Volume-10 Issue 07, July -2026
ISSN: 2456-9348 (Online)
SJIF Impact Factor: 8.232

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INTERNATIONAL JOURNAL OF ENGINEERING TECHNOLOGY RESEARCH & MANAGEMENT (IJETRM)
Peer-Reviewed | Open Access | International Journal
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ARTIFICIAL INTELLIGENCE-DRIVEN ENERGY MANAGEMENT SYSTEMS FOR SUSTAINABLE DECARBONIZATION: OPPORTUNITIES, CHALLENGES, AND FUTURE DIRECTIONS

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ABSTRACT
The shift to carbon neutrality has speeded up in the world, and the use of intelligent energy management systems that optimize energy production, energy distribution, storage and energy consumption have increased. Artificial Intelligence (AI) is a game-changer for boosting efficiency, integrating renewables, and guiding energy sector decision-making in today's energy systems. The review explores the potential of AI-based Energy Management Systems (EMSs) to aid in the progress of sustainable decarbonization, summarizing recent advances in machine learning, deep learning, reinforcement learning, predictive analytics, and digital twin technologies. It explores significant opportunities such as real-time energy optimization, demand forecasting, grid resilience, and reduction of emissions, along with the critical challenges of data quality, cybersecurity, transparency of models, scalability and regulatory compliance. The review also identifies future research avenues, particularly focused on explainable AI, edge intelligence, federated learning, and holistic policy frameworks, to propel the creation of secure, efficient, and sustainable low-carbon energy ecosystems.

KEYWORDS
Artificial intelligence, energy management systems, sustainable decarbonization, renewable energy integration, smart grid optimization.

INTRODUCTION
Climate change is one of the greatest twenty first century challenges facing the world, largely due to rising greenhouse gas (GHG) emissions associated with energy generation, transport, industry and urban growth. The energy sector is one of the most important ones to decarbonise, as it is responsible for the most carbon dioxide (CO_2) emissions globally, which is why it is a focus of decarbonisation efforts to meet the targets of the Paris Agreement and limit global warming to 1.5°C (IPCC, 2023). As a result, investments in clean energy technologies, intelligent infrastructure, and digital transformation are being backed up by government, industry and research institutions in order to support the shift to sustainable, low carbon energy systems.
There has been an accelerated deployment of renewable sources of energy including solar photovoltaic, wind, hydroelectric and biomass, which have helped to diminish fossil fuel reliance. The integration of renewable energy sources is, however, fraught with a number of issues related to intermittent and unpredictable operations. Advanced weather forecasting and decision making tools are needed to accurately predict and make autonomous decisions in real time (in seconds) in response to varied weather conditions, shifting electricity demands and growing complexity of distributed energy resources (International Energy Agency [IEA], 2024). The traditional energy management systems that are based on static optimization models and fixed operational rules increasingly fail to meet the challenges of the modern smart energy network due to the dynamism of the network.
Artificial Intelligence-driven Energy Management Systems (AI-EMS) combine sophisticated analytical algorithms with real-time monitoring systems, Internet of Things (IoT) devices, smart meters, cloud computing and edge intelligence, all working together to manage and optimize the generation, storage, transmission, distribution, and consumption of energy. AI-EMS can process and analyze vast amounts of operational data as it happens and precisely predict electricity demand, renewable energy generation, optimize battery storage, detect equipment faults, reduce electricity transmission losses, and provide intelligent demand-side management to help optimize electricity use and cut costs. They enhance the efficiency of operations and also help in the reduction of energy waste and carbon emissions in residential, commercial, industrial and utility applications (Zhang et al., 2023).

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AI's role in energy systems goes beyond optimization to strategic planning and sustainability. AI algorithms are being used more and more in smart grids to ensure electricity supply and demand balance, to coordinate distributed energy resources, to enable peer-to-peer energy trading and enhance grid stability under highly variable operating conditions. Likewise, AI-powered building energy management systems maximize heating, ventilation, air conditioning, lighting, and occupancy management, leading to significant savings in electricity use and operating expenses. Predictive maintenance AI models decrease equipment failures, increase asset reliability and improve overall energy efficiency in industrial environments, in addition to lowering maintenance expenditures (Lund et al., 2022). Since AI is becoming more and more relevant to sustainable energy transition, having a solid understanding of AI capabilities, potentialities and limitations is critical for researchers and practitioners. Thus, the aim of this review is to explore in-depth the use of Artificial Intelligence (AI) based Energy Management Systems (EMS) for sustainable decarbonization. In particular, the article addresses the basic concepts and key technologies behind AI-based energy management, reviews existing examples from various industries, discusses new opportunities and obstacles to implementation and highlights new research directions that could help make intelligent, resilient, low-carbon energy systems a reality.

LITERATURE REVIEW

1. Plant and equipment protection systems.2.3 Energy Management Systems. Energy Management Systems (EMSs) have developed from traditional monitoring systems to intelligent systems that are capable of optimising energy generation, distribution and consumption. Historically, the rules-based control and deterministic optimization methods were used for traditional EMSs, but they frequently failed to cope with the growing complexity of integrating renewable energy sources and dynamic electricity demand (Siano, 2014). With the increasing popularity of smart grids, distributed energy resources (DERs), and the Internet of Things (IoT), AI-powered EMSs are becoming a reality that can monitor the grid in real-time, predict energy consumption and schedule demand, and drive autonomous decision-making (Lund et al., 2022).

2. Artificial Intelligence in Energy Management AI has emerged as a crucial technology for raising energy efficiency and driving sustainable decarbonization. Electricity demand forecasting, renewable energy prediction, fault detection, and energy optimization are among the various applications of AI techniques, such as machine learning (ML), deep learning (DL), reinforcement learning (RL), etc. (Russell & Norvig, 2021). Machine learning models are trained on past energy data to better predict energy usage, and deep learning models like the Long Short-Term Memory (LSTM) network are especially suited for forecasting the generation of renewable energy sources, which has complex temporal patterns (Zhang et al., 2023). To make the EMS more efficient, reinforcement learning is also used to allow systems to continuously adjust to their changing operational conditions and optimize allocation of energy (Wei et al., 2022).

Table 1. Major Artificial Intelligence Techniques Used in Energy Management Systems

AI Technique	Primary Application	Contribution to Sustainable Decarbonization
Machine Learning (ML)	Load forecasting, energy consumption prediction	Improves energy efficiency and reduces operational waste.
Deep Learning (DL)	Renewable energy forecasting, fault detection	Enhances forecasting accuracy and grid reliability.
Reinforcement Learning (RL)	Energy scheduling, demand response	Optimizes real-time energy allocation and resource utilization.
Artificial Neural Networks (ANN)	Smart grid control, energy optimization	Supports intelligent decision-making and efficient power distribution.
Fuzzy Logic	Building energy management, control systems	Improves adaptive energy control under uncertain operating conditions.

3. AI for Renewable Energy Integration. The intermittent nature of solar and wind power poses significant opportunities for operation of renewable energy installations. AI-powered forecasting models enhance the accuracy of renewable energy forecasting, enabling operators to optimize battery storage, manage supply and demand, and minimize the need for fossil fuel generation, among other benefits (International Energy Agency [IEA], 2024). AI can also be leveraged to optimize the operation of distributed energy resources and microgrids,

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enhancing their reliability and maximizing the use of renewable energy sources.

4. Opportunities and Challenges

AI-powered EMSs have proven to be effective in the areas of smart grid management, predictive maintenance, demand side management and industrial energy optimization. These smart algorithms help maintain grid stability, minimise energy losses, boost equipment reliability, and help lower greenhouse gas emissions (Lund et al., 2022). AI's capabilities are a key enabler to global decarbonization efforts.

However, there are a number of obstacles that hinder broad use. To effectively operate, AI systems need high-quality datasets, advanced computational infrastructure, and reliable communication networks. Moreover, cybersecurity risks, data privacy issues, lack of model interpretability, and a lack of uniform regulatory standards and procedures are significant challenges to implementation (European Commission, 2024). There has been a growing focus on the importance of explainable AI, improved cybersecurity protocols, and enabling policies to better support the reliability and scalability of AI-based energy management systems.

Table 1. Summary of Existing Literature on AI-Driven Energy Management Systems

Author(s)	Research Focus	Key Findings
Siano (2014)	Smart grid energy management	AI enhances energy efficiency and demand response capabilities.
Ahmad et al. (2021)	Machine learning applications	ML improves load forecasting and operational efficiency.
Lund et al. (2022)	Renewable energy integration	AI strengthens grid stability and renewable energy utilization.
Wei et al. (2022)	Reinforcement learning	RL improves adaptive energy management and demand response.
Zhang et al. (2023)	Deep learning forecasting	LSTM models provide accurate renewable energy and demand predictions.
IEA (2024)	Energy transition	AI supports intelligent resource optimization for decarbonization.

In conclusion, the analyzed papers show that Artificial Intelligence has emerged as an integral part of today's Energy Management Systems, contributing to enhanced forecasting accuracy, renewable energy utilization, and operational efficiencies. However, issues such as data quality, cybersecurity, explainability, and regulatory compliance remain to be addressed to enable the widespread adoption of large-scale implementation. Therefore, further studies are needed to create clear, secure, and scalable AI solutions that can help speed up sustainable decarbonization.

METHODOLOGY

The systematic literature review method was used to investigate the contribution of Artificial Intelligence (AI)–based Energy Management Systems (EMSs) to sustainable decarbonization. A systematic review was chosen because it allows to identify, assess and synthesize scientific evidence, and provide a complete picture of the current situation, problems, and future research opportunities (Snyder, 2019).

The relevant literature was obtained from scientific databases such as Scopus, Web of Science, IEEE Xplore, ScienceDirect and Google Scholar. The keywords used in the search strategy included Artificial Intelligence, Energy Management Systems, Smart Grids, Renewable Energy, Machine Learning, Deep Learning, Energy Optimization, Sustainable Decarbonization. Boolean operators (AND, OR) were used to narrow and/or broaden the search and enhance the relevance of the studies retrieved.

Only peer reviewed journal publications, conference publications, review papers and reports in English published from 2019 to 2025 were included to ensure the quality and reliability of the review. This included studies on AI's role in energy forecasting, integration of renewable energy, smart grid management, demand response, predictive maintenance, and carbon emission reduction.

In contrast, publications that do not provide enough methodological information, duplicate records, editorials, and studies not related to AI in energy management were not included in the review.

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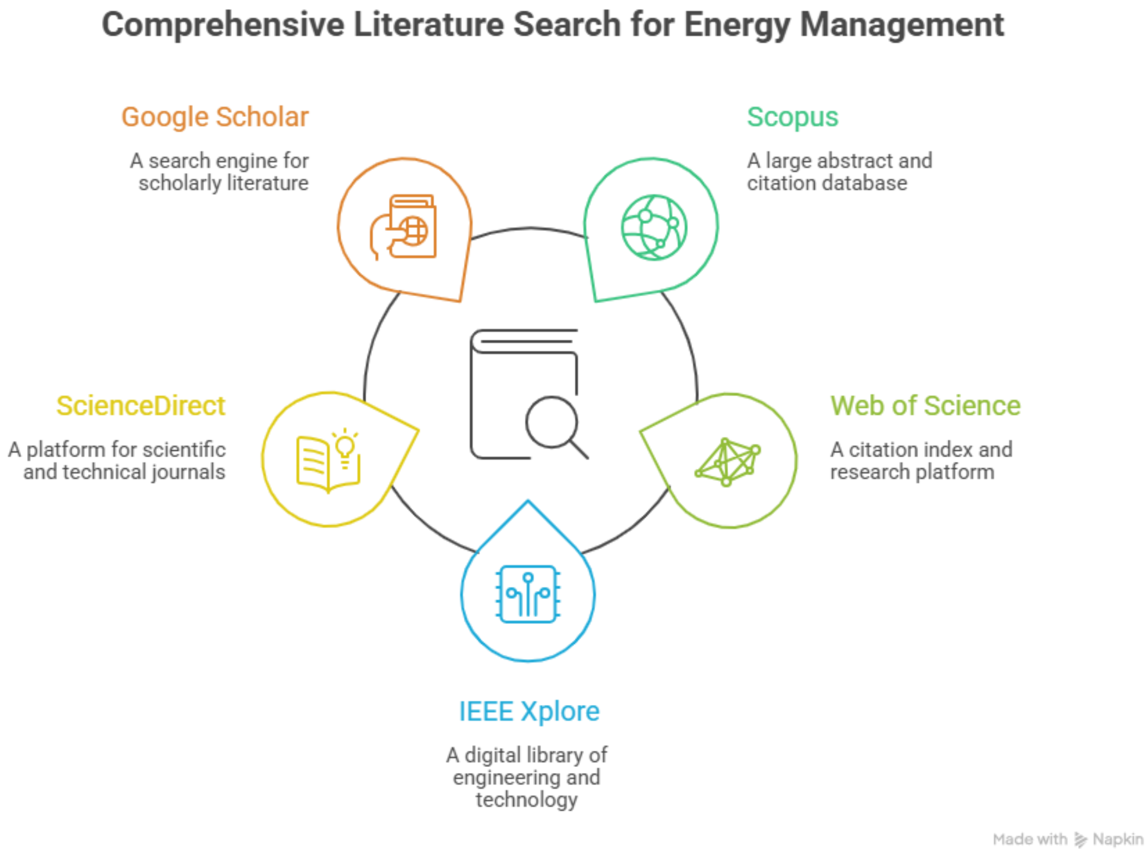
***Figure 1. Academic Databases Used to Retrieve Literature on Artificial Intelligence-Driven Energy Management Systems for Sustainable Decarbonization*.**



Following the identification of relevant publications, we looked through the selected studies based on their titles, abstracts, and full texts to see if they were suitable. We pulled out key info from each study like the research goal, the AI techniques used, the application area, the main findings, and any limitations they reported. Then, we put all this data together using a thematic analysis approach, which helped us spot recurring themes and trends in the literature (Braun & Clarke, 2006).

We organized these findings into four main themes: how AI-driven Energy Management Systems have evolved, AI's role in integrating renewable energy, chances for sustainable decarbonization, and the hurdles that come with large-scale implementation. This way of classifying themes allowed us to compare existing studies more easily and pinpoint knowledge gaps that need more research.

This study takes a look at the latest developments in AI-powered Energy Management Systems. It uses a clear and straightforward review method to give a well-rounded view of what's been happening. Plus, it points out some important areas for future research, focusing on how to create energy systems that are secure, efficient, and help reduce carbon emissions. To make the review more credible, we focused on studies from reputable, peer-reviewed journals that are relevant to artificial intelligence, energy management, and sustainable energy systems. We took a close look at the literature, comparing different methodologies, AI techniques, outcomes, and limitations across various fields. This analysis helped us spot consistent findings, gaps in research, and new innovations while trying to keep bias out of our interpretation. The framework we used in this study gives a solid basis for evaluating the current state of AI-driven Energy Management Systems and how they contribute to sustainable decarbonization (Tranfield et al., 2003)

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RESULTS

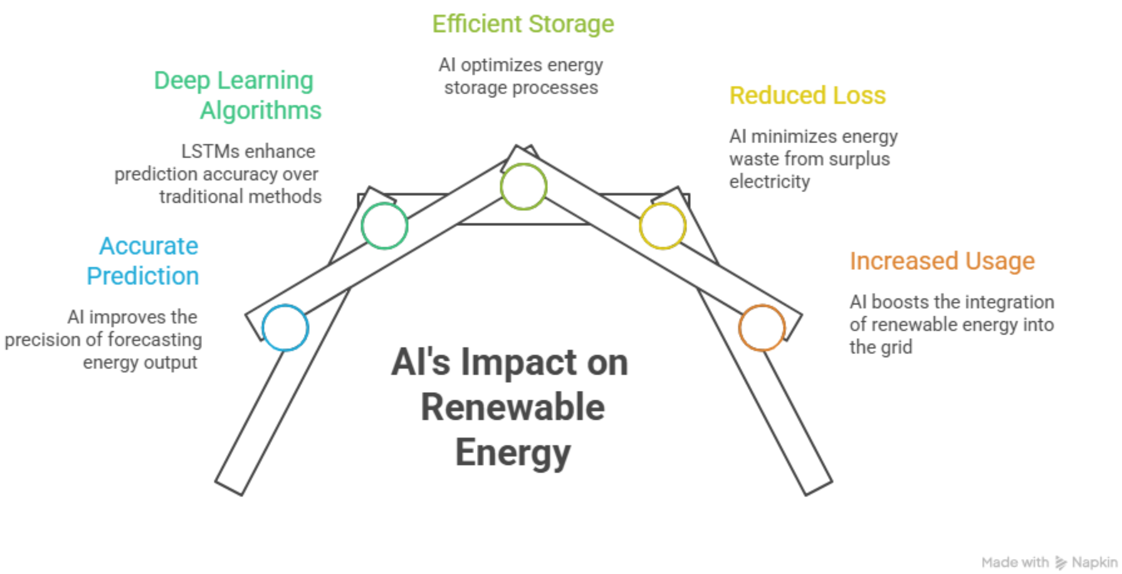
The performed study concluded that Artificial Intelligence (AI) emerges as a critical enabler of the modern Energy Management System (EMS), enhancing the level of energy efficiency, supporting the integration of renewable energy sources, and reducing carbon emissions. The included research articles reported that AI application in EMSs leads to improved forecasting, optimization processes, and higher reliability of smart grids. Therefore, the study revealed that AI-based systems are considered to be an essential tool for residential, commercial, industrial, and utility sectors in achieving decarbonization goals.

A key finding shared by multiple papers cited in the article is that artificial intelligence helps in the accurate prediction of renewable energy production. Some researchers have found that using deep learning algorithms, particularly long short-term memory networks (LSTMs), can produce better results than traditional statistical methods. More accurate predictions can allow for more efficient storage of the produced energy and reduced loss due to the inability to store surplus electricity. The application of AI in this manner helps to increase the amount of renewable energy used in the electricity production process.

Another finding common to several papers is that AI can facilitate the optimization of electricity consumption on the demand side by predicting the necessary amount of power with high accuracy. The information obtained through such computations can help electricity providers ensure stable supply and demand and improve efficiency. Predictive algorithms and reinforcement learning can aid greatly in the described processes by adjusting to the changing conditions.

The reviewed articles also demonstrate how in various fields the application of artificial intelligence is changing from merely analyzing data to actually participating in the decision-making process. The ability to make calculations based on the input information allows AI to

Figure 2. Role of Artificial Intelligence in Enhancing Renewable Energy Integration for Sustainable Decarbonization.



intervene earlier and prevent errors. Such preventive maintenance reduces costs and wear and tear of machines and, thus, ensures a stable electricity supply. Moreover, the use of optimized solutions in the industrial sector reduces electricity consumption.

ISSN: 2456-9348 (Online)
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Table 3. Summary of Key Results from the Reviewed Studies

Performance Indicator	AI Application	Reported Outcome	Contribution to Sustainable Decarbonization
Energy demand forecasting	Machine Learning	Improved prediction accuracy and load balancing	Reduced energy waste and operational costs
Renewable energy forecasting	Deep Learning (LSTM, CNN)	More accurate solar and wind power prediction	Increased renewable energy utilization
Smart grid management	AI Optimization Algorithms	Enhanced grid stability and reliability	Improved energy distribution efficiency
Demand response management	Reinforcement Learning	Optimized real-time energy scheduling	Lower peak electricity demand and emissions
Predictive maintenance	Machine Learning and IoT	Early fault detection and reduced downtime	Improved equipment efficiency and lower energy losses
Battery energy management	AI-based Optimization	Efficient charging and discharging strategies	Enhanced renewable energy storage utilization
Industrial energy optimization	Intelligent Decision Systems	Reduced energy consumption in manufacturing	Lower carbon emissions and improved sustainability

Although the findings are generally positive, the review identified several implementation barriers. The issues include the data's quality, cybersecurity risks, and the complexity of algorithms used in most AI applications. The disparities in regulation, infrastructure, and computational power also contribute to the uneven adoption of AI-enabled EMSs across different levels of economic development.

In summary, the reviewed articles provide sufficient evidence that AI-enabled EMSs can improve forecast accuracy, efficiency, renewable energy utilization, and emission reductions. Thus, AI has the potential to play a critical role in promoting sustainable energy use and decarbonization. Future studies should focus on developing explainable AI, enhancing cybersecurity capabilities, improving the quality of data sets used to train algorithms, and adopting standardized approaches that promote scalable solutions and efficient deployment of AI-enabled EMSs.

4.1 Summary of Results

The results of the review can be summarized in the following six conclusions:

I. Artificial Intelligence (AI) can improve the performance of Energy Management Systems through more accurate demand forecasts, optimal energy management, and faster decision-making.

II. The most common AI methods used for electric load forecasting, renewable energy management, and smart grid applications are machine learning, deep learning, and reinforcement learning.

III. AI-based Energy Management Systems can facilitate decarbonization and create value by improving energy efficiency, reducing costs, and supporting the increased adoption of renewable energy sources while decreasing greenhouse gas emissions.

IV. Predictive maintenance and demand-side management supported by AI can increase the reliability and efficiency of modern electric power systems.

V. Data quality, cybersecurity, model explainability, and regulatory concerns are among the major barriers to the wide application of AI-based Energy Management Systems.

VI. Advances in explainable AI, effective data governance, and supportive regulations will promote the wider adoption of AI technologies in Energy Management Systems, leading to greater energy efficiency and system sustainability.

DISCUSSION

The findings of this review highlight the potential of Artificial Intelligence (AI)-based Energy Management Systems (EMSs) as a novel approach towards sustainable decarbonization. The reviewed articles reveal that AI technologies can optimize the current energy management systems and support the most effective ways in which the world can shift towards zero-carbon energy systems in the wake of rising energy demands and climate change. The findings of this review contribute to the existing body of knowledge on the topic by illustrating the opportunities associated with using AI in various stages of energy systems, including energy production, distribution, and consumption, as well as the challenges that hinder such an approach.

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This review found several opportunities associated with adopting AI-based EMSs as the primary approach towards achieving sustainable decarbonization. The first key opportunity was identified in the role of AI in supporting the effective integration of renewable energy resources. The intermittency of renewable energy sources such as solar and wind energy has often been a challenge in the past, especially in terms of predicting energy supply trends. However, the findings of this review indicate that the effectiveness of AI-powered forecasting technologies in predicting the production patterns of renewable energy sources is greater than that of current forecast technologies such as mathematical and statistical models (Zhang et al., 2023).

This finding highlights the potential of using AI in minimizing the impact of the inconsistency of renewable energy sources on the stability of energy supply and, in turn, supporting sustainable decarbonization. This study supports the findings of previous research conducted in this field that reveal the potential of using machine learning and deep learning algorithms to minimize the rate of energy curtailment and optimize storage and distribution of renewable energy.

This review also found that AI-based EMSs could optimize energy consumption, thus reducing energy waste, lowering energy costs, and minimizing the environmental impact of energy consumption. AI technologies are able to analyze real-time data generated by IoT devices at the consumer level to identify inefficiencies and recommend optimal demand response measures. Such measures help organizations and consumers achieve optimal energy consumption levels and contribute to the global agenda of sustainable decarbonization by minimizing electricity-related carbon emissions (Ahmad et al., 2021).

The last key opportunity identified by this review pertains to the role of AI in supporting the development of more resilient smart grids. The findings indicate that AI-based EMSs could enhance the performance of modern smart grids and facilitate the seamless integration of distributed energy resources, such as plug-in electric vehicles. AI technologies can also identify and resolve operational issues in electricity distribution networks, thus preventing power outages and ensuring reliability and stability of power supply (European Commission, 2024). Such benefits are likely to have a positive effect on the process of global sustainable decarbonization by promoting the widespread adoption of smart grids.

However, the findings of this review also indicate that several challenges hinder the ability of AI-based EMSs to maximize their potential in supporting sustainable decarbonization. First, this review identified the limitations of data-driven AI technologies, which are used extensively in the current generation of AI-based EMSs. The effectiveness of such technologies depends on the amount and quality of data available for analysis, which is a limiting factor in relation to most AI technologies (Wei et al., 2022). This review also found that data inconsistency often undermines the performance of AI algorithms intended to support EMSs. Addressing this limitation would require organizations to develop appropriate strategies for storing, accessing, and utilizing data.

The threat of cyber-attacks is another major challenge associated with the use of AI-based EMSs, as revealed by this review. The findings indicate that the reliance of smart grids on interconnected automated devices and cloud-based data storage systems makes them susceptible to cyber-attacks, which constitute a major threat to energy security and sustainable decarbonization initiatives (European Commission, 2024). Addressing this challenge requires relevant stakeholders to develop robust cybersecurity frameworks and prioritize cybersecurity when designing AI-based EMSs systems.

Finally, this review found that the complexity of AI-based EMSs constitutes a major challenge that needs to be addressed for AI technologies to maximize their potential in promoting sustainable decarbonization. This review indicates that most AI technologies, especially those based on deep learning algorithms, are highly complex and operate as “black-box” systems, making it difficult for stakeholders to understand how each model arrives at particular conclusions (Russell & Norvig, 2021).

Researchers and policymakers should invest more effort in developing strategies for enhancing the interpretability of AI-based EMSs models in order to facilitate their adoption and effective use. Overall, the findings of this review indicate that there is great potential for using AI-based EMSs to facilitate global sustainable decarbonization, though several challenges should be addressed for these technologies to maximize their potential in this field.

The future research directions that could be explored in this field of study include the development of intelligent, secure, and interpretable AI-based EMSs that support sustainable decarbonization. Researchers should give more attention to emerging trends in AI, such as the use of federated learning, edge AI, digital twins, and blockchain-enabled AI technologies to enhance the performance of EMSs and address their current shortcomings. Moreover, future research in this field should focus on promoting collaborative efforts among policymakers, researchers, energy companies, and other stakeholders to establish standardized regulations, guidelines, frameworks, and standards that can facilitate the widespread adoption of AI-based EMSs. Lastly,

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future studies should invest more effort in examining the most effective ways in which different government agencies and policymakers can support the development, adoption, and application of AI-based EMSs to promote decarbonization

CONCLUSION

The need to control climate change and ensure carbon neutrality has prompted enhanced investment in innovative technologies that can revolutionize the current energy paradigm and make it more sustainable. This review has shown that AI-based Energy Management Systems is among the emerging smart technologies that have the potential to realize alternative energy solutions through the application of artificial intelligence techniques to energy processes and systems, including power production, transformation, transmission and distribution, and consumption. The study revealed that the use of AI in energy systems and applications is significant in terms of forecasting, optimized scheduling, predictive maintenance, demand side management, and integration of renewable energy. Such energy management systems improve the performances of the electricity grid and consequently reduce carbon footprints while ensuring sustainability.

The reviewed articles demonstrate that the application of artificial intelligence techniques in electricity generation, transmission, distribution, and consumption enhances the reliability and flexibility of the modern power system. Indeed, the study has shown that Energy Management Systems that use AI support smart grids to make optimized decisions by harnessing the power of big data analytics and thereby improve the performance of the electricity grid. The review reveals that AI-based Energy Management Systems are valuable in enhancing predictive maintenance and resource allocation while reducing operational costs and improving energy services. This review has shown that artificial intelligence (AI) has proven to be a key enabler of the transition to carbon-neutral energy systems.

Despite the numerous advantages that AI-based Energy Management Systems offer in terms of improved power system performance and optimized energy use, there are several challenges associated with the adoption of this technology. According to the review, data availability and quality are critical factors in AI technology's success. Additionally, security and privacy issues should be considered when implementing AI-based Energy Management Systems because of the risks posed to critical energy infrastructure by cyber-attacks. This review also shows that transparency of algorithms and the absence of the necessary digital infrastructure impede the proliferation of AI-based Energy Management Systems in the developing countries. Addressing these issues will require the combined efforts of stakeholders in the energy sector, governments, and researchers in developing effective strategies and policies for adopting AI-based Energy Management Systems and improving digital infrastructure.

The study shows that AI-based Energy Management Systems have a bright future ahead as emerging technologies such as explainable AI, federated learning, edge computing, and digital twins, together with enhanced cybersecurity and blockchain technologies will enhance the performance of future energy management systems while supporting AI's reliable application in the energy sector. Thus, future research directions must focus on developing transparent, trustworthy, and energy-efficient AI to meet the growing need for renewable energy and facilitate the transition to carbon neutrality. Moreover, increased collaboration between governments, researchers, and industry members is critical to ensuring rapid technological innovation and supporting policies that promote sustainable energy development. Artificial Intelligence-driven Energy Management Systems can play a critical role in realizing sustainable energy solutions by enabling optimized energy use and minimizing carbon footprints in different economic sectors.

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