Big Data Applications in Smart City Energy Management

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Abstract: The development of smart cities brings new challenges and opportunities for energy management. As urbanization rapidly advances, efficient energy use becomes a key factor in achieving sustainable development and enhancing urban competitiveness. Big data, as a disruptive technology, can provide data-driven decision-making support for urban energy management. By analyzing the application status of big data in smart city energy management domestically and internationally, this paper explores its advantages in optimizing energy efficiency and improving management capabilities, outlines the current challenges, and proposes corresponding solutions and future research directions.

Keywords: Smart City; Energy Management; Big Data; Energy Efficiency; Urban Energy Planning

1. Introduction

Energy management is a crucial part of smart city construction. Its efficiency and sustainability directly affect the urban ecological environment and the quality of life of residents. In the current urbanization process, traditional energy management methods struggle to meet the increasingly complex energy demand and supply challenges. Big data provides new tools and methods for energy management. By collecting and analyzing real-time data, big data can help city managers better understand and optimize energy usage, enabling more scientific energy management strategies. This paper aims to explore the specific applications of big data technology in smart city energy management and how these technologies can improve management efficiency, reduce waste, and support sustainable development.

2. Literature Review

2.1 Domestic Research Status

In China, the application of big data technology is primarily focused on energy monitoring, energy efficiency improvement, and environmental monitoring. Typical application scenarios include smart grids, building energy management systems, and urban environmental monitoring networks. For example, big data analysis can optimize energy usage patterns in buildings, achieving refined management of energy consumption and contributing to energy-saving and emission-reduction goals.

China's smart city construction is closely related to low-carbon development policies. Several studies have explored how these policies improve energy efficiency and reduce environmental pollution. Gao's research on China's dual pilot policies of low-carbon and smart cities found that these policies significantly improved urban energy efficiency, demonstrating the positive role of smart city development in supporting low-carbon growth and emission reduction [1].

Lu et al. analyzed data from 285 Chinese cities to study the spatiotemporal effects of smart transportation policies on urban carbon emissions. Their study shows that while smart transportation policies reduce urban carbon emissions, they may increase emissions in neighboring cities due to differences in economic and technological development levels [2].

Wang et al. examined the impact of smart city pilot policies (SCP) on environmental pollution by analyzing panel data from 236 cities. They found that, on average, SCP reduced pollution by 2.2%. The study also suggests that smart city construction, by promoting green innovation, optimizing industrial structures, and encouraging public participation, can effectively reduce environmental pollution, especially in regions with high administrative levels, human capital, and advanced information infrastructure [3].

Wan et al. focused on enterprises' carbon reduction technology strategies under low-carbon city and smart city environments.

They used a Hicks-neutral technology-based production function to analyze carbon reduction technology choices. The results show that different types of enterprises are significantly affected by the cost-effectiveness ratio when choosing clean production technologies or end-of-pipe treatment technologies. They recommend government subsidies and technological innovation to guide enterprises to participate in the carbon trading market and promote low-carbon technology adoption [4].

Rui et al. proposed a multi-objective energy planning framework for Xiamen, balancing cost, emissions, and resilience. Their research found that Xiamen's power transformation under resource constraints relies heavily on electricity imports, and the pursuit of the lowest emission path incurs significant additional costs. These findings offer valuable insights for coastal cities in China facing extreme weather events and stringent emission targets [5].

2.2 International Research Status

Internationally, the application of big data in energy management is more widespread and mature, particularly in cities such as London and Barcelona, where big data is used to enhance public service and energy efficiency. The application of big data in these cities extends beyond energy management, covering transportation, healthcare, public safety, and other areas. Through cross-sector data integration and analysis, city managers can better understand urban operations and optimize resource allocation.

Nikpour et al. developed an IoT-based comprehensive framework for energy management in smart cities. Their research highlights that IoT devices, through real-time monitoring and data integration, can significantly reduce energy waste and improve efficiency, making them an essential tool for smart city energy management [6].

Okonta and Vuković expanded the concept of smart cities, exploring the application of ICT in enhancing urban sustainability and resilience. Through case studies of 30 cities worldwide, they identified the critical role of energy management in smart city software solutions, such as IBM's and Cisco's platforms, which enable real-time management and optimization of urban infrastructure resources [7].

Mohamed and Alosman proposed an innovative IoT-driven city infrastructure management framework that integrates data from various infrastructures such as transportation, energy, and water resources. This framework improves operational efficiency and sustainability by providing a comprehensive perspective on urban management. The study demonstrates that by centralizing data storage and analysis, city managers can better understand the interdependencies between systems and optimize overall urban operations [8].

Hajaligol et al. explored the application of reinforcement learning in energy management within smart microgrids, proposing a system that enhances energy self-sufficiency. Their research shows that optimizing control strategies using reinforcement learning can significantly improve solar power consumption and reduce peak demand, offering a new approach to smart city energy management [9].

Finally, Farideh et al. examined how demand-side management (DSM) can optimize energy use in Portugal’s household energy systems. They developed a mixed-integer linear programming (MILP) model to reduce electricity bills and optimize distribution system loads, further enhancing smart city energy management strategies [10].

3. Advantages of Big Data in Smart City Energy Management

3.1 Real-Time Monitoring and Analysis

Big data allows real-time collection of vast amounts of energy consumption data through sensors and IoT devices. This data helps city managers monitor energy usage in real-time, identify abnormal consumption patterns, and make timely adjustments. For example, by predicting fluctuations in electricity demand, smart grids can reduce energy waste and ensure a stable power supply.

3.2 Energy Use Optimization

Big data makes energy management more intelligent by analyzing data to identify inefficient energy usage and offering optimization suggestions. In smart building management systems, for instance, big data can analyze energy consumption patterns, allowing buildings to automatically adjust energy usage and improve overall efficiency.

3.3 Decision Support and Forecasting

Big data provides robust data-driven decision-making support. By analyzing historical data and trends, big data helps city managers predict future energy demand more accurately and develop more effective energy allocation plans. For example, in renewable energy integration, big data helps forecast the generation capacity of wind and solar energy, optimizing energy dispatch.

3.4 Cross-Domain Data Integration

Big data enables the integration and interoperability of data from various fields such as energy, transportation, and buildings. Through cross-domain data integration, city managers can gain a comprehensive understanding of urban operations and develop more holistic energy management strategies.

3.5 Enhanced System Interoperability

Big data can effectively integrate smart grids, building energy management systems, and other energy management platforms, improving interoperability between systems. This integration creates a unified smart energy management ecosystem, helping to coordinate and dispatch energy resources more efficiently.

4. Applications of Big Data in Smart City Energy Management

4.1 Smart Grid Energy Efficiency Optimization

Through big data analysis, smart grids can achieve refined management of energy production, transmission, and distribution. A typical case is the integration of renewable energy sources (e.g., solar and wind energy) into the grid, improving grid stability and self-sufficiency. Studies show that big data analysis predicts grid failures, enhancing the reliability of power supply, particularly in renewable energy scenarios.

4.2 NEOM Smart City

Saudi Arabia’s NEOM project is an example of a smart city integrating big data, IoT, and AI technologies for energy management. Through real-time data collection and analysis, NEOM has made significant innovations in energy management, such as predicting energy demand and optimizing resource allocation, significantly reducing energy waste [11].

4.3 Smart Community Energy Management

In Norway, smart communities have implemented big data-driven energy management systems to optimize the "prosumption" (production-consumption) model. These systems collect energy production and consumption data from different communities and analyze how to optimize demand-side management, reducing peak loads and improving efficiency [12].

5. Conclusion and Outlook

This paper explores the application of big data technology in smart city energy management, revealing its critical role in optimizing energy use, real-time monitoring, and decision support. By analyzing application scenarios such as smart grids, renewable energy integration, and prosumption model optimization in smart communities, it is evident that big data significantly improves energy management efficiency, providing a strong technical foundation for the future development of smart cities.

Big data technology's strength lies in its ability to process massive, real-time, multi-dimensional data, enabling city managers to better understand energy use and make more informed decisions. Moreover, big data enhances system interoperability, integrating smart grids and building energy management systems into a unified smart energy management system.

However, the current application of big data in smart city energy management faces challenges, such as data privacy protection, technological standardization, and data integration complexity. To further enhance the practical value of smart city energy management, future research should focus on more specific technical implementation pathways. One key area is the introduction of deep learning models for energy demand forecasting. Utilizing time series forecasting models like Long Short-Term Memory (LSTM) networks to analyze historical energy consumption data enables high-accuracy predictions of future energy demand, thereby optimizing energy dispatch strategies.

Additionally, deploying low-power, high-performance edge computing devices—such as smart sensors and gateways within buildings—can facilitate real-time energy consumption monitoring and processing. This approach minimizes data transmission latency and enhances system responsiveness. Furthermore, strengthening cross-domain data integration and sharing by establishing open API platforms will enable interoperability between energy consumption data and other urban systems, such as transportation and power grids. This will foster data sharing and collaborative analysis, supporting more holistic and efficient energy management decisions.

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