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AI-driven innovations in energy efficiency: Transforming smart buildings and urban areas through technology and digital transformation

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Abstract

This study explores AI's transformative role in enhancing urban energy efficiency. Focusing on AI-driven innovations in smart grids, renewable energy integration, and predictive energy management, it evaluates AI's potential to optimize energy distribution, reduce waste, and improve sustainability. A comprehensive literature review and case studies are employed to analyze the application.

The findings indicate that AI technologies, including machine learning and predictive analytics, are crucial for optimizing energy consumption, managing renewable energy variability, and improving smart grid efficiency. AI enhances sustainability by forecasting energy demand and optimizing storage systems. However, challenges such as data privacy concerns, integration complexities with existing infrastructure, and the need for specialized AI expertise pose barriers to broader adoption of these technologies.

The study recommends that future research focus on advancing AI technologies for real-time optimization and explainability, as well as addressing the skills gap in AI development. Policymakers and energy stakeholders should invest in AI-driven solutions and establish supportive regulations to promote AI adoption in urban energy systems. In the long term, AI will be pivotal in creating more sustainable, resilient, and energy-efficient cities.

Keywords: Artificial Intelligence; Energy efficiency; Smart buildings; Digital Transformation.

1. Introduction

Artificial intelligence (AI) has emerged as a major force behind innovation in a number of industries, most notably energy management (Raman et al., 2024). With rising global urbanization and the growing urgency of climate change, optimizing energy efficiency in urban areas and buildings has gained prominence (Esfandi et al., 2024). Utilizing cutting-edge sensors and automation, AI-driven technologies in smart buildings offer a viable means of cutting down on energy use, operating expenses, and environmental effect (Aguilar et al., 2021). The concept of AI-driven innovations is not limited to individual buildings but extends to the development of smart urban areas that leverage digital technologies to create sustainable and energy-efficient ecosystems (Szpilko et al., 2023). This growing trend highlights the significance of understanding how AI and digital transformation can revolutionize energy efficiency practices.

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The goal of this study of the literature is to investigate how AI-driven innovations are revolutionizing energy efficiency in smart buildings and metropolitan regions. It looks at how AI and digital technologies are incorporated into energy management systems, evaluates the advantages and difficulties that come with it, and considers the consequences for future urban development. The review also identifies research gaps, offering insights for policymakers, urban planners, and technology providers on AI-powered solutions' potential to enhance energy efficiency. Drawing from diverse academic and industry sources, it offers a thorough grasp of how AI is changing energy management.

AI and digital transformation are improving energy management by analyzing data from smart meters, building sensors, and weather (Ukoba et al., 2022). These technologies allow for predictive maintenance, real-time monitoring, and automated energy adjustments to optimize energy use while maintaining comfort and functionality (Hanafi et al., 2024). This integration ensures more efficient energy use, reducing waste and enhancing the overall performance of energy systems in buildings. Furthermore, the transition to smarter, more responsive urban energy systems is happening faster thanks to the integration of AI with other digital advancements like the Internet of Things (IoT), cloud computing, and blockchain (Alahi et al., 2023). This transformation has the potential to create energy-efficient buildings and urban areas that are not only sustainable but also more adaptive to the evolving demands of the modern world.

The first half of this article will present an overview of AI-driven advancements in energy efficiency, as well as the drivers driving demand for better energy management systems. The literature review will next look at major research, paradigms, and technologies that have influenced our understanding of AI's role in increasing energy efficiency. The following part will go over the problems and prospects of incorporating AI into smart buildings and urban areas. The conclusion will summarize key insights, highlight future research areas, and offer recommendations for stakeholders aiming to leverage AI's potential in energy management.

This paper seeks to provide an in-depth analysis of AI-driven innovations in energy efficiency through a comprehensive review of existing literature. By examining the intersection of AI, digital transformation, and energy management, the study aims to contribute valuable insights into the future of sustainable urban development.

2. Overview of Existing Research on AI Applications in Energy Efficiency

The integration of artificial intelligence (AI) into energy efficiency has become an area of substantial academic and industry focus in recent years. This literature review provides a detailed exploration of the existing research on AI applications in energy management, analysing key studies, identifying gaps in the current body of literature, and highlighting emerging trends in AI-driven energy optimization. As energy consumption continues to rise due to rapid urbanization and technological advancement, AI's potential to transform energy systems into more efficient and sustainable models has generated widespread interest (Hoang, 2024).

2.1. Key Studies and Their Contributions

A significant body of research has explored how AI can enhance energy efficiency. Among the early contributors to this field is the study by Karduri (2019), which examines the transformative role of AI in optimizing energy systems, with a focus on improving efficiency, reliability, and sustainability. The study highlights AI's significant contributions to renewable energy forecasting, grid management, and energy consumption efficiency. Challenges that were however identified include data quality issues, scalability difficulties, cybersecurity risks, and the lack of clear regulatory frameworks. Technical limitations in AI's ability to predict under extreme conditions also pose challenges, requiring further research and development of robust solutions. Similarly, Olatunde et al. (2023) conducted a review on AI's impact on optimizing energy efficiency across multiple sectors. The study revealed that AI technologies, such as machine learning and neural networks, improve energy management by evaluating data to forecast demand and optimize use while accounting for variables such as weather and occupancy. AI's ability to adapt and learn leads to ongoing development, significant cost savings, and environmental benefits, such as improved integration of renewable energy sources. However, to fully unlock AI's potential in energy efficiency, challenges like data privacy concerns, the need for specialized skills, and integration complexities must be effectively addressed.

In the area of electricity demand, Aderibigbe et al., (2023) explores AI's role in transforming energy forecasting techniques. The findings show that AI and machine learning (ML) models, particularly those using deep learning and big data analytics, significantly surpass traditional electricity demand forecasting methods in accuracy and adaptability. These models excel at managing complex, nonlinear relationships and large datasets, making them ideal for dynamic, renewable energy markets. The study emphasizes selecting suitable ML models based on accuracy, forecasting flexibility, and environmental impact. However, challenges like data privacy, cybersecurity, and the need for skilled professionals remain key concerns.

Similarly, Barhmi et al. (2024) review advancements in solar energy forecasting across time horizons from ultrashort to 24 hours, emphasizing AI techniques, particularly Neural Networks, for enhanced accuracy. The study investigates supervised learning, regression, ensembles, and physics-based approaches by combining satellite imagery, weather forecasts, and historical data. It also emphasizes the importance of consistent datasets and benchmark procedures to allow reliable evaluations and comparisons in solar energy forecasts. By addressing key gaps in the literature and advocating for enhanced model precision, this review contributes significantly to optimizing solar energy resource management and planning.

Several studies have examined the integration of AI and IoT to optimize energy use in urban areas, revealing its transformative potential for smart cities. Hoang (2024) highlights how this synergy enhances real-time monitoring and control of energy systems, leading to more efficient energy use and better management of urban infrastructure. Hoang highlights that AI algorithms, when integrated with IoT sensors, provide actionable insights by analysing data from various sources, leading to optimized energy consumption and better demand response strategies. Li et al. (2024) examined the role of AI in data acquisition for power IoT systems, finding that AI-driven solutions greatly improve energy efficiency and system performance. By utilizing advanced data analytics and machine learning, AI can predict and manage energy loads more effectively, resulting in significant reductions in power consumption and operational costs. This study underscores the potential for AI to support high-efficiency and low-power consumption in energy systems, contributing to the broader goals of smart city development. In addition, Alahi et al. (2023) provide a comprehensive overview of recent advancements and future trends in IoT-enabled technologies and AI for smart cities. The paper discusses how integrating AI and IoT enables advanced energy management solutions, including real-time energy monitoring, predictive maintenance, and adaptive energy consumption. Alahi et al. highlight that this combination enhances energy efficiency and facilitates the integration of renewable energy sources, promoting a more sustainable urban energy landscape. Collectively, these studies illustrate that the synergy between AI and IoT significantly optimizes energy use in urban areas. By providing precise control, predictive analytics, and real-time adjustments, this integration advances the transition to smarter, more sustainable cities. However, ongoing research is essential to tackle challenges like data privacy, system integration, and scalability for full potential realization.

The integration of AI in predictive maintenance for energy systems has garnered significant attention, with recent studies highlighting its transformative potential. Shin et al. (2021) focus on the interplay between human inspectors and AI in wind farm maintenance. Their research, involving 54 inspectors and 2,301 images from 138 turbines, demonstrates that AI assistance markedly improves fault detection accuracy and efficiency. Specifically, generalists benefited more from AI, showing improvements in specificity and time efficiency of 24.6% and 25.3%, respectively, compared to specialists. This study underscores the value of combining human expertise with AI to enhance maintenance processes. Hamdan et al. (2023) explore AI's impact on predictive maintenance across renewable energy sources, including solar, wind, and hydro. Their review reveals that AI significantly optimizes energy output, infrastructure maintenance, and grid integration. By examining successful case studies, they illustrate how AI enhances predictive maintenance and energy optimization, contributing to more efficient and sustainable renewable energy systems. The study highlights AI's advanced analytics and predictive capabilities, which are crucial for meeting global renewable energy targets and improving infrastructure resilience. Ukoba et al. (2024) provide a comprehensive review of AI applications in renewable energy systems (RES), focusing on predictive maintenance among other aspects. They discuss how AI methods, such as machine learning and neural networks, improve resource assessment, energy forecasting, and system monitoring. The review also addresses challenges like data variability and real-time adaptability but emphasizes the benefits of overcoming these issues, including increased energy yield and reduced operational costs. Emerging trends in AI, such as explainable AI and edge computing, are also considered for their potential to advance RES optimization and integration.

3. The Role of AI in Smart Buildings

Artificial Intelligence (AI) is revolutionizing the development of smart buildings, particularly by optimizing energy usage and improving operational efficiency (Olatunde et al., 2024). AI's capabilities in predictive maintenance, adaptive control, load prediction, demand-response strategies, and occupancy and behavior analysis are transforming how energy is managed in modern buildings (Muniandi et al 2024). Key areas where AI plays a crucial role include smart HVAC systems, energy-saving algorithms, and occupancy monitoring, each contributing to significant energy savings and improved building performance.

3.1. Smart HVAC Systems: AI’s Role in Predictive Maintenance and Adaptive Control

Heating, ventilation, and air conditioning (HVAC) systems account for a considerable portion of building energy use. AI-enhanced smart HVAC systems address this challenge through predictive maintenance and adaptive control, reducing energy waste and extending system lifespans (Lee and Lee, 2023). AI-driven predictive maintenance enables HVAC systems to detect potential faults before they occur, unlike traditional maintenance models that rely on periodic checks, leading to inefficiencies and breakdowns (Es-sakali et al., 2022). AI-enabled systems use real-time data from embedded sensors to constantly assess performance (Cheng and Lee, 2019). Machine learning algorithms use past data and present conditions to uncover patterns that anticipate system faults. This preventive approach decreases equipment problems, downtime, and energy usage. For instance, AI can detect minor changes in airflow or temperature that signal maintenance needs before major issues arise.

In addition to predictive maintenance, AI greatly enhances the adaptive control of HVAC systems (Cheng and Lee, 2019). Instead of operating on fixed schedules, AI-powered systems adjust heating, cooling, and ventilation based on real-time factors like occupancy, weather patterns, and indoor air quality (Selvam et al., 2021). This ensures energy is used only when and where necessary. AI models can reduce cooling output during low occupancy and increase it when needed, optimizing HVAC operations for energy efficiency while maintaining occupant comfort, ultimately reducing energy consumption and operational costs.

3.2. Energy-Saving Algorithms: AI Models for Load Prediction and Demand-Response Strategies

AI also significantly enhances smart buildings through energy-saving algorithms, especially in load prediction and demand-response strategies (Long, 2023). These models analyze past energy consumption, weather forecasts, and other factors to predict future energy needs (Hou et al., 2022). This allows smart systems to dynamically adjust energy usage in real time, reducing waste during low-demand periods. For example, during off-peak hours, AI algorithms can lower energy consumption by adjusting lighting and HVAC settings (Olatunde et al., 2024). Conversely, during peak times, AI anticipates higher demand, managing energy distribution effectively to prevent grid strain and reduce costs.

Demand-response strategies, another AI-driven solution, enable buildings to adjust energy usage based on changes in energy supply and grid conditions (Sankarananth et al., 2023). These strategies allow smart buildings to respond to fluctuations in renewable energy production or shifts in grid demand. If renewable energy sources like solar or wind are plentiful, AI systems can prioritize their use for energy-intensive operations. During peak demand times, AI systems can reduce non-essential energy usage or switch to stored energy to alleviate grid pressure. (Ukoba et al., 2024). This results in more efficient energy management and lower operational costs.

Moreover, energy-saving algorithms are particularly effective when integrated with renewable energy sources (Javaid et al., 2018). AI models can predict renewable energy availability, such as solar power, based on weather forecasts, and optimize its use. This helps buildings maximize their reliance on clean energy, reducing the need for fossil fuels and lowering carbon emissions.

3.3. Occupancy and Behavior Analysis: AI Techniques for Monitoring and Adjusting Energy Usage

AI is vital for monitoring occupancy and analyzing behavior to optimize energy use in smart buildings (Aguilar et al., 2021). By employing techniques like computer vision, motion sensors, and machine learning algorithms, these buildings can track occupancy levels and adjust energy-consuming systems in real time (Tien et al., 2021). AI-enabled systems can detect when areas of a building are unoccupied and automatically reduce lighting or HVAC usage to conserve energy. For instance, if AI sensors detect that a conference room is not in use, they can turn off lights and lower the HVAC output. This ensures that energy is not wasted in unused spaces, contributing to overall efficiency.

Additionally, AI can learn from the behavior of building occupants to provide personalized energy management solutions (Yan et al., 2023). By analyzing individual preferences for temperature, lighting, or ventilation, AI systems can adjust building conditions to meet occupants' needs while minimizing energy waste (Hanafi et al., 2024). This personalization enhances comfort and improves energy efficiency over time.

Predictive analytics can also be used to forecast occupancy trends. For example, during holiday seasons or off-peak periods, AI systems can reduce energy usage in anticipation of lower occupancy levels (Kang and Reiner, 2022). This foresight enables more precise control over energy consumption, further reducing costs and improving sustainability.

Hence, AI plays a transformative role in smart buildings, particularly in optimizing energy use through advanced technologies such as predictive maintenance, adaptive control, load prediction, demand-response strategies, and occupancy analysis.

4. AI in Urban Energy Management

Artificial Intelligence (AI) is revolutionizing urban energy management by improving the efficiency of energy networks, integrating renewable energy sources, and enhancing predictive capabilities (Onwusinkwue et al., 2024). In contemporary cities, AI is essential for optimizing energy distribution, enabling smarter grids, and forecasting energy needs (Arevalo and Jurado, 2024). The increasing reliance on renewable sources like solar and wind makes AI crucial for the sustainable and effective management of urban energy systems.

4.1. Smart Grids and Energy Distribution: AI in Optimizing Urban Energy Networks

Smart grids are sophisticated energy networks that utilize AI technologies to enhance electricity distribution in urban areas (Marques and Oliveira, 2024). Unlike traditional grids, which often face inefficiencies due to fixed generation and demand patterns, AI-enabled smart grids dynamically balance energy supply and demand in real time (Sankarananth et al., 2023). By employing machine learning algorithms, these systems monitor consumption patterns, predict future demand, and adjust electricity flow accordingly (Aguiar-Pérez et al., 2024). They rely on data from diverse sources, including weather forecasts and real-time grid conditions, to optimize distribution. For instance, AI can redirect energy to high-demand areas during peak hours while decreasing supply in less critical zones. Furthermore, AI is critical for controlling decentralized energy sources like solar panels and tiny wind turbines by integrating them into the grid and balancing their contributions to ensure a stable and robust energy network (Ukoba et al., 2024).

4.2. Renewable Energy Integration: AI's Role in Managing Solar, Wind, and Other Renewable Sources

A major challenge in urban energy management is the integration of renewable energy sources, which are inherently variable and hard to predict (Wang et al., 2024). Solar and wind energy generation relies heavily on weather conditions, time of day, and seasonal variations. AI addresses these challenges by delivering accurate predictions and optimizing the incorporation of renewable sources into urban grids.

AI algorithms can analyse historical data and real-time weather information to forecast renewable energy generation (Benti, et al., 2023). It can predict, for instance, how much solar energy will be available based on cloud cover or forecast wind energy potential by analysing wind speed. These predictive capabilities enable grid operators to manage fluctuations in renewable energy supply more effectively, ensuring energy demand is met even when renewable sources are intermittent (Ukoba et al., 2024).

AI also enhances energy storage systems, such as batteries, by predicting when renewable energy generation will be high (Liu et al., 2022). By optimizing when to store excess energy and when to release it back into the grid, AI helps balance the energy supply-demand equation and ensures that renewable sources are used efficiently.

4.3. Data Analytics and Forecasting: Predictive Modeling and Optimization at the Urban Level

Data analytics and AI-powered predictive modeling are critical in urban energy management because they provide real-time insights into energy consumption and precise estimates of future needs (Le et al., 2024). These AI models assist city planners and energy operators in predicting demand spikes, optimizing resource allocation, and reducing operational costs. They can simulate the impacts of extreme weather, population growth, and shifts in energy consumption behavior on the urban energy grid (Chen et al., 2023; Esmaeili, 2023). For instance, AI helps cities prepare for heatwaves that lead to increased air conditioning use, ensuring energy availability during peak demand. Additionally, AI optimization models highlight improvement areas in energy production and consumption, recommending the best times for energy-intensive operations to mitigate grid strain and lower costs (Chen et al., 2023). AI-powered demand-response strategies enable energy managers to dynamically adjust consumption, aligning supply with current usage patterns. Overall, AI is transforming urban energy management by optimizing smart grids, facilitating renewable energy integration, and enhancing predictive capabilities, ultimately improving the efficiency and resilience of energy networks.

5. Technology innovation and Digital Transformation

Artificial Intelligence (AI)-driven solutions are at the forefront of technology innovation in energy management, significantly transforming how energy is generated, distributed, and consumed (Onwusinkwue et al., 2024). With the rapid adoption of AI and other digital technologies, energy management has become more efficient, sustainable, and adaptable to modern demands. The convergence of AI and digital transformation is reshaping energy infrastructures and practices, paving the way for smarter, greener, and more resilient systems (Olson, 2024).

5.1. AI-Driven Solutions Accelerating Technology Innovation

AI is essential for innovation in energy management, leveraging its capability to analyze vast data, make real-time decisions, and optimize energy flows (Ahmad, 2021). AI has a big impact on predictive maintenance, in which historical and real-time data are examined to predict equipment faults or inefficiencies (Raza, 2023). This proactive approach reduces downtime, enhances operational efficiency, and extends the lifespan of energy infrastructure, ultimately leading to cost savings for both energy providers and consumers.

Another major area of innovation is energy load forecasting. AI models can predict energy demand more accurately by analyzing consumption patterns, weather conditions, and historical data (Elhabyb et al., 2024). This enables energy suppliers to better match production with demand, reducing waste and minimizing reliance on non-renewable sources. Additionally, AI can dynamically optimize energy distribution across smart grids, improving the overall efficiency of electricity networks (Arevalo and Jurado, 2024). These systems can autonomously regulate energy flow according to real-time conditions, ensuring that urban areas receive reliable and uninterrupted power.

Furthermore, AI is improving the integration of renewable energy sources such as solar and wind into the grid. As renewable energy is intermittent and unpredictable, AI helps manage its variability by forecasting energy generation and adjusting grid operations accordingly. This allows cities and industries to rely more heavily on renewable energy without compromising the stability of the grid, thereby advancing sustainability goals.

5.2. The Role of Digital Transformation in Reshaping Energy Infrastructure

By incorporating cutting-edge technologies like big data analytics, cloud computing, and the Internet of Things (IoT) into energy management systems, digital transformation is changing the energy infrastructure (Nazari and Musilek, 2023). This change makes it possible to monitor energy networks in real time, make data-driven decisions, and automate more processes. A key outcome of this transformation is the development of smart grids, which utilize IoT devices, sensors, and AI-driven analytics to optimize energy distribution. Utilities can respond to outages and inefficiencies more quickly thanks to smart grids, which give them real-time data into energy use and grid problems (Ohanu, 2024). In order to promote a more decentralized and robust energy system, they also improve the integration of distributed energy resources, such as electric cars and rooftop solar panels.

Digital transformation is also significantly reshaping consumer energy practices. With the advent of smart meters and connected devices, consumers can monitor their energy usage in real time and modify their behavior to reduce consumption (Batalla-Bejerano, 2020). AI-driven applications empower homeowners and businesses to automate energy-saving measures, such as adjusting heating and cooling systems based on occupancy or minimizing usage during peak times.

In industrial contexts, digital twins-virtual replicas of physical systems, are utilized to simulate and optimize energy infrastructure (Soori et al., 2023). By creating digital models of power plants, substations, and other assets, energy companies can test various scenarios, anticipate maintenance needs, and identify opportunities for efficiency improvements without interrupting operations.

Additionally, the adoption of cloud computing and big data analytics enables energy providers to manage large volumes of data more effectively (Mostafa et al., 2022). This capability enhances forecasting, operational efficiency, and personalized energy services, allowing providers to offer customized pricing models, incentives for conservation, and improved service reliability to consumers.

6. Gaps in the Current Literature

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) in optimizing energy systems has made notable progress, yet significant gaps remain in the literature. Studies by Shin et al. (2021), Hamdan et al. (2023), and Barhmi et al. (2024) offer valuable insights but indicate areas needing further research. For instance, Shin et al. highlight the advantages of AI-assisted inspections for predictive maintenance in wind farms, showing improvements in fault detection. However, this research mainly addresses the interaction between human inspectors and AI, neglecting broader human factors in AI adoption. Future studies should examine how user interfaces, training protocols, and cognitive load influence AI effectiveness in maintenance contexts. Additionally, investigating the optimal integration of human expertise with AI-driven decision-making tools across various sectors could yield deeper insights into enhancing predictive maintenance strategies.

Hamdan et al. (2023) review AI applications in renewable energy, highlighting its impact on predictive maintenance and energy optimization. However, their study could benefit from a more detailed examination of the limitations and challenges associated with specific AI techniques across various renewable energy sources. For instance, the effectiveness of different AI methods in managing intermittent energy sources like wind and solar compared to more stable sources like hydro remains underexplored. Further research should address how emerging AI technologies can address these challenges and integrate effectively with existing grid infrastructure.

Barhmi et al. (2024) focus on advancements in solar energy forecasting, particularly using AI and neural networks. Despite their comprehensive review of forecasting techniques and the call for standardized datasets, there is a notable gap in the implementation and adoption of these standards in practical applications. The study highlights the importance of benchmarking and standardized evaluation methods but lacks detailed strategies for achieving widespread adoption and integration of these practices. Future research should develop frameworks for standardizing datasets and evaluation metrics, ensuring that these standards are adopted consistently across different forecasting models and applications.

The investigation of real-time adaptation and integration issues of AI and IoT systems in energy management is another area of common deficiency among the studies. Although AI has demonstrated promise in energy optimization, little is known about how these systems respond in real-time to dynamic circumstances, such as abrupt shifts in the supply or demand for energy. Addressing these challenges involves developing robust AI algorithms that can handle real-time data and provide actionable insights for immediate decision-making.

Another critical gap is the lack of comprehensive studies that assess the long-term sustainability of AI-driven energy systems. Although many studies highlight the short-term benefits of AI for energy optimization, there is limited research on how these systems perform over extended periods and under varying conditions, such as extreme weather events or changes in energy policy.

7. Challenges and Barriers

The integration of Artificial Intelligence (AI) in energy efficiency management holds great promise for transforming energy consumption, distribution, and generation, particularly in urban settings. AI-driven innovations are advancing energy systems through smart grids, predictive maintenance, renewable energy integration, and advanced data analytics. However, challenges remain that hinder widespread adoption, including technical, financial, regulatory, and ethical issues. Unlocking the full potential of AI-driven solutions to improve energy efficiency and accomplish sustainable energy goals requires addressing these obstacles.

A primary challenge in AI-driven energy efficiency solutions is integrating AI into existing energy infrastructure (Danish, 2023). Legacy systems were not designed for AI or modern technologies, often lacking compatibility for seamless integration. This results in difficulties with data collection, processing, and real-time monitoring. AI's effectiveness depends on high-quality, real-time data, which is frequently fragmented across various sources (Nivedhaa, 2024). Without a coherent and centralized data structure, the effectiveness of AI solutions in optimizing energy efficiency is significantly reduced. Moreover, AI models require massive amounts of data to train machine learning algorithms effectively (Nivedhaa, 2024). In many cases, this data is unavailable or incomplete, especially in sectors where data-sharing protocols and digitalization are still in the early stages. Additionally, the variability and uncertainty in energy data, especially from renewable sources like solar and wind, present another layer of complexity for AI systems. Accurately forecasting energy demand and generation under these conditions can be challenging.

Second, a major obstacle to the adoption of AI-driven energy efficiency solutions is the high upfront costs, which are especially problematic for emerging economies and small and medium-sized businesses (SMEs) (Alijoyo, 2024). These technologies necessitate substantial investments in infrastructure, data collection systems, skilled personnel, and AI software platforms. For example, installing sensors for real-time energy monitoring or upgrading legacy systems to be compatible with AI-driven solutions can be cost-prohibitive for many organizations (Khan et al., 2024). The return on investment (ROI) for AI-driven energy solutions, while promising in the long term, can take time to materialize. This delayed ROI can deter businesses, particularly those with limited financial resources, from adopting AI technologies. Furthermore, without clear case studies or success stories that showcase the cost-benefit analysis of AI in energy efficiency, it remains difficult for organizations to justify the high upfront costs.

AI-driven innovations in energy efficiency also face significant regulatory and policy challenges (Olatunde et al., 2024). Energy systems, especially in urban areas, are heavily regulated, with stringent rules governing energy generation, distribution, and consumption. These regulations often lag behind technological advancements, making it difficult for

AI-driven solutions to comply with existing legal frameworks. Integrating renewable energy sources into the grid necessitates coordination with slow-to-adapt government agencies and utility companies. Furthermore, the absence of standardized regulations for data privacy and security complicates AI adoption (Olatunde et al., 2024). In the energy sector, concerns over data ownership and cybersecurity are particularly heightened. Governments and regulators also need to create more supportive policies to incentivize AI adoption in energy management. This includes providing tax incentives, subsidies, or grants for businesses investing in AI technologies, and establishing clear guidelines for AI applications in energy systems.

The rapid adoption of AI technologies in energy efficiency raises several ethical and social concerns. A significant issue is the potential job loss due to automation (Soueidan & Shoghari, 2024). AI systems, particularly in smart grids and predictive maintenance, may reduce the need for human intervention, displacing workers in energy monitoring and system maintenance. While AI can create new roles in data science and energy consulting, the transition for affected workers can be challenging without adequate retraining programs.

Another ethical concern involves bias in AI algorithms (Saeidnia, 2023). If trained on incomplete or biased data, AI systems may yield flawed predictions, impacting energy efficiency and renewable integration. This is especially critical when balancing grid stability, energy demand, and environmental factors. Additionally, accountability concerns are raised by the "black box" dilemma, or the lack of transparency in AI decision-making (Cheong, 2024). In energy, stakeholders must trust that AI-driven decisions are accurate and fair; without explainability, achieving this trust becomes difficult.

Additionally, AI-driven energy systems rely on extensive data from diverse sources, such as sensors, smart meters, weather forecasts, and historical energy usage. While this data is crucial for optimizing energy systems, it also raises significant privacy and security concerns (Olatunde et al., 2024). Unauthorized access to sensitive energy data can lead to cybersecurity threats, including grid sabotage or the manipulation of energy prices. Given the critical nature of energy infrastructure, ensuring robust cybersecurity measures is paramount. Data privacy is another concern, particularly in smart buildings and urban areas where AI systems may collect detailed information about individual energy consumption patterns (Bakar et al., 2024). Without robust data protection policies, there is a risk that personal information may be misused or sold without consent, resulting in violations of privacy rights.

Successful implementation of AI-driven energy efficiency solutions depends on a highly skilled workforce proficient in designing, deploying, and maintaining these systems. But a major obstacle to progress in this industry is the lack of personnel with experience in AI, machine learning, data science, and energy management (Fearns et al., 2023).. This skill gap poses a significant barrier to the widespread adoption of AI technologies, as organizations struggle to find qualified personnel to lead AI projects. To overcome this challenge, there is a need for more education and training programs focused on AI applications in energy systems. Collaboration between industry, academia, and government can help address this skill shortage by providing upskilling opportunities and encouraging the development of new talent in the field.

8. Future direction and opportunities

The role of AI in energy efficiency is set for significant advancements, presenting numerous opportunities for future development, research, and contributions to sustainable urban growth. As energy systems become more complex and urban populations increase, AI's capacity to manage, optimize, and innovate will be increasingly crucial.

Future developments in AI for energy efficiency will likely focus on improving the accuracy, scalability, and adaptability of AI algorithms (Aderibigbe et al., 2023). Advancements in machine learning (ML) and deep learning (DL) technologies are anticipated to produce more robust predictive models for energy consumption, generation, and distribution. This will lead to even greater efficiencies in managing energy resources, particularly in smart grids and decentralized energy systems. One potential area of growth is in real-time energy optimization. Currently, many AI systems operate with time delays due to data collection and processing constraints. The development of faster, more efficient algorithms could allow AI-driven energy management systems to respond to energy demand fluctuations in real time, optimizing energy distribution instantaneously (Olatunde et al., 2024). Integrating AI with edge computing and Internet of Things (IoT) devices offers a promising approach to energy optimization. This integration minimizes latency and enhances accuracy, allowing smart meters and AI-powered HVAC systems to collaborate effectively, optimizing energy use based on real-time data from users, appliances, and weather conditions.

Secondly, while AI's role in energy efficiency is growing, there are several areas ripe for further research. One key area is the development of AI algorithms that can handle incomplete or sparse data more effectively. Energy systems, particularly those involving renewable energy, often suffer from data gaps or irregularities (Leal et al., 2022). Research into AI models that can function accurately even with limited or imperfect data will be crucial for advancing AI-driven energy efficiency. Another research opportunity is to improve the transparency and explainability of AI systems (Cheong 2024). Many current AI models, particularly those based on deep learning, function as "black boxes," making it difficult for stakeholders to comprehend how choices are made. Developing more interpretable AI systems would increase user trust, especially in key energy areas. Furthermore, research into AI's function in predictive maintenance of renewable energy infrastructure, such as solar panels and wind turbines, has enormous potential. Enhanced predictive maintenance has the potential to reduce operational downtime and increase the lifespan of renewable energy assets, hence improving energy efficiency and sustainability (Ukoba et al., 2024).

In addition, AI is set to significantly impact sustainable urban development, particularly as cities confront the challenges of population growth and climate change. In the long run, AI will enhance energy efficiency in urban areas, reducing carbon footprints and dependence on non-renewable energy sources (Olawade et al., 2024). AI-powered smart cities will successfully balance energy usage by using algorithms to regulate decentralized energy sources like solar panels, wind turbines, and energy storage units. This method will reduce demand on central power grids, resulting in more robust urban energy systems that can withstand environmental and economic challenges. Furthermore, AI will help to develop and build energy-efficient urban infrastructure. AI can direct the development of energy-efficient transportation systems, smart buildings, and green spaces by analyzing data on traffic patterns, weather conditions, and energy use (Bharadiya, 2023; Olatunde et al., 2024). These developments will promote sustainability by reducing waste, conserving energy, and enhancing the quality of life for urban residents.

In the long-term, energy efficiency driven by AI will be necessary for cities to meet their sustainability targets. Urban regions will have an advantage in reducing energy consumption, emissions, and shifting to sustainable and renewable energy sources due to the increasing adoption of AI technologies.

9. Conclusion

This study highlights the revolutionary influence of AI-driven innovations on improving energy efficiency, particularly in metropolitan areas. AI technologies, such as machine learning and predictive analytics, are improving energy distribution, integrating renewable sources, and increasing energy system resilience. AI enables smart grids, which allow for real-time supply and demand balancing, minimizing waste and operating expenses. Furthermore, AI plays an important role in managing the fluctuation of renewable energy sources such as solar and wind, optimizing storage, and projecting energy requirements to assist sustainable urban growth.

However, the study identifies key challenges hindering the widespread adoption of AI in energy efficiency, including data privacy concerns, the complexity of integrating AI with existing infrastructure, and the need for specialized skills. Addressing these barriers is vital for maximizing AI's potential in transforming energy management systems.

Future opportunities include advancing AI for real-time optimization, enhancing the explainability of models, and further research into predictive maintenance and edge computing. As AI evolves, its long-term influence on urban energy efficiency promises to create more sustainable, resilient, and efficient cities worldwide

Compliance with ethical standards

Disclosure of Conflict of interest

No conflict of interest/ Competing Interests in the publication of the manuscript or with any institution or product that is mentioned in the manuscript and/or is important to the outcome of the study presented.

Statement of informed consent

The study did not involve information about any individual. Hence, no informed consent was obtained.

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