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Optimizing Renewable Energy in Smart Cities by Integrating Big Data and Decision Support Systems

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Abstract. The rapid development of the smart city concept encourages the need for energy management that is more efficient, sustainable and adaptive to the needs of modern urban communities. In this context, renewable energy is the main solution to reduce dependence on fossil energy sources that are limited and pollute the environment. This research aims to optimize the utilization of renewable energy in smart cities by integrating Big Data technology and Decision Support Systems (DSS). The approach used in this research is a case study and system modeling method, which involves collecting energy data from various sources such as IoT sensors, weather stations, and energy distribution systems in real-time. The data is then analyzed using Big Data Analytics techniques to identify energy consumption patterns, potential renewable energy production, and peak load predictions. Furthermore, a decision support system was designed to assist policy makers and city managers in determining optimal energy distribution and usage strategies based on the available data and simulations. The results show that the integration of Big Data and DSS is able to increase the efficiency of renewable energy utilization up to 25% compared to conventional systems. In addition, the system is also able to dynamically respond to changing conditions and provide more accurate and adaptive decision recommendations. These findings indicate that the synergy between data technology and decision support systems plays a strategic role in creating sustainable and environmentally sound smart cities.

Keywords: Big Data, Decision Support Systems, Optimizing, Renewable Energy, Smart Cities.

INTRODUCTION

The rapid increase in global urbanization in the last two decades has led to the emergence of the concept of smart cities, which are cities that utilize information and communication technology to improve the efficiency of public services, the convenience of citizens' lives, and environmental sustainability. One of the main challenges in developing smart cities is the ever-increasing demand for energy as urban populations and activities grow. Dependence on fossil-based energy not only causes significant environmental impacts, but also poses a risk to long-term energy security. Therefore, the utilization of renewable energy is a strategic key in realizing an environmentally friendly and sustainable smart city. [1]

However, optimizing renewable energy in urban environments is not simple. The intermittent nature of energy sources such as solar and wind, fluctuations in energy demand, and limitations in energy storage and distribution create complexities. [2] Meeting these challenges requires data-driven approaches and decision-making systems capable of managing large-scale, complex and dynamic information. This is where the role of Big Data and Decision Support Systems (DSS) technology becomes very relevant. Big Data enables real-time collection and analysis of information from various sources, such as energy consumption data, weather, power grid conditions, and user behavior. [3] Meanwhile, DSS can be used to generate data-based recommendations that support the decision-making process in planning and managing renewable energy optimally. [4]

This research focuses on the development and integration of Big Data and DSS systems in the context of renewable energy management in smart cities. [5] The goal is to produce a system model that is able to analyze large amounts of data and provide strategic recommendations in the allocation and utilization of renewable energy. [6] This research not only emphasizes on the technological aspects, but also on its practical value in supporting public policy, operational efficiency, and overall sustainability of the city. [7] This approach is expected to create an energy system that is more adaptive, efficient, and aligned with the vision of sustainable development. [8]

Renewable energy management in the context of smart cities has been the main focus of many studies in the last decade, mainly due to the increasing demand for clean and efficient energy in urban areas. [9] A number of previous studies have examined the utilization of digital technologies to support decision-making in complex and dynamic energy systems. In these studies, the integration of the Internet of Things (IoT) with smart city energy management systems was shown to improve operational efficiency and accuracy in monitoring energy consumption in real-time. [10] However, the research is still limited to the monitoring aspect without touching the predictive analysis-based decision-making mechanism. [11]

Meanwhile, the potential use of Big Data Analytics in managing the variability of renewable energy resources such as solar and wind energy was raised. [12] The study utilized machine learning algorithms to predict fluctuations in energy production based on historical weather data and energy sensors. However, the approach has not yet been fully integrated into a decision support system (DSS) capable of providing strategic recommendations for policy makers at the city level. [13]

Several other studies have tried to incorporate DSS in the context of energy planning. [14] For example, a Geographic Information System (GIS)-based DSS model was developed to identify optimal locations for solar panel installations in urban areas. [15] The model shows effectiveness in supporting technical and spatial decisions, but it does not yet accommodate real-time processing of large-scale data that is a key characteristic of modern smart cities. [16]

In the broader context of integration, an intelligent system architecture for renewable energy management that combines Big Data, cloud computing, and multi-criteria optimization-based DSS modules is proposed. [17] Although the approach offers a comprehensive solution, the complexity of the system and the limitations of implementation at the city level are challenges that have not been fully resolved. [18]

From the above studies, it can be concluded that each component-both Big Data, DSS, and renewable energy technology-has been studied separately or partially. [19] However, there is still a lack of an integrative model that is able to combine the three elements synergistically to support renewable energy optimization in a smart city environment. This research comes to bridge the gap by developing a Big Data and Decision Support System integration model specifically designed to manage and optimize the distribution and utilization of renewable energy in real-time and data-driven, in accordance with the characteristics and needs of modern smart cities. [20]

RESEARCH METHOD(S)

This research uses a descriptive-qualitative approach with a combination of system modeling and big data-based analysis to design an integrated system that optimizes the use of renewable energy in the context of a smart city. The research methodology consists of several main stages, namely: (1) identification of smart city energy system needs; (2) design of Big Data and Decision Support Systems (DSS) integration architecture; (3) collection and processing of energy data; (4) implementation of a DSS model based on data analysis; and (5) evaluation of system performance.

1. **Identification of Smart City Energy System Needs**
   The initial stage was carried out with a literature study and analysis of energy needs in the context of smart cities. This process includes identifying the characteristics of energy consumption, the potential of renewable energy (such as solar and wind power), and the challenges in managing it. In addition, the main actors involved, such as the city government, energy providers, and end-users, were also identified.
2. **System Architecture Design**
   Based on the results of the needs identification, a system architecture was designed that integrates the Big Data Analytics module with the Decision Support System module. This architecture is designed modularly to allow flexibility in development and scalability to large volumes of data. The main components of the system consist of:

A. Data sources: including IoT sensors, weather data, energy consumption, and renewable energy output.
B. Data Lake: where large-scale data is stored.
C. Big Data Analytics Engine: which uses machine learning techniques to analyze consumption patterns and predict energy demand.
D. Decision Support Interface: which presents analysis results in the form of visualizations and recommendations for decision makers.

3. **Data Collection and Processing**
   Data is collected from a simulated city energy system that incorporates household electricity consumption parameters, renewable energy generation performance, and historical weather data. The data is stored in a cloud-based data lake platform and processed using Apache Hadoop and Spark frameworks to accommodate high data volume and velocity. The data is cleaned and categorized before further analysis.
4. **DSS Model Implementation**
   The decision support system was developed by utilizing multi-criteria decision making (MCDM) algorithms such as Analytic Hierarchy Process (AHP) and fuzzy logic to produce optimal recommendations related to energy distribution, load regulation, and priority use of renewable energy. The output of big data analysis becomes the main input in the dynamic decision-making process.
5. **System Evaluation and Validation**
   System evaluation is conducted through scenario-based simulation on a virtual smart city built using urban energy simulation software such as EnergyPlus and MATLAB Simulink. System performance is measured based on energy efficiency indicators, increased use of renewable energy, accuracy of energy load prediction, and system response to changes in environmental conditions. Validation of the results is done by comparing the system performance with conventional methods that do not integrate Big Data and DSS.

This methodology is designed to produce a system that is adaptive, accurate, and able to assist decision makers in managing energy sustainably and efficiently in a smart city environment. With this approach, the research is expected to make a significant contribution in the application of digital technology for more optimized renewable energy management.

FINDINGS AND DUSCUSSION

This research produces an integrated system capable of optimizing renewable energy utilization in a smart city environment by combining Big Data Analytics and Decision Support Systems (DSS) technologies. The developed system is tested in an urban environment simulation scenario that represents the characteristics of a smart city with dynamic energy consumption, fluctuating use of renewable energy sources, and the need for fast and adaptive decision making.

1. Implementation Results of Big Data and DSS Integration System

The system implementation starts with data collection from various sources: household energy consumption, energy production from solar panels and wind turbines, and real-time weather data. This data is analyzed using a Big Data framework that utilizes machine learning algorithms such as Random Forest and K-Means Clustering to identify consumption patterns and classify energy loads based on time, location, and weather factors.

The analysis results are then used as input in the DSS module, which applies the Multi-Criteria Decision Making (MCDM) method to generate operational policy recommendations. The system is able to recommend energy allocation based on priority needs, peak consumption times, and potential renewable energy supply. For example, the system suggests shifting loads from conventional energy sources to renewable sources when the intensity of sunlight reaches its peak, increasing the efficiency of solar panel usage by 27%.

Table 1 Comparison of Renewable Energy Usage Efficiency (Before and After System Integration)

Table I. Before and After System Integration

Scenario	Average Renewable Energy Utilization (%)	Efficiency Improvement (%)
Conventional System	48%	-
System with Big Data + DSS	73%	+25%

2. Improved Energy Efficiency

The system performance evaluation shows that the integration of Big Data and DSS can significantly improve the efficiency of renewable energy use. In the trial scenario, the renewable energy utilization rate increased from 48% (in the conventional system) to 73% after the system implementation. In addition, the level of energy supply reliability increases as the system is able to respond to supply and demand dynamics more quickly. In addition to increased efficiency, the system also successfully reduced carbon emissions due to decreased reliance on fossil-based energy. The higher use of renewable energy directly impacts the reduction of CO_2 emissions by 18% during the three-month simulation period. This is an indicator of success in supporting environmental sustainability in accordance with smart and green city principles.

3. System Adaptability and Scalability

One of the main advantages of the developed system is its ability to adapt to changing environmental conditions and user needs. The system automatically calibrates its predictive model based on the latest incoming data, so that the recommendations provided are always relevant to actual conditions. Stress testing of the system also shows that the performance of the system remains stable even when the volume of data increases significantly, indicating that the architecture is scalable and can be implemented in cities with higher population and complexity.

4. Critical Discussion

The results of this study show that the integration of information technology, especially Big Data and DSS, has a real impact on the optimization of renewable energy in smart cities. Nevertheless, there are several challenges that need to be considered in real implementation in the field. Among these are the availability of adequate digital infrastructure, interoperability of systems between institutions, and regulatory policies that support data integration and automated decision-making.

In addition, data security and privacy are important issues that must be addressed by future systems. The utilization of real-time data on a large scale can open up vulnerabilities to cyberattacks, so it is necessary to integrate with a strong cybersecurity system.

Overall, this research proves that data-driven approaches and smart decision-making technologies are key to realizing efficient, adaptive and sustainable energy management in the context of future smart city development.

Table II. Reduction in CO_2 Emissions During the Simulation Period (3 Months)

Parameters	Conventional System	Big Data + DSS System	Difference in Decrease
Total CO_2 Emissions (Tons)	1500	1230	-18%
Fossil Energy Used (kWh)	320,000	260,000	-18.75%

Table III. Energy Load Prediction Accuracy Based on Big Data Algorithm

Algorithm	MAE (Mean Absolute Error)	RMSE (Root Mean Square Error)	Prediction Accuracy (%)
Linear Regression	18.3	24.1	86.7%
Random Forest	11.6	16.5	92.4%
Gradient Boosting	10.2	14.9	93.8%

Table IV. System Scalability Evaluation Against Increasing Data Volume

Data Volume (GB/day)	Runtime (s)	System Status	Performance Score (1-10)
10	3.1	Optimal	9.5
50	4.7	Stabilized	9.0
100	6.3	Slight delay	8.3
200	10.8	Needs optimization	7.2

Discussion

The results show that the integration between Big Data Analytics and Decision Support Systems (DSS) can significantly contribute to the management and optimization of renewable energy in smart cities. The findings reinforce the premise that data-driven decision-making is an essential element in creating a more efficient, adaptive and sustainable energy system.

A key discussion of the research results lies in the effectiveness of integration between large-scale data analytics and decision support systems. Big Data enables the collection, storage and analysis of real-time data from various sources such as IoT sensors, weather data, energy consumption and renewable energy generation output. This data is then analyzed using machine learning algorithms to more accurately predict energy consumption and production patterns.

Furthermore, the DSS utilizes the analysis results to generate strategic recommendations for optimal management of energy distribution. In the simulation, the system succeeded in increasing renewable energy utilization by 25%, as well as reducing dependence on fossil energy sources, which implies a significant reduction in carbon emissions.

The smart city concept emphasizes the use of information and communication technology to improve the quality of life of urban communities. In the context of energy, smart cities are required to not only provide sufficient energy supply, but also ensure that the energy is sourced from environmentally friendly, efficient and renewable systems.

The findings of this research show that the use of Big Data and DSS technology enables cities to perform predictive rather than reactive energy management. Thus, cities can respond more quickly and appropriately to the dynamics of energy demand and supply, and minimize the risk of energy overload or waste.

Sustainability is a central issue in this discussion. By maximizing the utilization of renewable energy sources such as solar and wind power, the developed system is able to reduce carbon emissions by 18% in a three-month simulation. This is a concrete step in supporting the transition to a low carbon city, as mandated in various global sustainable development agendas such as the Sustainable Development Goals (SDGs).

In addition, the system also supports the reduction of fossil-based energy use at peak consumption hours, which is often the biggest contributor to carbon emissions and wasteful operational costs.

Although the results show great potential, implementing this system on a real scale requires the support of adequate digital infrastructure, open data policies, and multi-stakeholder collaboration between the government, energy providers, and communities. Another challenge is the need for system standardization between regions and cybersecurity guarantees for systems that rely on real-time data.

The policy implications arising from these results are the need for regulations that support the use of analytics and DSS technologies in energy management, as well as local government investment to build a smart city architecture that supports the integration of these technologies as a whole.

This research is limited by the use of simulated data, which although designed to be as similar as possible to real conditions, still does not fully reflect the complexity of the actual urban environment. Therefore, testing the system in a pilot project in a city with an existing smart grid infrastructure would be an important next step.

In addition, the development of more sophisticated DSS systems using real-time reinforcement learning or adaptive algorithms could be an interesting topic for further research, to strengthen the system's ability to respond to energy dynamics autonomously and more precisely.

CONCLUSION AND RECOMMENDATION

This research confirms that the integration of Big Data Analytics and Decision Support Systems (DSS) technology is an effective strategic approach to optimize renewable energy utilization in the context of smart cities development. Through the utilization of real-time data generated from various sources such as IoT sensors, weather systems, and energy consumption history, the developed system is able to perform predictive analysis and generate data-based decisions for energy allocation dynamically and efficiently.

Simulation results show that this integrative approach not only increases the efficiency of renewable energy use by 25%, but also contributes to an 18% reduction in carbon emissions during the simulation period. In addition, the system proved to be able to adaptively adjust energy distribution to variations in environmental conditions and load demand, which is an important element in creating a sustainable energy ecosystem.

From the conceptual side, this research contributes to the literature related to modern energy management, especially in terms of implementing smart technology to support energy sustainability and operational efficiency in urban areas. Meanwhile, from the practical side, the results of this research can be used as a basis for designing public policies and future energy system architectures that are more responsive, sustainable and adaptive to changing needs.

However, this research also has limitations, especially in terms of the scope of trials that are still simulative and do not include direct application in the field. Therefore, further research is recommended to be carried out on a real implementation scale in areas that already have smart grid infrastructure or cities with a clear smart city development roadmap. Future research can also expand the scope by integrating other approaches such as reinforcement learning, blockchain for energy trading, and demand response load management.

Overall, the integration of Big Data and DSS opens up great opportunities for the transformation of modern city energy systems, as well as being an important foundation in the realization of smart cities that are not only efficient, but also oriented towards environmental sustainability and community welfare.

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