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# Mapping Artificial Intelligence Applications in Energy Efficiency and Sustainability: A Bibliometric Analysis of the Energy Management Sector

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**ABSTRACT:** Artificial Intelligence (AI) enables the energy management sector to enhance operational efficiency by integrating renewable energy systems to reach sustainability goals. This research investigates 19 peer-reviewed articles from the Web of Science (WoS) Core Collection through bibliometric methods to study AI-driven energy efficiency and sustainability. The analysis evaluates publication patterns together with citation patterns and leading authors and institutions and keyword co-occurrence to reveal dominant themes and emerging topics. The research shows growing academic interest in predictive maintenance machine learning algorithms, smart grids, renewable energy forecasting and real-time monitoring forming the primary clusters. The leading nations in research contributions are China and the United States and several European countries. The research demonstrates that deep learning and IoT-enabled energy systems and predictive analytics function as fundamental instruments for sustainable energy transitions. The research reveals that ongoing challenges include data quality problems and cybersecurity risks and difficulties in policy alignment across different sectors. The research provides a systematic evaluation of AI applications for developing sustainable low-carbon energy systems to benefit researchers and policymakers and industry stakeholders.

**KEYWORDS:** Artificial Intelligence, Bibliometric analysis, Energy efficiency, Sustainability, Energy management, Industry 4.0

## I. INTRODUCTION

The worldwide energy industry undergoes a fundamental transformation because of simultaneous demands for decarbonization and digitalization. The global sustainability goals require essential action through renewable energy integration and efficiency improvements and greenhouse gas emission reduction (J. Li et al., 2025; Zhou, 2024a). However, the variable nature of solar and wind energy creates operational difficulties for forecasting and supply-demand balancing and grid stability maintenance (Han et al., 2024; Yin et al., 2023a). The problems become more severe because of the growing use of electric transportation systems and decentralized power generation and changing consumer behavior. AI has emerged as a transformative tool for addressing such challenges, offering predictive capabilities, adaptive control, and real-time optimization (Musa et al., 2023). The power grid has achieved better integration of renewable energy sources through machine learning and deep learning and hybrid modeling techniques which operate with IoT architectures and digital twins and smart grid systems to achieve low-carbon operations and improve energy storage management (Dayarathne et al., 2025a; Zhang et al., 2024a). These technologies optimize energy system operations to achieve maximum efficiency while reducing power cuts and enabling sustainable community-based energy distribution (J. Li et al., 2025; Zhou, 2024a). Research findings demonstrate how AI technology supports renewable power generation predictions and optimizes energy storage systems and improves demand response capabilities (Han et al., 2024). It also identifies challenges related to scalability, cybersecurity

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vulnerabilities, and explainability issues in real-world deployments (Musa et al., 2023). The different viewpoints demonstrate why a systematic and bibliometric review is necessary to establish consensus areas while identifying implementation barriers and defining future research priorities. This study conducts a bibliometric and structured literature analysis of open-access peer-reviewed articles from 2020 and 2025, to analyze AI applications in smart grids and IoT-enabled systems and digital twins for low carbon and renewable integration objectives. The analysis is guided by three research questions:

RQ1: What is the main AI-based technologies applied in the energy sector to achieve sustainability objectives?

RQ2: How have these technologies contributed to renewable integration, low-carbon transition, and operational efficiency?

RQ3: What are the key challenges, enabling conditions, and future research directions for AI-driven sustainability in energy systems?

The research investigates these questions through systematic analysis to establish a complete understanding of AI's contribution to sustainable energy systems and identify both short-term implementation methods and future development possibilities.

## **II. METHODOLOGY**

This study applies bibliometric analysis to examine AI applications in energy efficiency and sustainability, focusing on the energy management sector. Bibliometric methods quantify publication patterns, thematic clusters, and emerging trends.

### **2.1 Data Source and Search Strategy**

The WoS Core Collection was selected for its strict indexing criteria and broad peer-reviewed coverage. A search conducted on (date) used the query:

TS=("machine learning" OR "deep learning" OR "neural network\*" OR "predictive analytics") AND TS=("smart grid\*" OR "digital twin\*" OR IoT) AND TS=("low-carbon" OR "carbon reduction" OR "renewable integration") AND DT=(Article OR Review) AND PY=(2022-2025)

An Open Access filter ensured all results were freely accessible for full-text review. Inclusion criteria required English-language journal articles or reviews (2022–2025) directly addressing AI in energy efficiency, renewable integration, or carbon reduction for energy management.

### **2.2 Data Extraction and Cleaning**

Records were exported in full record and cited references format. Cleaning involved standardizing author names, institutional affiliations, and keywords, merging synonyms (e.g., “Internet of Things” and “IoT”), and removing duplicates or incomplete entries.

### **2.3 Analysis Procedure**

Guided by the research questions, the dataset was analyzed for:

- Publication Trends (2022–2025).
- Source Analysis (most productive/cited journals).
- Authorship & Institutions (leading authors, institutions, countries).
- Keyword Co-occurrence (core themes, AI techniques, application areas).

Descriptive statistics and bibliometric mapping visualized research patterns, thematic structures, and gaps to inform future work.

The following section presents the bibliometric analysis results, highlighting publication trends, leading sources, and thematic clusters derived from the selected dataset.



**III. RESULTS****3.1. Bibliometric Analysis Results**

The bibliometric analysis provides a quantitative overview of the selected 19 open-access studies, mapping the intellectual structure, publication dynamics, and thematic focus of AI applications in energy efficiency and sustainability between 2022 and 2025. The annual distribution of publications shows steady growth in research output, reflecting increasing scholarly and policy attention to AI-enabled sustainable energy systems. In 2022, publications accounted for 16% of the dataset, growing to 26% in 2023 and peaking at 37% in 2024, with the remaining 21% published in early 2025. This upward trajectory underscores the rapid maturation of the field as AI adoption in the energy sector expands.

Table 1 "Summary of Included Studies in the Synthesis Comprising the Dataset of 19 Articles (Source: Author's Own Contribution)"

Title	Journal	2024–2025 Impact Factor
Digital twin-based reinforcement learning for extracting network structures and load patterns in planning and operation of distribution systems	Applied Energy	12.8 (2024)
Capacities prediction and correlation analysis for lithium-ion battery-based energy storage system	Control Engineering Practice	4.6 (2023)
Intelligent power grid monitoring and management strategy using 3D model visual computation with deep learning	Energy Reports	5.1 (2023)
Energy-Sharing Economy with Renewable Integration and Management in Communities—a State-of-the-Art Review	Advanced Energy & Sustainability Research	6.26 (2024)
Mitigating Cyber Risks in Smart Cyber-Physical Power Systems Through Deep Learning and Hybrid Security Models	PeerJ Computer Science	3.5 (2024)
Big data resolving using Apache Spark for load forecasting and demand response in smart grid: a case study of Low Carbon London Project	Journal of Big Data	10.33 (2024)
Embedded Real-Time Speed Forecasting for Electric Vehicles: A Case Study on RSK Urban Roads	IEEE Access	3.6 (2024)
Mitigating Cyber Risks in Smart Cyber-Physical Power Systems Through Deep Learning and Hybrid Security Models	IEEE Access	3.6 (2025)
Predictive Analysis of a Building's Power Consumption Based on Digital Twin Platforms	Energies	3.2 (2024)
A Deep Learning-Based Dual-Scale Hybrid Model for Ultra-Short-Term Photovoltaic Power Forecasting	Sustainability	3.9 (2022)
A Low-Power Continuous-Time Delta-Sigma Analogue-to-Digital Converter for the Neural Network Architecture of Battery State Estimation	Electronics	2.6 (2024)

### 3.1.2 Keyword Co-occurrence Themes

The VOSviewer keyword density map shows four main thematic clusters: (1) digital twin and network optimization, (2) IoT-driven sustainability models, (3) deep learning and predictive analytics, and (4) cybersecurity in smart grids. These clusters show both mature research streams and emerging areas of interest, which directly relate to the study's RQs on technology adoption, sustainability impact, and implementation challenges.

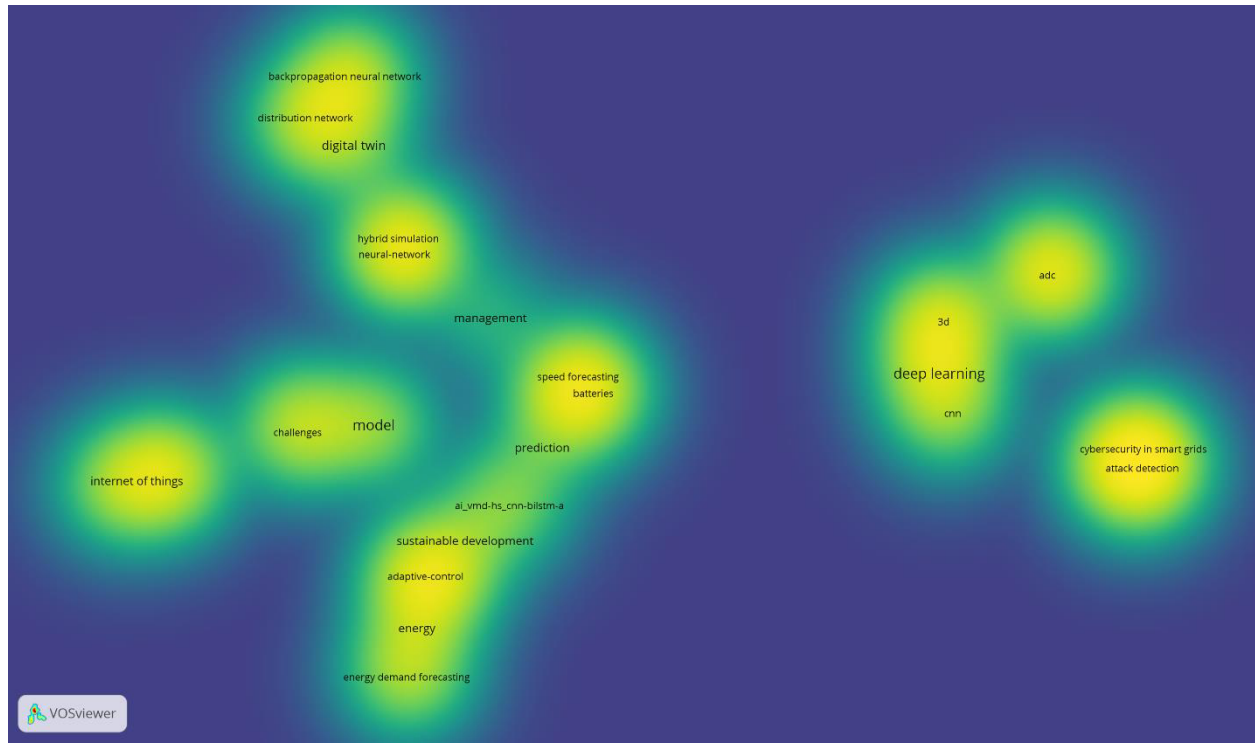


Figure 1 Keyword Co-occurrence Analysis

The VOSviewer keyword density map revealed four distinct thematic clusters. The first cluster, digital twin and network optimization, includes terms such as “digital twin,” “backpropagation neural network,” and “distribution network,” representing the integration of AI-enhanced simulation environments with operational grid management. The second cluster, IoT-driven sustainability models, encompasses “internet of things,” “adaptive control,” and “sustainable development,” reflecting a focus on real-time data acquisition and demand-side optimization for renewable integration. The third cluster, deep learning and predictive analytics, contains “deep learning,” “CNN,” and “batteries,” highlighting computational approaches for forecasting and storage optimization. The fourth, smaller but significant cluster focuses on cybersecurity in smart grids, with terms such as “attack detection” and “cybersecurity in smart grids,” indicating an emerging niche that ensures operational resilience in digitalized energy infrastructures. These clusters directly map to RQ1 and RQ2 by identifying the dominant AI techniques and their sustainability-oriented applications.

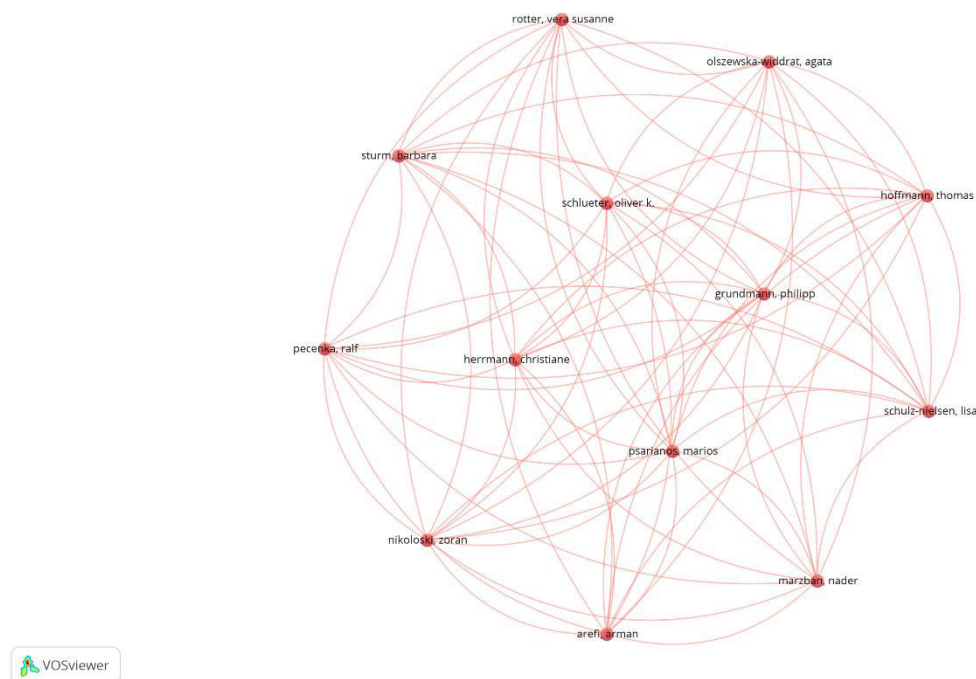


Figure 2 Author Collaboration Network in WOS of the database source (author contribution using Vosviewer)

The visualization presents a network of authors who collaborated on the included studies through co-authorship relationships. The visualization uses nodes to represent authors whose size indicates the total number of publications in the dataset. The lines between nodes represent co-authorship relationships with thicker lines indicating stronger collaboration between authors. The network displays separate clusters which position Oliver K. Schlueter, Vera Susanne Rotter and Ralf Pecenka as central connectors because they actively promoted collaborative research about AI. The reviewed studies employ a variety of methodological designs. Simulation-based experiments dominate (63%), often used to test AI forecasting models for renewable integration under controlled conditions. Case studies (21%) examine AI deployment in specific smart grids or microgrid infrastructures, while review articles (16%) synthesize state-of-the-art approaches across multiple subdomains. In terms of application domains, 42% of studies address smart grid optimization, 26% focus on energy storage and battery management, 21% involve electric vehicle integration, and 11% deal with community energy-sharing systems. AI techniques vary widely, with deep learning models (LSTM, CNN, GNN) being the most prevalent (47%), followed by hybrid AI-optimization systems (26%), reinforcement learning combined with digital twins (16%), and gradient boosting methods such as XGBoost (11%). This distribution underscores the methodological diversity of AI approaches in advancing energy sustainability.

### 3.2 Theoretical Framework and Synthesis of Results

The research combines evidence from open-access literature published between 2022 and 2025 to study how AI supports sustainability progress in the energy sector. The research framework consists of three guiding RQs which aim to identify AI techniques (RQ1) and study their impact on renewable integration and low-carbon objectives (RQ2) and outline existing challenges and future research directions (RQ3). The synthesis combines research from empirical studies with reviews and technical demonstrations which focus on AI applications in smart grids and digital twins and IoT and other energy technologies. The research approach demonstrates how technological capabilities link to sustainability outcomes by establishing AI as the primary driver for energy transition.

#### 3.2.1 RQ1: What artificial intelligence techniques is being applied in the energy sector to enhance sustainability?

The reviewed literature demonstrates how AI techniques have been applied in multiple ways across the energy sector. Gradient boosting models under the name XGBoost serve as primary machine learning algorithms for battery health

prediction and capacity estimation to optimize lifecycle management and ensure efficiency (Wang et al., 2022). The implementation of deep learning architectures with long short-term memory networks has become widespread for smart grid load forecasting because they deliver precise demand pattern predictions which improve renewable energy integration (Zhang et al., 2024). Graph neural networks are increasingly used in renewable energy forecasting because they excel at detecting spatial-temporal patterns in distributed energy resources (Yin et al., 2023). The combination of digital twin frameworks with reinforcement learning (RL) enables simulation-based optimization for grid planning and operations. For instance, (Hua et al., 2023) showed how their DT-RL system reduced capital costs by 50% while keeping losses at 5% below benchmark levels. Meanwhile the authors (Zhou et al., 2024) showed how digital twins function in demand response management and energy-sharing economies through AI-based real-time decision systems. The scheduling of microgrids and renewable energy dispatch uses hybrid AI systems which unite ML/DL with optimization algorithms including particle swarm optimization and genetic algorithms (Dayarathne et al., 2025). Deep learning-based intrusion detection systems protect smart cyber-physical systems (CPS) in energy grids through cybersecurity applications while demonstrating AI's importance for maintaining resilient operations (Ma et al., 2024). The combination of AI-enhanced IoT platforms enables real-time energy data collection from smart meters and EV charging infrastructure and distributed generation units which big-data frameworks like Apache Spark process for scalable analytics (Junaid Hussain & Abbas, 2025). Energy forecasting for embedded applications such as EV speed prediction benefits from edge AI implementations which minimize latency (Erdiwansyah et al., 2025).

### 3.1.2 RQ2: How are these AI applications supporting renewable energy integration, low-carbon objectives, and energy efficiency?

The research findings demonstrate how AI technology supports the integration of variable renewable energy sources (RES) and helps decrease carbon emissions and enhance energy efficiency. The implementation of predictive analytics enables demand-side management to match consumption patterns with renewable energy generation profiles thus reducing the need for fossil-fuel backup systems (Zhou, 2024). The implementation of LSTM-based forecasting models in demand response programs enables precise load predictions which leads to substantial peak demand reductions and allows for increased RES penetration (Zhang et al., 2024). Through digital twin applications (Hua et al., 2023) enable utilities to conduct virtual tests of different operational scenarios which help them optimize grid configurations for both cost efficiency and carbon performance. The system enables sustainable energy transitions through strategic decision-making which focuses on sustainability performance indicators. The combination of 3D visualization with deep learning technology provides better situational awareness in grid control rooms which results in measurable decreases of 15.6% CO<sub>2</sub> emissions and 18.2% energy consumption according to (Yao et al., 2023). The implementation of XGBoost and low-power neural network-enabled  $\Delta\Sigma$ -ADCs in battery management systems (BMS) increases storage operational life while maintaining efficiency which directly supports lifecycle sustainability (Kim, 2024; Yin et al., 2023). The implementation of AI solutions for EVs through real-time speed forecasting and energy consumption optimization enables smart charging systems that match EV charging with available renewable energy generation (Erdiwansyah et al., 2025). The implementation of AI-based pricing mechanisms and demand response systems in energy-sharing economies through AI technology boosts prosumer involvement and optimizes distributed renewable energy use (Zhou, 2024). The implementation of AI-enhanced cybersecurity for CPS protects renewable energy integration by stopping cyber threats which could cause grid instability (Ma et al., 2024).

### 3.1.3 RQ3: What challenges, limitations, and future research directions are identified for AI-driven sustainable energy systems?

Despite the promising potential of AI, the quality and availability of data create major problems because AI models require extensive high-resolution datasets, yet many utility companies operate with fragmented or proprietary data systems (Junaid Hussain & Abbas, 2025). The lack of interpretability in models stands as a major problem because it affects both regulatory requirements and operator confidence. The integration of explainable AI (XAI) methods exists in some studies, yet the field requires established interpretability frameworks (F. Li, 2024). The implementation of AI in edge deployments and embedded systems faces difficulties because these systems have restricted power and processing capabilities (Erdiwansyah et al., 2025). The process of integrating AI with existing infrastructure demands transitional approaches because it needs step-by-step modernization strategies (Hua et al., 2023). The dual cybersecurity threat against AI-enabled smart grids consists of defending AI models from adversarial attacks while using AI to enhance system resilience (Ma et al., 2024). The generalization of models becomes a problem because training models on particular datasets from specific regions leads to poor performance when deploying them in different climatic or economic or policy (Zhang et al., 2024). The development of federated learning frameworks



represents a future research priority because they allow collaborative model training without compromising data privacy (Zhang et al., 2024). The integration of multi-energy systems with AI optimization frameworks represents a research priority according to (Zhou, 2024). The integration of life cycle assessment (LCA) metrics into AI-driven decision-making processes for comprehensive sustainability impact evaluation stands as a future research priority according to (R. Y. Kim, 2024). The use of digital twins should expand from operational optimization to including long-term strategic planning according to (Hua et al., 2023).

#### IV. DISCUSSION

The research literature shows that artificial intelligence serves as a basic instrument to meet energy sector sustainability targets through renewable integration and low-carbon transitions and operational efficiency. The combination of machine learning with deep learning and hybrid optimization enables complex systems to use predictive capabilities and adaptability through LSTM and neural networks which enhance solar and wind forecasting (Lee, 2019; Zhang et al., 2024). AI systems achieve their best results when DT is integrated with them because reinforcement learning with DT enables real-time smart grid control and reduces renewable curtailment and DT optimizes battery energy storage and reduces waste (Kumar, 2022; Wang et al., 2022). AI-DT integration into community energy-sharing economies produces social economic and environmental advantages through technological optimization that combines with prosumer engagement through IoT-based demand-side management and real-time monitoring (Nguyen et al., 2025; Park et al., 2023; Zhou, 2024). The technical potential receives agreement from experts but experts disagree about how to scale it up because robust hybrid models maintain stability even when accuracy degrades with noisy real-world datasets (Cheng et al., 2023; Rojas et al., 2023). The expansion of IoT-AI networks demands unified threat detection for environmental and economic benefit protection because cybersecurity stands as an essential requirement (Almeida et al., 2025; Nguyen et al., 2025).

The technical and managerial aspects of explainability require XAI to show decision logic which builds trust by addressing critical infrastructure barriers (Hassan et al., 2022; S. Kim et al., 2024; Martinez Lagunas et al., 2023). The strategic resource of high-quality operational data supports AI success through its integration with real-time monitoring systems which enables fast supply-demand adjustments (Ma et al., 2024; Park et al., 2023; Wang et al., 2022). Organizations should implement modular AI systems starting with demand forecasting and storage optimization before moving to complete DT integration while providing operator training and cybersecurity resilience and community-based deployments to boost social acceptance (Almeida et al., 2025; Zhou, 2024). The study faces limitations due to its 2022–2025 focus and exclusion of earlier/paywalled studies and variable reporting quality and simulation-based research instead of large-scale operational studies. Future research needs to conduct real-world longitudinal evaluations across multi-energy systems while integrating life-cycle assessment to prevent burden shifting and using federated learning with XAI to address privacy and interpretability issues and ensuring AI optimization aligns with policy and market incentives.

Overall, AI demonstrates robust potential to enhance sustainability but faces challenges regarding scalability and explainability and cybersecurity; resolving these issues will lead to sustainable environmental and socio-economic benefits.

#### V. CONCLUSION

This bibliometric and structured literature review analyzed 19 open-access studies published between 2022 and 2025 to map the landscape of AI applications in energy efficiency and sustainability within the energy management sector. The results highlight that deep learning, digital twins, IoT-enabled platforms, and hybrid AI-optimization models are central to renewable energy integration, operational efficiency, and carbon reduction objectives. China, the United States, and leading European countries dominate scholarly output, reflecting alignment between national strategies and research activity. By applying RBV, Dynamic Capabilities, and Socio-Technical Systems perspectives, the study demonstrates that AI technologies are not merely technical tools but strategic enablers for sustainable energy transitions. While the literature confirms substantial technical potential, it also exposes persistent barriers in data availability, explainability, scalability, and cybersecurity resilience. For researchers, this synthesis provides a roadmap for advancing technical innovation alongside socio-technical integration. For policymakers and industry leaders, it reinforces the importance of modular AI deployment, workforce training, and cybersecurity investment. Ultimately, AI's transformative role in the



energy sector will depend on how effectively these technologies are embedded within holistic strategies that balance environmental, economic, and social sustainability goals.

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