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The Transition To Artificial Intelligence -Based Solutions For Improving Energy Efficiency In Urban Environments

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Abstract

The urban landscape is rapidly evolving towards sustainable, energy-efficient practices, thanks in large part to the integration of artificial intelligence (AI) solutions. This study explores the dynamic transition to AI-based technologies for improving energy efficiency in urban environments. AI is emerging as a powerful tool for optimizing energy consumption, streamlining infrastructure operations and fostering smart, resilient urban ecosystems. The study examines various applications of AI, highlighting the essential role advanced technologies play in revolutionizing conventional approaches to urban energy management, and illustrating how these technologies can contribute to the creation of self-sufficient urban spaces. It examines the implementation of AI-based energy networks, smart energy storage solutions and the integration of renewable energy into urban planning, and also looks at the potential challenges and ethical considerations associated with its adoption. It addresses issues such as data privacy, algorithmic biases and the need for transparent decision-making processes. This research is a literature review that aims to contribute to the current discourse on creating smart, energy-efficient cities.

Keywords: Urban environments; urban design; Artificial intelligence (AI); Energy efficiency; Sustinability.

Introduction:

Faced with rapid urbanization and growing environmental concerns Contemporary urban design aims to strike a balance between meeting the changing needs of urban populations while ensuring sustainable development (Carmona, 2010; Amen & Nia, 2020; Aziz Amen, 2022; Gün, 2023; Odunlade & Abegunde, 2023). As urban environments rapidly evolve, the growing demand for energy is driven by increasing population activity, the need for advanced services and the integration of technical infrastructures (Ranosz et al., 2020; Bluszcz & Manowska, 2020 ; Jelonek & Chomiak-Orsa, 2018). Currently, almost 50% of the world's population lives in cities, and this figure is set to rise to 80% by 2030. In particular, cities account for over 70% of global CO2 emissions due to their high energy consumption (Vassiliades et al., 2022). Inefficient development patterns and consumption habits, particularly in the building and transport sectors, lead to significant energy waste in urban areas (Khodabakhsh et al., 2017).

As cities grow, the need to create energy-efficient urban environments becomes ever more urgent. Energy efficiency is crucial to the sustainability of current and future cities (Anthopoulos & Kazantzi, 2022). To meet growing energy demand and mitigate environmental impact, effective measures must be implemented to improve energy efficiency and minimize energy waste (Cai et al., 2019; Nižetić et al., 2019). Accurate predictive models of urban energy consumption are essential to enable planners and designers to anticipate the impact of planning and design decisions, and for policymakers to develop informed energy and pricing policies (Ahmad, Zhang, & Huang, 2021).

The integration of artificial intelligence (AI) into urban energy management is developing rapidly, driven by the growing need for sustainable and efficient energy solutions in growing urban areas. AI is transforming the optimization of energy efficiency by enabling advanced analysis and control of energy systems (Olatunde et al., 2024). Energy sustainability is a central issue in the development of cities and urban areas. Simultaneously, artificial intelligence and cognitive computing are becoming catalysts for designing and optimizing the provision and use of intelligent services in urban spaces (Chui et al., 2018).

The application of AI in the energy sector can be classified into several areas. Firstly, AI optimizes energy production plans and improves the efficiency of energy production. Secondly, AI facilitates efficient energy use through intelligent management systems. In addition, AI offers innovative solutions for energy consumption, reducing energy waste through technologies such as smart homes and smart transportation, and promoting the intelligent transformation of energy consumption (Peng et al., 2024).

Materials and Methods

The literature review method was used, focusing on publications exploring the transition to AI-based solutions for urban energy efficiency. The review process included the following steps:

Firstly; The initial search was carried out using several search engines such as Web of Science and google scholar. A search of publications from recent years was carried out to capture the latest research on AI applications in urban energy solutions. The search included the keywords “artificial intelligence” and its abbreviation “AI”; “energy efficiency” and “urban environments”. Secondly; The abstracts of the articles found were read and those corresponding to the defined scope were selected. The final selection included articles dealing specifically with AI-based urban energy solutions. Thirdly; The selected publications were categorized according to their primary focus or area of application in AI-based urban energy solutions. This categorization facilitated a structured analysis and a better understanding of the different applications and impacts of AI on urban energy.

The main objectives of this literature review are:

- O1: Identify trends, emerging technologies and applications of artificial intelligence in the energy sector.
- O2: Provide up-to-date information on the use of artificial intelligence in energy-related applications.
- O3: Gain a comprehensive understanding of the current state of AI-based urban energy solutions.
- O4: Explore emerging trends and challenges in AI-based energy solutions.

Results

AI is defined as “machines or computers that mimic the cognitive functions that humans associate with the human mind, such as learning and problem solving” (Schalkoff, 1990). other words, AI, where machines mimic human cognitive functions, can make decisions, think, learn and improve (Yigitcanlar et al., 2020).

AI systems process vast amounts of data, utilize learning algorithms, and identify patterns to predict outcomes (Chang et al., 2018). Today, cities are implementing machine learning systems to leverage data from various sources, including sensors in public infrastructure, machine-readable maps providing access to city services (e.g., public transport), images and videos capturing city movement, and devices collecting auditory, olfactory, and tactile data (K. C. Desouza & Smith, 2016; K. Desouza, 2018).

In cities, AI can be leveraged to optimize energy infrastructures, contributing to a more sustainable and resilient urban future. AI provides numerous solutions across various human activities, including the energy sector Bluszcz & Manowska, 2021). The implementation of AI can enhance energy efficiency by forecasting energy demand, optimizing energy production and consumption, and enabling intelligent control. This results in reduced energy costs, decreased environmental pollution, and the promotion of sustainable development (Khalilpourazari et al., 2021;Lee & Yoo, 2021). Consequently, the relationship between artificial intelligence and energy efficiency has become a significant topic within the research community (Chen et al., 2023). AI-based methodologies play a crucial role in identifying inefficiencies, forecasting future energy needs, and mitigating energy waste (Hanafi et al., 2024).

Looking at previously published research in the field, we can find a significant number of articles offering analyses of AI-based techniques in the energy sector: Ali & Choi, 2020, highlight how AI techniques have revolutionized the energy market by offering effective solutions for demand response and real-time decision-making. Similarly, Zambrano & Giraldo, 2020, discuss the potential of AI-based predictive models for renewable energies, which should provide valuable insights for future energy improvements. Ahmad, Zhang, Huang, et al., 2021, look at recent advances in AI technology, in particular its application to balancing supply and demand and producing energy from solar and hydrogen sources. Yan et al., 2021, explore the use of AI-based technologies to improve the energy efficiency of buildings. They highlight AI as a practical approach to achieving zero energy in buildings. In addition, Zhao et al., 2022, conduct an in-depth review of fault detection and diagnosis techniques for building energy systems using artificial intelligence. However, further research is needed to assess the effectiveness, efficiency, scalability and reliability of these systems in real-life scenarios.

AI applications in the energy sector focus on optimizing energy management systems through data analysis and AI algorithms, aiding decision-making departments in better understanding urban energy use and enhancing the accuracy and feasibility of resource allocation to fine-tune urban energy management (Guo et al., 2023).For example: To integrate building energy performance into the optimization process, a standardized indicator of whole-building energy consumption (Medjeldi et al., 2023), based on an artificial intelligence system, will have to be developed. AI is also used for forecasting energy needs; uncertainties in demand and production variability significantly increase the risks and costs associated with maintaining a reliable energy supply. Traditionally, the main solution to address variability was to install backup generation capacity. However, the advent of digital solutions has introduced algorithms designed to forecast the potential supply-demand curve and optimize assets for optimal dispatch. Forecasting was one of the initial areas where AI was applied in the electricity sector (Franki et al., 2023).

AI is extensively applied to energy consumption, production, storage, and transportation, leveraging intelligent technologies for planning, management, and optimization (Cioffi et al., 2020; Liu et al., 2022). Over the past decade, the European Union has implemented energy efficiency policies promoting the transition from fossil fuels to renewable energy sources with less environmental impact (Kirati et al., 2023), where the need for efficient and reliable energy storage solutions has become increasingly critical (Zheng et al., 2023). AI is revolutionizing energy storage by optimizing the performance and longevity of storage systems. AI algorithms continuously analyze and refine charge and discharge cycles, enhancing the efficiency of energy storage solutions. These AI-based systems effectively stabilize the grid by responding rapidly to fluctuations in renewable energy supply, ensuring a consistent energy flow and minimizing interruptions (Stecuła et al., 2023). In the realm of renewable energy, AI plays a pivotal role in improving grid stability and reducing dependence on fossil fuels. As the world transitions to a more sustainable and cleaner energy future, AI technology is increasingly being used to optimize the integration and management of renewable energy sources.

Developing countries typically exhibit lower energy efficiency due to limited technological capabilities and a lesser focus on environmental protection, resulting in significant energy wastage and severe environmental issues (Shahbaz et al., 2022). Therefore, studying energy efficiency in developing countries and proposing measures to enhance it can help alleviate the global energy crisis and mitigate the risks of climate change (Li et al., 2024). Studies conducted in Italy and Japan indicate that the adoption of artificial intelligence (AI) technologies in energy management systems has become prevalent, yielding positive outcomes. Similarly, research in the UK suggests that although the application of AI in predictive maintenance is nascent, it has shown promising effectiveness. Furthermore, in countries like China and India, AI is being leveraged for fault detection and diagnosis, as well as for integrating renewable energies and demand response measures (Chen et al., 2023).

The ongoing integration of artificial intelligence (AI) into energy efficiency initiatives in urban settings hinges significantly on the accuracy of input data and the careful selection of AI algorithms. However, implementing AI to optimize urban energy efficiency comes with its own set of challenges. These include concerns regarding data privacy, the requirement for specialized skills to develop and deploy AI solutions, and the complexity of integrating AI systems into existing energy infrastructure. Overcoming these hurdles will be crucial for realizing the full potential of AI in energy efficiency optimization (Olatunde et al., 2024). Moreover, the development of these systems demands substantial investment, which may surpass the financial capacity of certain organizations (Ahmed et al., 2022).

Discussion

Artificial intelligence is a powerful tool for improving energy efficiency and promoting sustainable development. By integrating AI into urban infrastructures, cities can optimize energy-related solutions. Previous studies confirm that: even if AI is not a miracle solution, it brings new perspectives to the problem. AI offers new hope for solving complex urbanization problems that were previously difficult to solve. Rapidly developing AI technologies are making significant contributions to our urban environments, fostering a more efficient, effective and sustainable transformation.

AI applications in smart urban environments focus primarily on business efficiency, data analytics, education, energy, environmental sustainability, health, land use, safety, transportation and urban management. Thanks to its advanced technology, algorithms and learning capabilities, AI can automate problem-solving and decision-making processes, reshaping urban landscapes and supporting the development of smarter cities. By optimizing resource management, monitoring energy consumption and planning future needs more effectively, urban environments can use resources more efficiently and better achieve their renewable energy targets.

Although AI has demonstrated its effectiveness in various fields, its widespread adoption is currently limited by a lack of expertise and financial constraints. Despite these challenges, the future looks bright for the increased use of AI in urban energy efficiency.

Conclusion

In conclusion, the imperative of transitioning to AI-based solutions to improve energy efficiency in urban environments cannot be overstated. Faced with an ever-growing urban population and the urgent need to mitigate the environmental impacts of energy consumption, AI offers a transformative path to sustainable urban development. By optimizing energy consumption, predicting demand patterns and seamlessly integrating renewable energy sources, AI-based solutions have the potential to dramatically reduce carbon emissions, improve energy resilience and drive economic prosperity in cities around the world. The adoption of these technologies represents not only a pragmatic response to today's challenges, but also a proactive step towards building smarter, more resilient and environmentally conscious urban communities for future generations.

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