

The Impact of Artificial Intelligence on Managing Energy Infrastructure Development in the Age of Global Digital Transformation

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Keywords: Artificial Intelligence, Energy Infrastructure Development, Smart Energy Systems, Digital Energy Transformation, Critical Energy Infrastructure, Cybersecurity, Cyber-Resilience, Sustainable Energy Development, Energy System Resilience, Decision Support Systems, Machine Learning, Digital Twins, Sustainable Development.

Abstract: The article is devoted to the study of the development of scientific discourse on the application of artificial intelligence (AI) technologies in managing the development of energy infrastructure in the context of global digital transformation and the transition to low-carbon energy systems. The aim of the work is to identify the dynamics of publication activity, key thematic priorities and international scientific clusters based on the results of bibliometric analysis of publications indexed in the Scopus database for the period 2000–2025. The results obtained showed a rapid growth in scientific interest after 2020, which correlates with the development of Smart Grid, IoT, machine learning, predictive analytics technologies, as well as with the growing need to increase the resilience and cybersecurity of critical energy infrastructure. It was determined that the greatest intensity of research is observed in India, China, the USA, as well as in a number of European countries, which indicates the global nature of the topic. Semantic analysis of keywords allowed us to identify the dominant areas of scientific research: optimization of energy consumption and integration of renewable energy sources, development of intelligent energy grids and “smart” cities, implementation of digital twins of energy systems, use of forecasting algorithms and decision support. Based on the results, the conclusion was formulated that AI is becoming a strategic tool for the energy transition, ensuring increased energy efficiency, accuracy of network balancing, acceleration of response to emergencies, strengthening cybersecurity and achieving the Sustainable Development Goals. Practical recommendations include the development of standards for the use of AI in critical infrastructure, the creation of national energy data platforms and digital twins, strengthening institutional interaction between governments, businesses and scientific institutions, as well as the development of ethical and regulatory frameworks for the use of AI.

1 INTRODUCTION

In a rapidly digitalizing global economy, energy infrastructure remains a fundamental condition for the stability, competitiveness, and national security of states. The growth of technogenic complexity, the decentralization of energy generation, the development of renewable energy sources, and the growth of cyber threats make energy systems increasingly interdependent and vulnerable. According to analysts from Markets and

Markets [1], the vulnerability of critical infrastructures stimulates the steady growth of the global cyber defense market: in 2020-2030 it will increase by 11.5%, to over 24 billion dollars. This emphasizes the urgent need to increase the cyber resilience of the energy sector as a strategic prerequisite for the sustainable functioning of the economy. In such conditions, traditional mechanisms for planning and modernization of energy systems are gradually losing their effectiveness, as they are unable to process large

data sets, integrate decentralized generation, and provide high forecasting accuracy [2]-[6].

Therefore, artificial intelligence (AI) is becoming a key tool for managing energy infrastructure in the era of digital transformation [7]-[11]. According to Statista [12], the global AI market has grown from 93.3 billion dollars in 2020 to 184 billion dollars in 2024, almost doubling. S. Ghimire's forecast [13] indicates that by 2027 the market volume will exceed 407 billion dollars.

International surveys confirm the public and institutional demand for the implementation of AI in the management of critical infrastructure facilities. According to a German study in 2022, 46% of citizens consider AI to be an effective tool for increasing the resilience of energy and transport systems to natural disasters [14]. At the same time, 41% of respondents fear the negative impact of algorithmic systems on the security of critical facilities, and 15% express a high level of concern about potential risks [15]. This demonstrates the ambivalence of the perception of intelligent technologies and the need to improve risk management policies.

According to the Center for Security and Emerging Technologies at Georgetown University [16], the integration of artificial intelligence into critical sectors creates both new opportunities for increasing efficiency and predictability, as well as new vulnerabilities associated with cyber risks and the human factor. At the same time, 81% of technology company executives predict that the use of advanced artificial intelligence models will provide at least a 25% increase in operational efficiency in the next three years, in particular in the area of load management, demand forecasting and optimization of renewable energy generation [17].

In the corporate sector, artificial intelligence is increasingly being used as a tool to improve productivity. According to a Celonis survey [18], 48% of companies identified automation and process optimization as the main motivation for implementing artificial intelligence. In the field of energy infrastructure development, this means moving to new models of asset management, monitoring of technical condition, forecasting of emergency situations and reducing energy losses [19]-[21].

The integration of artificial intelligence acquires special importance in the context of national and energy security. According to the conclusions of D. Araya and M. King [22], artificial intelligence forms a new architecture of defense and

infrastructure systems, combining data analysis, autonomous technologies, neuromorphic computing and integration with IoT. This creates a large-scale potential for increasing the resilience of the energy sector, while at the same time generating the need for global risk regulation and standardization of algorithmic solutions [23]-[25].

Therefore, the study of the impact of artificial intelligence on the management of energy infrastructure development is a priority area of scientific research. It allows you to form the scientific foundations of effective digital transformation, increase energy sustainability and security, minimize risks, and implement sustainable development goals.

2 LITERATURE REVIEW

The analysis of modern scientific publications shows the increasing scientific interest in the relationship between artificial intelligence and critical infrastructure development management. Researchers K. Chen, X. Zhou, Z. Bao, M. J. Skibniewski and W. Fang [24] summarized the areas of application of artificial intelligence in infrastructure construction, highlighting the dominance of machine learning, computer vision and natural language processing technologies.

C. Sambucci and C. Paraschiv [25] identified the spectrum of cyber threats for artificial intelligence systems in critical sectors and proposed the concept of security auditing of AI models. Scientists H. Jing, W. Wei, C. Zhou and X. He [26] developed a system framework for artificial intelligence security, covering the stages of the life cycle from design to operation.

Japanese scientists T. Takeda, J. Kawamura, T. Murakami, T. Matsumura and A. Arai [27] focused on the gaps in the legal regulation of the use of artificial intelligence in water infrastructure. At the same time, J. J. Reddy, A. Mittal, V. Reddy and H. Das [28] proved the potential of combining artificial intelligence, blockchain and IoT to form sustainable "smart" infrastructures.

Summarizing the results, it can be stated that modern research forms three leading scientific directions:

- 1) security and reliability of artificial intelligence systems;
- 2) institutional management and legal support for their integration into critical infrastructure;

- 3) the transformative role of artificial intelligence in creating sustainable and digitally adaptive infrastructures.

The generalization of scientific achievements shows that research in the field of the impact of artificial intelligence technologies on the management of the development of critical infrastructure is gradually moving into the phase of sectoral specification. One of the priority and extremely important areas has become the management of energy infrastructure development, where artificial intelligence is considered not only as a technological tool, but as an integrative mechanism for the transformation of energy systems [29-34], combining digitalization, decentralization, security and resilience.

Scientific research by M. Ashok, K. Ganesan, R. Saravanan and R. Kumar [35] demonstrates that artificial intelligence algorithms provide systemic management of the balance between energy production, distribution and consumption, increasing the efficiency of network processes and reducing losses in energy systems.

Research by V. Pavlenko et al. [36] emphasizes the synergy between AI, blockchain and smart grids, which creates the basis for the formation of decentralized energy ecosystems with transparent management of data flows and energy resources.

B. Hanna, G. Xu, X. Wang, J. Hossain [37] emphasize that the potential of artificial intelligence is crucial for achieving the seventh goal of sustainable development, as it contributes to increasing energy efficiency, equitable energy access and the development of “clean” technologies.

The conceptual principles of integrating artificial intelligence into the energy sector are systematized in the work of A. M. S. Derbali [38], where the author considers artificial intelligence as the core of a future energy ecosystem capable of ensuring climate neutrality and maintaining energy balance in the face of technological variability.

The analysis of P. Arévalo & F. Jurado [39] shows that artificial intelligence is becoming a key factor in the optimization of distributed energy systems – from demand forecasting to the integration of renewable sources, ensuring the adaptability and flexibility of “smart” networks.

The studies of C. Biswas, A. Chakraborti, S. Majumder [40] present a wide range of methods (from neural networks to fuzzy logic systems) that provide predictive management and technical diagnostics in renewable energy.

A significant contribution to the formation of the theoretical basis was made by the work of B. Zohuri,

F. Mossavar-Rahmani and F. Behgounia [41], where the concept of Business Resilience System (BRS) was proposed, which integrates elements of machine and deep learning to predict energy processes and increase the systemic resilience of energy markets.

Taken together, the results of the analysis allow us to state the emergence of a new scientific direction – AI-driven energy infrastructure management, which combines intelligent decision support systems, big data analytics, digital twins and cyber-physical energy models. Unlike previous studies of critical infrastructure development, which mostly emphasized protection and risks, the energy discourse focuses on innovation, sustainability and climate neutrality, identifying artificial intelligence as a strategic driver of the transition to a new architectonics of energy systems.

In view of this, the aim of the article is to theoretically substantiate and systematize the areas of influence of artificial intelligence on the management of energy infrastructure development in the era of global digital transformation; to identify the potential, risks and mechanisms for using intelligent technologies in ensuring energy security and increasing the efficiency of energy systems.

3 METHODOLOGY

The methodological basis of the study combines systemic, comparative-institutional, analytical and bibliometric approaches, which in combination provide a comprehensive assessment of the impact of artificial intelligence technologies on the management of energy infrastructure development in the context of global digital transformation.

The theoretical basis of the study is the system paradigm, according to which energy infrastructure is considered a complex socio-economic and technical system in which technological, institutional and managerial subsystems interact. This approach makes it possible to identify feedback loops, adaptive mechanisms and dependencies that determine the efficiency and resilience of the energy system under the influence of digital technologies and artificial intelligence algorithms.

The comparative-institutional approach was used to analyze models of integration of artificial intelligence technologies into the practice of energy system management of different countries and organizations (based on materials from the IEA, IRENA, WEF, and the European Commission). This allowed us to identify effective management models,

state regulation tools and organizational mechanisms that can be adapted to the Ukrainian energy context.

The empirical part of the study is based on quantitative and qualitative analysis of international data and scientific publications. The information base was formed on the basis of reports of leading international organizations – the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the World Economic Forum (WEF) and the European Commission. These sources contain current indicators of the level of digitalization of the energy sector, the effectiveness of the use of artificial intelligence technologies, the dynamics of reducing operating costs and increasing the accuracy of demand forecasting.

In order to identify scientific trends and conceptual structures, a bibliometric analysis was conducted using the Scopus database as the main source of scientific information. The search query “Artificial Intelligence” and “Energy Infrastructure Development Management” covered publications for the years 2000-2025, with a detailed analysis carried out for the period 2013-2025, which is characterized by the highest scientific activity.

VOSviewer v.1.6.19 software was used to process and visualize the results, which allows building maps of keyword co-occurrence, co-authorship networks and citations. This made it possible to identify dominant scientific clusters, identify influential authors and trace interdisciplinary connections between the topics of artificial intelligence, energy efficiency and digital management.

Integration of the results of bibliometric, comparative and system analyzes made it possible to carry out a system-analytical synthesis aimed at identifying key determinants that shape the impact of artificial intelligence on the development of energy infrastructure.

The proposed methodological approach ensures the objectivity, reproducibility, and scientific validity of the research results, creating a basis for forming strategic management decisions to increase the efficiency, adaptability, and resilience of energy infrastructure in the context of digitalization.

4 RESULTS

A search of the Scopus database using the keywords “Artificial Intelligence” and “Energy Infrastructure Development Management” revealed 453 documents published between 2000 and 2025. The dynamics of scientific papers demonstrate a

significant increase in publications after 2018 (Fig. 1), reflecting the rapid digital transformation of the energy sector, the introduction of 5G–6G technologies, the active development of “green” energy concepts, and the strengthening of global sustainable development programs.

Until the mid-2010s, the number of papers remained insignificant, but after 2020 there has been a sharp acceleration with peak indicators in 2024–2025, which confirms the sharp increase in the relevance of research on the application of artificial intelligence in energy infrastructure management.

Calculations showed an exponential growth of scientific interest: the average annual growth rate (CAGR) was 21.7%, and the period for doubling the number of publications was about 3.2 years. The peak of activity in 2024–2025 (+139%) correlates with the strategic initiatives of the EU and the IEA, in particular the Digital Energy Action Plan 2022–2025 and AI for Energy Transition. The value of the coefficient of determination of the model ($R^2=0.52$) indicates that more than half of the variation in the dynamics of publications is explained by the exponential trend, typical of rapidly growing interdisciplinary areas.

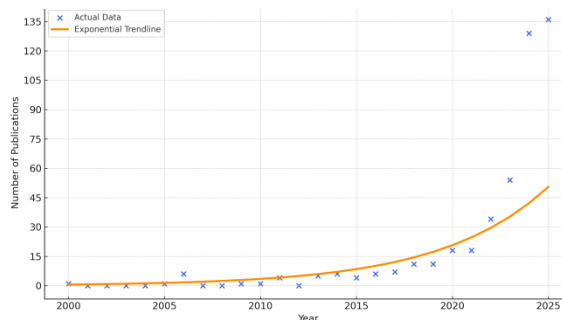


Figure 1: Exponential growth of publications on “AI in energy infrastructure development management” (2000–2025).

The evolution of the publication flow allows us to identify four stages of the development of scientific interest (Fig. 2): the period of emergence (2000–2010) with isolated works; the period of formation (2011–2017) with a gradual increase in applied research on machine learning in energy; the period of active development (2018–2021), when the integration of AI is associated with the concepts of Industry 4.0, Smart Grid and IoT; the period of intensive expansion (2022–2025), within which sustainable scientific schools were formed in the USA, India, China and the EU.

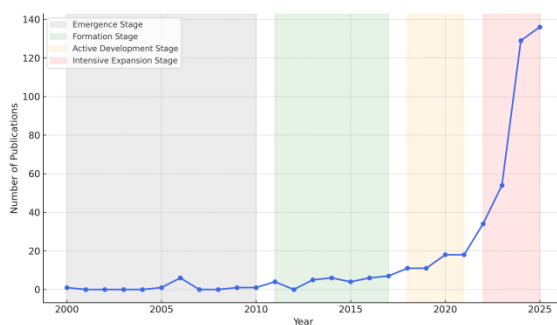


Figure 2: Stages of scientific interest in AI-driven energy infrastructure development management.

The most cited publications (Table 1) focus on the intersection of artificial intelligence, energy efficiency, digital management technologies and sustainable development. Field-Weighted Citation Impact (FWCI) indicators range from 1.84 to 16.11, which is 2-8 times higher than the industry average, confirming the high level of innovativeness of research.

Table 1: Most cited publications on “Artificial Intelligence in Energy Infrastructure Development Management” (Scopus, 2000-2025) [42]-[48].

Author(s), Year	Article Title	Source	Citations	FWCI	Core Subject / Scientific Focus
H. Yang et al. (2020) [42]	Artificial-Intelligence-Enabled Intelligent 6G Networks	IEEE Network	428	15.80	AI-based 6G network architectures; intelligent resource management; energy-efficient communication systems
A. Sun & B. Scanlon (2019) [43]	How can Big Data and machine learning benefit environment and water management	Environmental Research Letters	409	4.28	Big Data and ML for environmental and water resource monitoring; predictive analytics for sustainability
J.-P. Correa-Baena et al. (2018) [44]	Accelerating Materials Development via Automation, Machine Learning, and High-Performance Computing	Joule	277	1.84	Machine learning and automation in materials science; high-performance computing for energy materials
B. J. Singhet al. (2023) [45]	A systematic review of industrial wastewater management: Evaluating challenges and enablers	Journal of Environmental Management	260	9.01	Environmental management of industrial water systems; circular economy; sustainable development
S. Bruno et al. (2018) [46]	Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management	Automation in Construction	243	3.29	BIM/HBIM for infrastructure management; cognitive automation and diagnostic modelling
B. Mao et al. (2022) [47]	AI Models for Green Communications Towards 6G	IEEE Communications Surveys and Tutorials	220	16.11	AI models for green communications; energy-efficient 6G networks; ML/DL in network management
Y.-H. Lin & M.-S. Tsai (2014) [48]	Development of an improved time-frequency analysis-based nonintrusive load monitor for load demand identification	IEEE Transactions on Instrumentation and Measurement	163	4.94	Non-intrusive load monitoring (NILM); smart grid applications; load optimization algorithms

Several leading research areas were identified (Table 2): AI in Smart Grid networks and 6G communications; intelligent energy resource monitoring and management systems; application of Big Data and machine learning in the water-energy

nexus; automation of materials science and energy technology processes; and integration of AI in ensuring the sustainable development of industrial systems.

Table 2: Leading Scientific Publication Outlets on “Artificial Intelligence in Energy Infrastructure Development and Management” (Scopus, 2000–2025).

Journal / Book Series (Publisher)	Source Type	Scopus Coverage Years	Subject Areas	CiteScore 2024	SJR 2024	SNIP 2024	Core Scientific Focus
Energies (MDPI)	Open Access Journal	2008-2025	Energy Engineering, Renewable Energy, Electrical and Electronic Engineering, Sustainability	7.3	0.713	1.027	Digitalisation of energy systems; intelligent grid management; decarbonisation and energy efficiency
Lecture Notes in Networks and Systems (Springer Nature)	Book Series	2016-2025	Control and Systems Engineering, Signal Processing, Computer Networks	1.0	0.166	0.233	Networked systems; modelling of cyber-physical infrastructures; AI-based process control
IEEE Access (IEEE)	Open Access Journal	2013-2025	Engineering (General), Computer Science, Materials Science	9.0	0.849	1.504	Applied machine learning; energy consumption forecasting; Smart Grid AI models
Sustainability (Switzerland) (MDPI)	Open Access Journal	2009-2025	Environmental Science, Energy, Computer Science, Geography & Planning	7.7	0.688	1.113	Sustainable development policy; energy transition; socio-economic assessment of AI impacts
Lecture Notes in Computer Science (Springer Nature)	Open Access Book Series	1973-2026	Theoretical & Applied Computer Science	2.4	0.352	0.555	Algorithmic approaches; machine learning; big data processing in technical systems
Studies in Systems, Decision and Control (Springer Nature)	Book Series	2014-2025	Decision Sciences, Control & Systems Engineering, Economics	1.5	0.116	0.000	Decision-making theory; infrastructure risk management; AI in control systems
Sustainable Civil Infrastructures (Springer Nature)	Book Series	2018-2025	Civil & Structural Engineering, Environmental Engineering	0.3	0.140	0.108	Sustainable infrastructure technologies; energy-efficient engineering solutions; digital modelling

The leading publishers in the research topic are MDPI, Springer Nature and IEEE (Table 3), which generate more than 70% of the analyzed publications. The Energies and Sustainability journals (MDPI) are characterized by high CiteScore (>7) and SNIP (>1.0), IEEE Access demonstrates one of the highest citation rates (CiteScore=9.0, SNIP=1.504), and the Springer series (Lecture Notes in Networks and Systems, Studies in Systems, Decision and Control) dominate the segment of algorithmic methods and digital technologies for energy systems management. The geography of publications indicates the formation of a global scientific network. The largest number of documents was prepared by researchers from India (106), China (52), the USA (50), the UK (24), Italy (23) and Australia (22). Ukraine (12 documents), Germany, South Korea, Ireland and Canada also provide significant contributions.

The analysis of scientific collaboration revealed several stable clusters (Fig. 3), which form a global network of research on artificial intelligence in energy infrastructure management. Each cluster has

its own institutional core, research focus and thematic dominants, reflecting the socio-economic and technological priorities of the respective regions. The first is the Indian-Asian cluster, the core of which is India. The key participants are Saudi Arabia, the UAE, Egypt, Iraq, Taiwan and Nigeria. The cluster is characterized by a high intensity of inter-university collaborations, in particular between the Indian Institutes of Technology, the National Institutes of Technology, Sharda University, Lovely Professional University and a number of technical universities in the Middle East.

The main focus of research is related to the optimization of energy network management, renewable energy, the integration of solar and wind power plants into national energy systems, load forecasting and the application of machine learning for electric power Smart Grid platforms. A feature of this cluster is its focus on practical engineering solutions that are scalable in rapidly developing countries, and significant government investment in energy technologies as part of national energy security strategies.

Table 3: Thematic Clusters of Key Research Concepts on “Artificial Intelligence in Energy Infrastructure Development Management” (Scopus, 2000–2025).

Cluster Name	Dominant Keywords	Scientific Focus	Features
AI and Sustainable Resource Management	artificial intelligence, machine learning, optimization, decision support systems, water management, waste management, circular economy, carbon emission	Application of AI and ML for natural resource governance, optimisation of water supply and treatment, reduction of CO ₂ emissions, and the development of circular economy models	Formation of intelligent environmental management ecosystems and advancement of the “green AI” concept in the context of SDG 7, SDG 9, SDG 11, SDG 13
Intelligent Energy Systems	smart grid, energy management, renewable energy, energy storage, demand side management, electric vehicle, cyber security, learning systems	AI-based energy governance: demand-side management, load forecasting, network security and renewable energy integration	Combination of technical (Smart Grids, IoT) and managerial (decision support, predictive analytics) approaches within AI-driven energy system control
Information Management and Data Analytics	information management, data analytics, IoT, blockchain, cloud computing, big data, decision making, learning algorithms	Digital analytics and data governance: IoT and Big Data for monitoring, blockchain platforms for energy transactions, cloud computing for analytics applications	Forms the technological core of digital energy systems, linking analytical models with risk management and cybersecurity
Digital Infrastructure and Next-Generation Communications	cloud-computing, 5G, 6G, network architecture, network security, smart infrastructure, real-time systems	AI-based management of next-generation communication and infrastructure systems: 5G/6G networks, real-time systems, and energy-efficient telecommunications	Development of AI-driven communication networks supporting intelligent energy platforms
Urban Energy and Sustainable Urbanism	smart city, urban growth, urban transportation, autonomous vehicles, planning, environmental management systems, sustainable city	AI for urban energy and infrastructure planning, optimisation of transportation and smart mobility, and development of sustainable cities	Integration of Smart City and Sustainable Urban Development concepts enabled by artificial intelligence

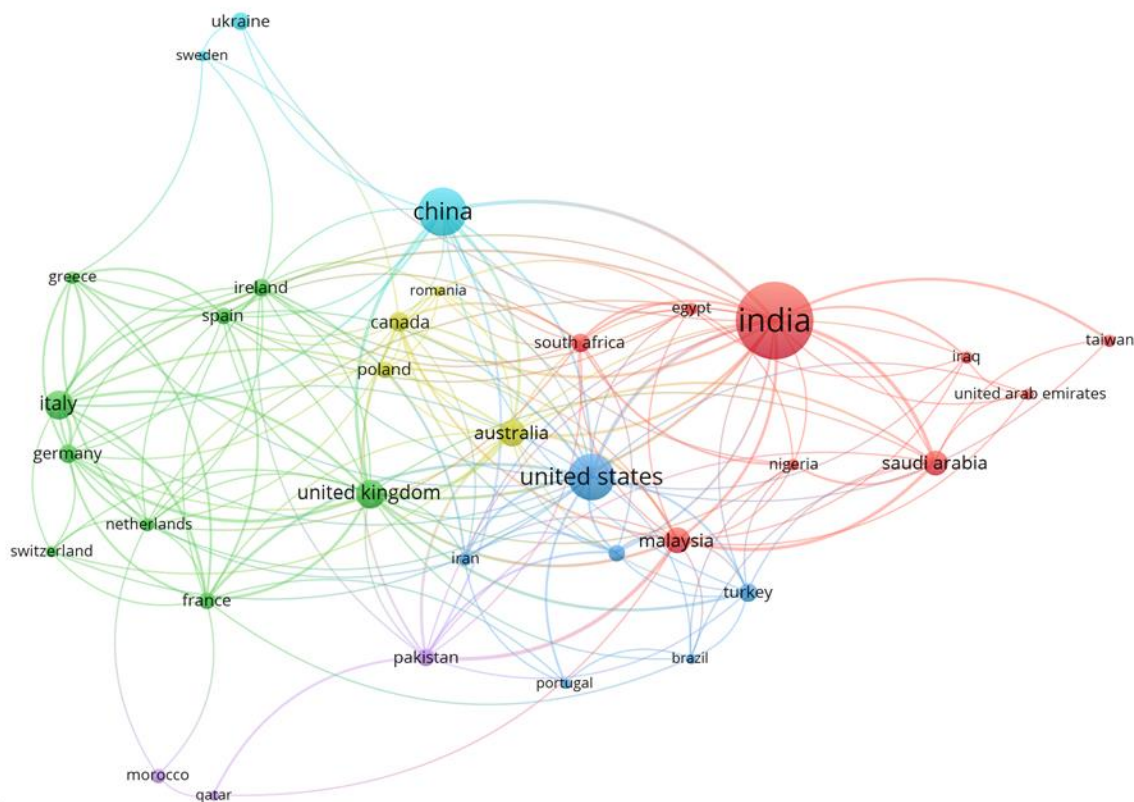


Figure 3: Identified clusters of international research collaboration on the selected topic.

The second is the Anglo-American cluster, which is formed by the USA, the UK, Australia, Malaysia, Turkey and partly Brazil, Portugal and Iran. Its research focuses on creating AI-based decision-making systems, predictive analytics and machine learning for load management and preventing accidents in energy networks. Significant attention is paid to green communication networks, the use of 5G–6G technologies, energy cybersecurity and protecting infrastructure from cyberattacks.

Leading organizations in the cluster include the Massachusetts Institute of Technology, the National Renewable Energy Laboratory (NREL), the University of Oxford, Imperial College London, the University of California and the University of Melbourne. The cluster is dominated by publications in highly ranked IEEE and Springer journals, which is due to the high level of algorithmic and analytical research.

The third is the European cluster, which unites research centers in the UK, Italy, Germany, France, Spain, the Netherlands, Ireland, Switzerland and Greece. Its distinctive feature is the close integration of EU environmental and energy policies with digital technologies for power system management.

The cluster demonstrates the highest density of internal collaboration, reflecting the joint research programs Horizon 2020, Horizon Europe, Digital Europe, Green Deal and the institutional role of ACER-CEER in shaping regulatory approaches. The thematic focus covers modelling of sustainable energy transition, risk management and the development of Smart Cities/Smart Regions, digital twins of infrastructures, as well as the impact of AI on the decarbonization of industrial systems.

The fourth is the North African and Middle Eastern cluster, which includes Qatar, Morocco and partly Romania, which is in a transitional position. The main specificity of this cluster is related to the climatic vulnerability of the territories and the need for digital control of energy systems in conditions of increased risks associated with water scarcity, record temperatures and growing demand for electricity. Research focuses on the integration of renewable energy sources, optimization of energy generation and storage, as well as the use of artificial intelligence to reduce losses in networks and manage energy security. The fifth is the Chinese cluster, in which China acts as a coordinating center, supporting cooperation with Canada, Poland,

The generalized results of the bibliometric analysis also demonstrate the growing influence of international scientific cooperation, the increasing importance of interdisciplinary research clusters and the gradual institutionalization of a scientific school focused on AI-driven energy infrastructure development management. That is, the research topic moves from the stage of conceptual understanding to the stage of forming mature theoretical and methodological approaches and practical solutions for the energy sector.

The above conclusions create the basis for further critical analysis of the results obtained, which makes it possible to proceed to a discussion of their theoretical and applied implications, as well as to identify the limitations of the research conducted and the directions of future scientific explorations.

5 DISCUSSION, RESEARCH LIMITATIONS AND FUTURE RESEARCH AGENDA

The results of the bibliometric analysis make it possible to rethink not only the current state, but also the internal logic of the evolution of scientific research on the application of artificial intelligence in managing energy infrastructure development. The identified dynamics of publication activity, thematic clusters and international collaboration patterns show that AI-driven energy infrastructure management has moved beyond a purely technological niche and is gradually transforming into a core component of sustainable, digitally governed energy systems.

5.1 Why Do Certain Thematic and Collaboration Clusters Dominate?

The predominance of specific thematic clusters – in particular Intelligent Energy Systems, AI and Sustainable Resource Management and Information Management and Data Analytics – is not accidental. It reflects a combination of at least three groups of drivers.

First, these clusters correspond to areas with the highest data availability and technological readiness. Smart grids, non-intrusive load monitoring, predictive maintenance and energy efficiency optimisation generate large volumes of time-series and sensor data that are particularly suitable for machine learning and deep learning methods. This

technological “fit” explains why AI applications concentrate around forecasting, optimisation and anomaly detection in networks rather than, for example, long-term socio-institutional reforms.

Second, the leading clusters are strongly aligned with commercial incentives and investment priorities. Energy companies and technology vendors obtain direct, measurable benefits from reducing network losses, optimising asset management, improving demand forecasting and integrating renewable energy sources. This makes projects in the domains of smart grids, 5G/6G-enabled energy communications and digital twins more attractive for both corporate and public funding than research on, for instance, social perception of AI or ethics-by-design in critical infrastructure.

Third, the structure of scientific collaboration mirrors regulatory and funding architectures. The Indian–Asian and Chinese clusters benefit from large-scale national programmes for energy transition and digitalisation; the Anglo-American and European clusters are shaped by US federal programmes, EU Green Deal, Horizon Europe and Digital Europe initiatives. These frameworks explicitly prioritise AI, cybersecurity and sustainable energy, reinforcing research streams around those policy priorities. By contrast, topics with less clear funding lines – such as distributive justice of AI-driven tariffs or long-term labour market implications in the energy sector – remain underrepresented.

Altogether, the dominance of certain clusters indicates a path-dependent evolution of the field, in which data-rich, commercially profitable and policy-promoted directions systematically receive more scientific attention than equally important, but less easily quantifiable social, ethical and regulatory dimensions.

5.2 Underexplored Dimensions and Knowledge Gaps

The current structure of the field reveals several substantive gaps that limit a holistic understanding of AI-driven energy infrastructure development.

First, social acceptance and public perception of AI in critical energy infrastructure remain insufficiently studied. While sociological and behavioural studies on AI in healthcare or consumer services are growing, the specific perceptions of citizens, local communities and energy consumers regarding AI-based control of grids, dynamic pricing or automated outage management are rarely

addressed in a systematic way. This creates a risk of overlooking resistance, mistrust or low willingness to share data, which may become a binding constraint for large-scale deployment of AI solutions.

Second, there is a lack of integrative research on regulatory and governance frameworks for AI in critical infrastructure. Existing studies usually focus either on technical cybersecurity requirements or on general AI regulation, without fully capturing the interplay between sectoral energy regulation, cybersecurity directives (e.g. NIS2), emerging AI-specific acts and national security strategies. As a result, there is no widely adopted analytical framework that would connect AI capabilities, risk profiles, liability allocation and regulatory design in the energy sector.

Third, economic and financial aspects of AI deployment in energy infrastructure are underrepresented compared to technical studies. Only a limited number of publications provide robust cost-benefit analyses, business models or financing schemes for AI-based retrofitting of networks, creation of digital twins or deployment of advanced decision support systems. Without such analyses it is difficult for regulators and operators to prioritise projects, assess payback periods or design incentives for private investment.

Fourth, the identified geographical asymmetry – with dominance of India, China, the USA and several EU countries, and a weaker representation of Central and Eastern Europe, the Middle East, North Africa and post-conflict economies – indicates a contextual bias of the existing evidence base. The majority of case studies are based on relatively stable, well-capitalised energy systems, whereas the specific challenges of war-affected, highly fragmented or institutionally weak energy sectors remain largely outside the mainstream discourse.

Addressing these gaps requires a deliberate shift from purely technological optimisation towards an integrated perspective that includes governance, economic feasibility, social acceptability and geopolitical vulnerabilities of AI applications in energy infrastructure.

5.3 Conceptual Framework: AI-Enabled Energy Infrastructure Governance

Building on the results of the network and cluster analysis, a conceptual framework of AI-enabled Energy Infrastructure Governance can be proposed to structure the relationships between AI

technologies, infrastructure management tasks and target outcomes of energy systems.

The framework consists of three interrelated levels:

Technological layer (AI capabilities and digital enablers).

This layer includes machine learning and deep learning algorithms, reinforcement learning, digital twins, optimisation models, IoT platforms, blockchain-based transaction systems and advanced data analytics. These technologies provide the functional tools for forecasting, optimisation, detection and control.

Infrastructure management layer (decision domains and operational tasks). At this level, AI is embedded into concrete management functions of energy infrastructure, including:

- 1) long-term planning and investment prioritisation;
- 2) operational dispatch and balancing of generation, storage and demand;
- 3) asset health monitoring, predictive maintenance and outage management;
- 4) cyber-physical security and anomaly detection;
- 5) market design, tariff setting and demand response programmes.

Feedback loops connect these tasks with the technological layer: improved data quality and model performance enhances decision-making, while operational decisions generate new data for model refinement.

Outcome layer (system performance and societal goals). The upper level reflects the target indicators that energy infrastructure governance aims to achieve:

- 1) sustainability and decarbonisation (GHG emissions, share of renewables, circularity of resource use);
- 2) security and resilience (reliability indices, recovery times after disruptions, cyber-resilience);
- 3) efficiency and affordability (technical and non-technical losses, operating costs, energy prices);
- 4) inclusiveness and fairness (equitable access, distributional effects of AI-driven tariffs and services).

Horizontal “governance” and “ethics and regulation” components cut across all three layers. Governance determines how responsibilities for AI deployment are allocated among regulators, operators, technology providers and consumers; the

ethical and regulatory dimension shapes transparency requirements, accountability, data protection and risk-sharing rules.

Graphically, the framework can be presented as a multi-layer diagram linking AI technologies (bottom layer) with management tasks (middle layer) and outcome dimensions (top layer), with bi-directional arrows indicating feedbacks and learning cycles. Such a conceptual model translates the essentially descriptive bibliometric findings into an analytical architecture that can guide empirical studies and policy design.

5.4 Methodological Limitations and Future Research Agenda

The study inevitably faces several methodological limitations typical for bibliometric research. The exclusive use of the Scopus database, without complementary integration of Web of Science, IEEE Xplore or regional databases, may lead to incomplete coverage of relevant works, particularly those published in languages other than English.

Recent publications (2023–2025) have not yet accumulated enough citations to fully reflect their scientific influence, which introduces a time lag into citation-based metrics. Automatic keyword clustering and mapping in VOSviewer may group semantically distinct concepts together or generate doublets, complicating the interpretation of some thematic links.

Finally, bibliometric indicators capture quantitative dimensions of research activity, but they do not directly assess the robustness of empirical methods, the quality of evidence or the practical impact of AI applications on real energy systems.

Recognising these limitations, the findings of this study should be interpreted as a structured “map” of the field rather than a definitive evaluation of specific technologies or projects. At the same time, the results provide a solid foundation for formulating a more focused research agenda that moves beyond description towards explanation and evaluation.

In particular, future research could prioritise the following non-trivial questions:

- 1) Causal impacts of AI deployment. Under what conditions do AI-based solutions in grid operation, maintenance and planning deliver measurable improvements in energy efficiency, resilience and decarbonisation compared to conventional approaches, once costs and risks are fully accounted for?

- 2) Regulation–innovation nexus. How do different combinations of energy market design, cybersecurity regulation and emerging AI governance frameworks shape the direction, pace and distribution of AI adoption in critical energy infrastructure?
- 3) Societal acceptance and distributive effects. How do citizens and energy consumers perceive AI-based decision-making in critical infrastructure, and what are the distributional consequences of AI-driven tariff structures, demand response programmes and automated service provision for vulnerable groups?
- 4) Economics and financing of AI-enabled infrastructure. What business models and financing mechanisms are most effective for scaling AI solutions in energy infrastructure, especially in countries with constrained fiscal space, high sovereign risk or post-conflict reconstruction needs?
- 5) Context-sensitive resilience modelling. How can AI-based models incorporate the specific vulnerabilities of energy systems in regions exposed to armed conflict, hybrid threats or extreme climate events, and what indicators best capture AI’s contribution to multi-hazard resilience?

Addressing these questions will require combining bibliometric and network analysis with empirical case studies, system dynamics, multi-criteria decision analysis, scenario planning and expert elicitation. Strengthening international cooperation, including with countries in Central and Eastern Europe, the Middle East, North Africa and other transition or post-conflict economies, will be crucial for expanding the empirical basis and ensuring that AI-enabled energy infrastructure governance frameworks are both globally informed and locally relevant.

6 CONCLUSIONS

The study provides an integrated bibliometric and conceptual analysis of the global research landscape on artificial intelligence in energy infrastructure management over 2000–2025. The findings reveal that AI has become a structurally important driver of energy system transformation, shaping the technological, operational and governance foundations of modern energy infrastructures. The exponential growth in publications since 2020 reflects not only technological advances but also the

deepening interdependence between digitalisation, renewable energy integration, cybersecurity and energy resilience.

The analysis demonstrates that the dominance of specific research clusters – such as smart grid optimisation, predictive analytics, digital twins and AI-enabled energy efficiency – is shaped by the interplay of three forces:

- 1) high data availability and methodological compatibility of these domains with machine learning;
- 2) strong commercial incentives and investment priorities that favour operational optimisation tasks;
- 3) regulatory and funding architectures that systematically support digitalisation of energy systems.

At the same time, the study identifies notable knowledge gaps, including limited attention to social acceptance of AI in critical infrastructure, underdeveloped governance and regulatory frameworks, as well as insufficient economic evaluations of AI deployment, especially in countries with constrained resources or post-conflict recovery needs.

Building on the network and thematic mapping results, the research outlines the conceptual foundations of an AI-enabled Energy Infrastructure Governance model, which integrates three analytical layers:

- 1) technological capabilities (machine learning, digital twins, IoT, optimisation algorithms);
- 2) infrastructure management tasks (planning, balancing, predictive maintenance, cybersecurity, market design);
- 3) target outcomes (sustainability, resilience, efficiency, affordability and fairness).

The model emphasises the system-wide feedback loops between data, decision-making and performance indicators, while also incorporating transversal elements of regulation, ethics and accountability. Although presented in an initial conceptual form, the model provides a structured foundation for developing applied tools for evaluation, strategic planning and policy design.

The study contributes to the literature by transforming a predominantly descriptive research field into a more analytical one, offering insights into why certain clusters dominate, what structural gaps persist, and how AI can be embedded into energy infrastructure governance in a way that strengthens sustainability and resilience. These results support policymakers, operators, regulators

and researchers in identifying priority directions for responsible AI deployment in the energy sector.

At the same time, the research has several methodological limitations related to reliance on Scopus data, the predominance of English-language publications, and the interpretive nature of cluster aggregation. This implies that the findings should be seen as a comprehensive mapping of global trends rather than an exhaustive evaluation of the effectiveness of AI technologies.

Future research should deepen the analytical implications of the results by focusing on: empirical assessment of the causal impact of AI solutions on energy system performance; integrative regulatory frameworks for AI in critical infrastructure; distributive and societal effects of AI-driven energy management; economic and financial models for large-scale AI deployment; adaptation of AI-based resilience frameworks to fragile, high-risk or post-conflict energy systems.

A separate direction of future work is the full formalisation, operationalisation and empirical testing of the proposed AI-enabled Energy Infrastructure Governance model, which can evolve into a robust analytical and decision-support framework for national and international energy policy.

ACKNOWLEDGMENTS

We acknowledge support by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) and the Open Access Publishing Fund of Anhalt University of Applied Sciences.

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