest processes associated with radical structural changes in national economies.

As the analysis of the literature [3-8] shows, the concept of "transformation" is defined as:

1) the process of adapting elements of economic systems at different levels to the regularities of the functioning and development of the national economy;
2) movement from form to form through the negation of the old form and the formation of a new one;
3) changing the structure of any object;
4) the process of transformation and formation of the system;
5) the general form of development of economic systems associated with evolutionary and revolutionary changes;
6) qualitative transformations of the economic system;
7) quantitative and qualitative changes in system components of various scales.

Therefore, transformation means the process of changing the form, appearance, nature or character of a society or individual structure. This is the transformation of essential components of society, all aspects of spheres of economic activity and social life as a whole.

It is proposed to interpret the transformation as a qualitative transformation and formation of the energy system, which enables the transition to a fundamentally new level of its functioning and development, which is carried out consistently and continuously at all stages.

Based on the generalization of special literature, it was established that currently there are many definitions of the concept of "digital transformation". For the most part, scientists and practitioners [9-13] understand digital transformation as:

1) maximum use of the potential of digital technologies in all aspects of business;
2) large-scale business transformation, which concerns the entire set of functions of the enterprise; the path to the implementation of digital technologies and business models to increase productivity in quantitative terms;
3) use of technologies to radically increase productivity or availability of resources for enterprises;
4) a change in business thinking in the new conditions of the digital economy, the driver of which is the modern consumer and the changing culture of communications;
5) the process of transition of the organization to new ways of thinking and working based on the use of social, mobile and other digital technologies;
6) the process of a radical change in the form of the economic system, as a result of the search, development, implementation and use of digital technological innovations to increase the efficiency of the performance of their functions by all structural divisions;
7) conscious, management-initiated process of radical improvement of business processes both in the company's internal and external environment based on research and development, as well as further implementation and use of digital technologies;
8) radical changes in the complex of business processes, starting from product development and ending with customer service;
9) implementation of modern digital technologies in the organization of business processes at enterprises.

Therefore, digital transformation involves the integration of digital technologies and solutions in all areas of business. This is a cultural and technological shift that requires organizations to make fundamental changes in their work methods and customer experience management. Under this term, it is proposed to consider a fundamental rethinking of customer experience, business models and operations. This is the search for new ways of creating value, generating revenue and improving the efficiency of business processes.

At the same time, it should be noted that energy infrastructure belongs to strategic objects of critical infrastructure. This is due to the fact that interruptions in the functioning of the energy sector negatively affect other critical infrastructure facilities. Traditionally, the energy infrastructure is considered as a complex system consisting of many components designed for the production, distribution and supply of energy [14].

In this work, energy infrastructure is understood as a set of objects, enterprises and energy networks that are priority and strategically important for the development of a competitive national economy and ensuring an adequate level of energy security, the neutralization or malfunction of which can harm the national interests of the state, lead to the emergence possible threats and risks, significant damages and losses (economic, financial, investment, transport, logistics, environmental, informational, etc.).

The digital transformation of the energy infrastructure is considered as the strategic implementation of digital technologies, which allows the elements of the energy system to function and develop in the digital age. This concept involves the use of digital tools and platforms to transform traditional business processes, improve interaction with customers, introduce innovative technologies and form a digital energy ecosystem. The main components of the digital transformation of the energy infrastructure include:

1) digital technologies (cloud computing, artificial intelligence, big data analytics and the Internet of Things (IoT), which allow energy infrastructure objects to collect, analyse and use huge amounts of data to make informed decisions, automating processes and providing a personalized experience);
2) organizational changes (restructuring of processes to increase their flexibility, introduction of new methodologies (DevOps, Agile), formation of a digital culture);
3) customer orientation and integration of digital channels (the use of websites, mobile applications and social network platforms will improve the quality of customer service, provide personalized content, and ensure smooth interaction at various contact points).

3 RESULTS

Let's have a deeper look at the genesis of scientists' views on the issue of digital transformation of the energy infrastructure. For this, a bibliometric analysis of scientific publications on the development of energy infrastructure in the conditions of digitalization, which are indexed in the Scopus database using the VOSviewer toolkit, was carried out. 19,955 documents were found by the title of articles, abstracts and keywords.

As the analysis showed, the first publication on the selected topic appeared in the international scientometrics database Scopus in 1974 [15]. Until the 1990s, an insignificant level of publishing activity was observed. After that, the works of scientists, including C. Hull [16], appeared in scientometrics databases. A. Farrell et al. [17]; V. Gungor et al. [18]; D. Mengnuo [19] and others, in which attention is focused on the development of the concept of energy infrastructure protection in crisis phenomena; application of smart technologies and intelligent systems in the energy sector.

Among the most cited publications, the following articles deserve special attention:

1) O. Younis, S. Fahmy [20], published in 2004, which was cited in a journal indexed by the Scopus scientometrics database 4232 times. In this paper, the authors proposed a new approach to distributed clustering for long-lived special sensor energy networks.
2) X. Fang et al. [21], published in 2012, which was cited, 2295 times. The article examines three main systems, namely, a smart infrastructure system, a smart management system, and a smart protection system.
3) A.-H. Mohsenian-Rad et al. [22], published in 2010, which was cited, 2258 times. The paper presents an autonomous and distributed user demand-side energy management system that takes advantage of the two-way digital communication infrastructure envisioned in the future smart grid. Based on game theory, an energy planning game is formed, where players are users and their strategies are daily schedules of their household appliances and loads.
4) V. C. Güngör et al. [23], published in 2011, which was cited in a journal indexed by the Scopus scientometrics database 2058 times. The authors consider important issues of smart grid technologies, primarily from the point of view of problems and opportunities of information and communication technologies.

Among the key publications that publish works on the selected topic, the following can be mentioned: Energies (358 documents); IEEE Access (310); Applied Energy (191); Energy Policy (133); Sustainability Switzerland (124); Energy (122); Renewable and Sustainable Energy Reviews (117).

There are 36 documents of scientist A. Tzanakaki in the Scopus database; 30 documents – D. Simeonidou; 27 documents each – N. Javaid, H. Mouftah; 25 documents - scientist P. Siano; 23 documents each – S. Rinaldi, N. Shah; 22 documents each – M. Anastasopoulos, A. Flammini; on 21 documents - H. Gabbar, J. Guerrero, M. Longo, B. Mohammadi-Ivatloo, A. Orgerie, J. Rodrigues, C. Verikoukis, C. Wietfeld.

The key organizations involved in solving the problems of digital transformation of energy infrastructure are Politecnico di Milano (155 documents); Imperial College London (142); Delft University of Technology (139); Tsinghua University (129); CNRS Center National de la Recherche Scientifique (123); Universitat Politécnica de Catalunya, ETH Zürich (117); Beijing University of Posts and Telecommunications, Aalborg University, Massachusetts Institute of Technology (113 documents each).

The results of the analysis show that most of the works on the studied issue are published by scientists from the USA (3898 documents), India (2521), China (1975), Great Britain (1574), Italy (1,378), and Germany (1351).

According to the types of documents, scientific works can be ranked as follows: materials of conferences (9430 documents or 47.3% of the total number); scientific articles (8034 or 40.3%); chapters of books or monographic publications (1031 or 5.2%); review articles (670 or 3.4% of the total).

For the most part, scientific works on the problems of digital transformation of energy infrastructure are published in the following fields of knowledge: engineering (10,726 documents); computer science (10423); energy (5073); ecology (1966); social sciences (1730); business and management (651 documents).

The main sponsors that finance scientific publications on the problems of energy infrastructure transformation in the conditions of the digital economy include the following: National Natural Science Foundation of China (672 documents); National Science Foundation (546); Horizon 2020 Framework Program (429); European Commission (341); Engineering and Physical Sciences Research Council (298); U.S. Department of Energy (245); European Regional Development Fund (173 documents).

So, the analysis of publishing activity confirmed that starting from the beginning of the 90s of the 20th century, there is a growing scientific interest in the study of transformational changes in the energy infrastructure using information technologies and systems. At the same time, the interdisciplinary nature of research is followed, and the geography of scientists and researchers studying this topic is diverse (but with a noticeable predominance of scientists and institutions from the USA, India, China, Great Britain, Italy, Germany, Canada, Spain, France).

Further processing and analysis of bibliographic data was carried out using the VOSviewer software, which is a software tool for constructing and visualizing maps of bibliometric networks [24]. VOSviewer software was used to construct network maps of relationships between keywords based on bibliographic records from Scopus databases. The visual results of the obtained map of the bibliometric network are shown in Figure 1.

The map of the bibliometric network displays the frequency of use of terms by the size of the circle and the intensity of communication, and allows you to track variants of combinations of terms both within clusters and between them. The colour of the circle indicates that the keyword belongs to a certain cluster. The larger the diameter of the circle, the more often this term appears in scientific publications. Links on the map show the frequency of repetition of keywords in publications, while the smaller the distance between keywords, the stronger the connection between them [24].

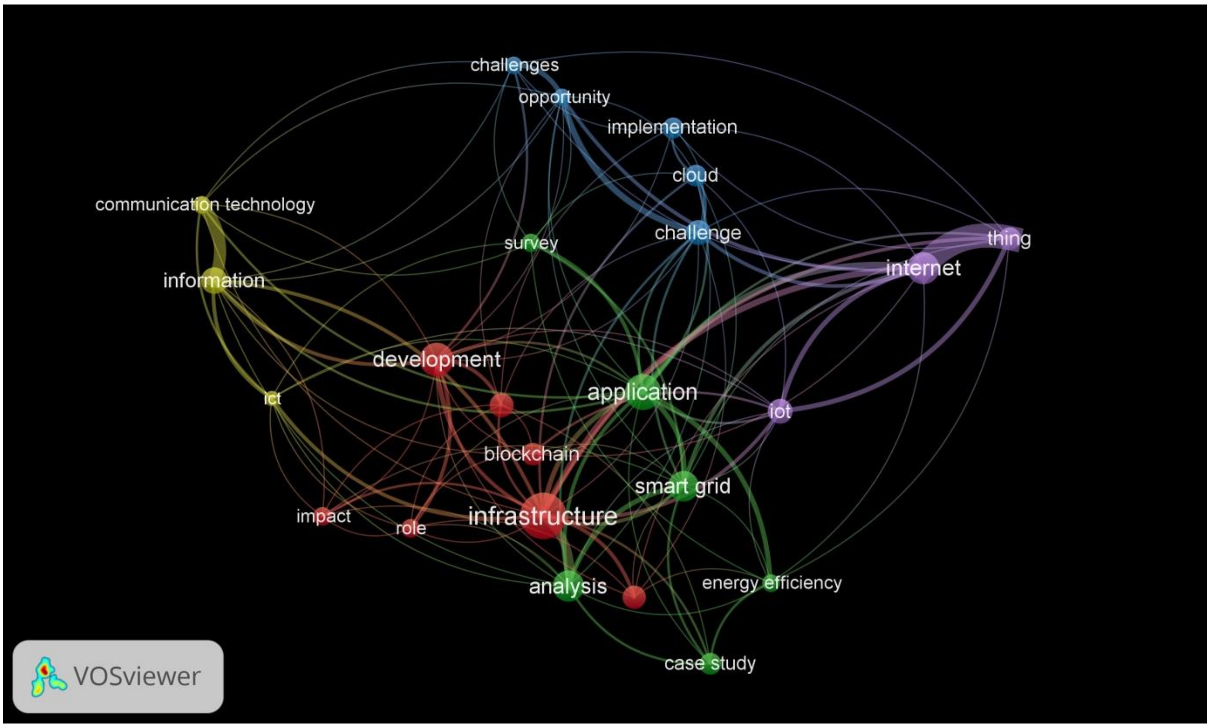

Figure 1: Network visualization of citations of articles on issues of digital transformation of energy infrastructure, implemented using the VOSviewer tool[1].

According to Fig. keywords can be grouped into 5 clusters using the VOSviewer program. A generalized description of clusters of key phrases in scientific research on the digital transformation of energy infrastructure is presented in Table 1.

Table 1: Characterization of clusters of key phrases in scientific studies of transformational changes in energy infrastructure in the context of digitalization[2].

Cluster	The most used term	Num-ber of key-words	Related keywords
1 (red)	infrastruc-ture	7	development, digital transformation, blockchain, impact, digitalization, role
2 (green)	applica-tion	6	analysis, energy efficiency, smart grid
3 (blue)	implemen-tation	5	challenge, cloud, opportunity,
4 (yellow)	Informa-tion	3	communication technology, ICT
5 (purple)	intelligent systems	3	Internet, Internet Things

Thus, based on the results of the study, the following conclusions can be drawn:

1) The number of publications indexed in Scopus, whose titles, abstracts and keywords contain the term “energy infrastructure”, is growing at an accelerated pace every year. Research on the transformational changes of the energy infrastructure in the conditions of the rapid development of the digital economy is gaining more and more popularity, starting from the 90s of the 20th century. The main reasons for the growing popularity of these scientific studies are: the search for new ideas, the transformation of the energy management paradigm, the introduction of the concept of sustainable development, the development of digital technologies and intelligent systems.
2) The term “energy infrastructure” has an interdisciplinary nature, it is used in studies of various branches of science, namely: it is found in publications on engineering, computer science, ecology, social science, management, business, decision science, etc.
3) Visualization of the network map of keywords based on bibliographic data made it possible to single out 5 clusters that characterize the key areas of research: infrastructure, energy system,

[1]Built on the basis of data from the Scopus scientometrics database using the VOSviewer program.

[2]Created by the authors using the VOSviewer program.

digital transformation, information technologies in energy, intelligent systems.

The Network Readiness Index (NRI) was used to determine the current problems of the development of the energy system and the implementation of information and communication technologies in the countries of the world; ICT Development Index (IDI).

The Network Readiness Index (NRI, Portulans Institute, USA) (Table 2) was developed to assess the network (technical) readiness of the countries of the world to use the possibilities of information and communication technologies and systems. From 2002 to 2016, this index was published by the World Economic Forum as part of the Global Information Technology Report. Today, on the basis of NRI, 134 countries of the world are evaluated according to 60 indicators, which are systematized according to 4 main groups: technologies, personnel, management, influencing factors. NRI covers issues from artificial intelligence technologies and the Internet of Things to the role of the digital economy in achieving the Sustainable Development Goals.

The ICT Development Index (IDI) is a combined indicator that characterizes the achievements of the countries of the world in terms of the development of information and communication technologies. The index was developed according to the methodology of the International Telecommunication Union, a specialized division of the United Nations, which defines global standards in the field of ICT. The IDI is calculated on the basis of summing up 11 indicators to an integral criterion, which allows comparing the achievements of the countries of the world in the development of the ICT sector. The index can be used as a benchmarking tool at the global, regional and national levels.

Table 2: Network Readiness Index on the example of the Surveyed European Countries (source [25]).

Country	Year		Rank changes
	2020	2022	
Germany	9	9	unchanged
Czech Republic	28	25	↑+3
Portugal	31	29	↑+2
Estonia	23	22	↑+1
Poland	33	34	↓-1
Croatia	43	45	↓-2
Latvia	37	39	↓-2
Hungary	39	41	↓-2
Romania	49	52	↓-3
Lithuania	29	33	↓-4

As the analysis shows, the leaders in the field of information and communication technologies in 2007 were Sweden, South Korea, Denmark, the Netherlands, and Iceland. In 2017, Iceland, South Korea, Switzerland, Denmark, and Great Britain were the leading countries in the field of ICT.

During 2007-2017, the positions of some European countries worsened. Thus, the rank of Ukraine in the rating of the development of information and communication technologies decreased by 28 points; Portugal and Hungary – by 13; Romania – by 12; Poland – by 10; Lithuania – by 8; Czech – by 3 points. At the same time, Estonia's position improved by 9 points, and Croatia's by 7 (Table 3).

Table 3: The ICT Development Index of the Surveyed European Countries (source [26, 27]).

Country	Year				
	2007	2010	2014	2015	2017
Croatia	43	31	37	42	36
Czech Republic	40	37	41	34	43
Estonia	26	33	21	20	17
Hungary	35	34	46	48	48
Latvia	36	40	33	37	35
Lithuania	33	35	40	40	41
Poland	39	38	44	44	49
Portugal	31	27	43	43	44
Romania	46	48	58	59	58

For the purpose of rating the countries of the world according to the “Energy Efficiency” indicator, the American Council for an Energy-Efficient Economy (ACEEE) has developed a world rating of global energy efficiency. The organization studied the energy-saving models of 23 countries that consume the largest amount of electricity (75% of all consumption in the world) and ranked them in order. In 2016, Germany ranked 1st, Italy and Japan – 2nd, France – 4th.

In addition, the Energy Information Administration (EIA) compiled a list of countries on electricity consumption. Average electricity consumption per capita reflects the level of socio-economic development. The higher this indicator, the more “comfortable” a person lives, the more electrical equipment can be used in production.

In view of the above, it can be noted that digital transformation of the energy infrastructure is the process of introducing modern technologies into the business processes of enterprises in the energy sector to increase productivity, improve service and customer service. These are radical changes in management methods, corporate culture and ethics, external and internal interaction of stakeholders and energy market participants.

Therefore, under the digital transformation of energy infrastructure, it is proposed to consider the process of transition of the energy system as an important element of critical infrastructure to a qualitatively new state, taking into account such a modern challenge as digitalization.

4 CONCLUSIONS

Based on the above, we can come to the following conclusion. Currently, the problems of energy infrastructure transformation in the context of the implementation of the digital strategy of the European Union are gaining special relevance. At the same time, the EU's single digital market is the most attractive for the development of digital energy. In the future, this may become a "development driver" of the national economies of European countries.

As a result of the study, it was established that many methodologies are used to determine the current problems and trends in the development of energy infrastructure in the countries of the world. But it is worth emphasizing that all methodologies for evaluating the development of energy infrastructure are imperfect and do not fully correspond to modern economic conditions. As the analysis showed, there is no integral index that would take into account the impact of information and communication technologies on the development of the energy system. In this regard, there is currently a need to develop a proper methodical approach to assessing the development of energy infrastructure in the countries of the world, taking into account the global challenges of the modern digital environment.

For this, it is necessary to make changes and additions to the Energy Strategies of the European countries, in which to provide for the use of information technologies, intelligent and smart systems for the transformation of the energy infrastructure. This, in turn, can become one of the tools for guaranteeing energy and information security as important components of the national security of states.

Therefore, the digital transformation of the energy infrastructure is a key component of the overall strategy for the transformation of the energy system. Correctly selected digital technologies in combination with the competencies of employees, processes and operations will allow energy infrastructure facilities to quickly adapt to crisis situations, use promising opportunities to modernize work processes, meet new and constantly changing customer needs, stimulate growth and implement innovative and management solutions in energy industry.

For effective digital transformation of the energy infrastructure on a practical level, it is advisable to pay attention to such key aspects as:

- having a clear vision and strategy that meets business goals;
- involvement of interested parties (stakeholders) and ensuring the interest of the entire organization;
- constant monitoring and assessment of the implementation of digital transformation initiatives;
- an adaptive and iterative approach that allows you to navigate the changing digital landscape.

Prospects for further research consist in substantiating the theoretical and methodological provisions of the formation of the digital energy ecosystem.

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