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Recent Advances in Smart Grid Technologies for Sustainable and Intelligent Electric Power Systems

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ABSTRACT

The development of modern electric power systems is driving the transformation of conventional power grids towards smarter, more reliable, efficient, and sustainable Smart Grids. Smart Grid integrates information and communication technology with electric power systems through the use of Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, Cloud Computing, Advanced Metering Infrastructure (AMI), and Energy Storage Systems to improve the reliability, operational efficiency, and quality of electrical energy services. This research aims to examine the development of Smart Grid technology, identify supporting technologies, implementation benefits, challenges faced, and the direction of smart power system development. The research uses the Systematic Literature Review (SLR) method by analyzing scientific articles published in the 2018–2022 period and obtained through Google Scholar. The results of the study show that the implementation of Smart Grid is able to improve energy distribution efficiency, system reliability, integration of renewable energy sources, real-time monitoring capabilities, and the effectiveness of electricity load management. However, its implementation still faces challenges in the form of system interoperability, cybersecurity, infrastructure investment, and technology standardization. The results of the study show that the integration of AI, IoT, and other digital technologies is the main factor in supporting the development of Smart Grids that are adaptive, sustainable, and able to meet the needs of future electric power systems.

Keywords: *Artificial Intelligence; Internet of Things; Power System; Smart Grid; Systematic Literature Review*

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1. | INTRODUCTION

The increasing need for electrical energy, population growth, the development of the industrial sector, and the integration of renewable energy sources are driving the transformation of the electric power system from a conventional grid to a Smart Grid. Conventional power grid systems have limitations in terms of two-way communication, real-time monitoring of grid conditions, load management, and the ability to accommodate distributed energy generation. This condition causes the electrical system to face various challenges, such as increased power losses, decreased system reliability, fluctuations in power quality, and low operational efficiency. Therefore, an electrical system that is more intelligent, adaptive, and able to respond to changes in grid conditions quickly is needed to meet the needs of modern electric power systems (Amin, 2019; Ghasempour, 2019).

Smart Grid is a modern concept of electric power system that integrates electrical infrastructure with information and communication *technology*, smart sensors, automation devices, and two-way communication systems to improve the efficiency, reliability, safety, and sustainability of electrical energy supply. Unlike traditional power grids, Smart Grids allow for real-time information exchange between electricity providers and consumers so that monitoring, control, and decision-making processes can be carried out automatically. This ability makes Smart Grid the main foundation in the development of a more flexible electric power system and able to accommodate changes in energy consumption patterns in the digital era (Bedi et al., 2018; Radecke et al., 2020).

The development of Smart Grid is inseparable from the advancement of various digital technologies, such as Artificial Intelligence (AI), *Internet of Things* (IoT), *Big Data Analytics*, *Cloud Computing*, *Machine Learning*, and *Advanced Metering Infrastructure* (AMI). AI and *Machine Learning* are used to predict electrical loads, detect faults, optimize power system operations, and make data-driven decisions. Meanwhile, IoT allows various electrical devices, sensors, and control systems to be connected to each other through communication networks so that they are able to generate operational data in real-time. The integration of these various technologies results in a Smart Grid system that is more responsive to changes in grid conditions while improving the efficiency of electrical energy management (Sarker et al., 2021; Hussain et al., 2021).

In addition to improving operational efficiency, Smart Grids also play an important role in supporting the integration of renewable energy sources, such as solar and wind power, which have intermittent characteristics. The presence of *the Energy Storage System* (ESS), an AI-based prediction system, and *a Demand Response* mechanism allows the balance between energy generation and consumption to be maintained despite fluctuations in renewable energy production. Thus, Smart Grid is one of the main solutions in supporting the transition to a sustainable low-carbon energy system while increasing the resilience of the electric power system to changes in loads and operational disruptions (Kumar et al. 2020).

Although it offers various benefits, the implementation of Smart Grid still faces various challenges, including the high need for infrastructure investment, interoperability between devices, cybersecurity, data privacy, and the lack of uniform communication standards used in various components of the electric power system. In addition, the increasing number of interconnected devices also causes the volume of data generated to be larger, requiring an efficient and secure data management system. These challenges are a major concern in the development of Smart Grids because the success of its implementation depends not only on technological advances, but also on the readiness of infrastructure, regulations, and human resources that support system operations (Khan et al., 2021; Moreno et al., 2021).

Various research on Smart Grids has developed rapidly over the past few years with a focus on technology development, optimization of power system operations, integration of renewable energy, and improvement of the security and reliability of the power grid. However, the results of the research are still scattered in various aspects so that a study that is able to synthesize technological developments comprehensively is needed. Therefore, this study uses the Systematic Literature Review (SLR) method to analyze scientific publications for the 2018–2022 period regarding the development of Smart Grid Technologies, identify supporting technologies, implementation benefits, challenges faced, and directions for the development of smart power systems towards more efficient, reliable, adaptive, and sustainable energy infrastructure.

2. | RESEARCH METHOD

This study uses the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize research results regarding the development of Smart Grid technology in modern power systems. (Pati & Lorusso, 2018) The SLR method was chosen because it is able to present a systematic literature review in a systematic, transparent, and scientific evidence-based manner so that it can provide a comprehensive picture of technological developments, research trends, implementation benefits, challenges, and directions for Smart Grid development. This approach also allows the literature selection process to be carried out objectively based on predetermined criteria so as to minimize bias in data collection and analysis.

The research stage begins with the formulation of research objectives, namely examining the development of Smart Grid technology and identifying supporting technologies that play a role in improving the efficiency, reliability, and sustainability of the electric power system. Furthermore, a literature search was conducted using Google Scholar with the keywords *Smart Grid*, *Electrical Power System*, *Advanced Metering Infrastructure*, *Artificial Intelligence*, *Internet of Things*, *Machine Learning*, *Renewable Energy Integration*, *Energy Storage System*, *Demand Response*, and *Cybersecurity*. The literature used is limited to scientific articles published during the period 2018–2022 to be in line with technological developments prior to the year of publication of the article.

The selection process is carried out by applying inclusion and exclusion criteria. The inclusion criteria include journal articles and conference proceedings that discuss the implementation of Smart Grid, supporting technologies, electric power system optimization, renewable energy integration, and power grid security. Meanwhile, articles that are not related to the scope of the research, are not available in full manuscript form, or have limited information are excluded from the analysis process. Literature that meets all criteria is then analyzed using a qualitative descriptive approach through a grouping process based on the theme of discussion, comparison of research results, identification of implementation benefits and challenges, and synthesis of technological developments. The results of the analysis are the basis for compiling a discussion on research trends and the direction of Smart Grid development as the foundation of smart power systems in the future.

3. | RESULTS AND DISCUSSION

The results of the literature synthesis show that the development of Smart Grid is one of the most significant innovations in the modern electric power system. Various studies published during the 2018–2022 period show a paradigm shift from conventional power grids to more intelligent, adaptive, and two-way communication-based power systems. In traditional power grids, the flow of energy and information generally takes place in one direction, so operators have limitations in monitoring network conditions in real-time and responding to disturbances quickly. Instead, Smart Grid integrates information technology, communication, smart sensors, and automation systems to enable continuous data exchange between power plants, transmission networks, distribution, and consumers. The integration improves the system's ability to monitor network conditions, control loads, detect faults, and optimize energy distribution more efficiently (Bedi et al., 2018; Kim et al., 2019).

The development of Smart Grids is further accelerated by advances in Artificial Intelligence (AI) and Machine Learning technology. Various studies show that AI algorithms are able to improve the ability of electric power systems to predict loads, optimize network operations, detect disturbances, and speed up the decision-making process. Machine Learning methods such as Artificial Neural Network, Support Vector Machine, and Deep Learning are widely applied to predict energy consumption patterns based on historical data and network operational conditions. The results of these predictions help operators in regulating the balance between generation and electricity consumption so that system efficiency can be improved. In addition, AI is also used to detect anomalies in the distribution network, identify potential equipment failures, and support predictive maintenance strategies that can reduce the risk of power outages and maintenance costs (Sarker et al., 2021; Hussain et al., 2021).

The implementation of the Internet of Things (IoT) is an important factor in supporting the success of the Smart Grid. IoT technology allows various devices such as sensors, *smart meters*, *relays*, transformers, and distribution equipment to be connected to each other through communication networks resulting in real-time operational data. Data collected from various points in the electric power system is then sent to the control center to be analyzed using AI algorithms and *Big Data Analytics* platforms. With two-way communication, operators can monitor network conditions more accurately, identify load changes, and take automatic control actions in the event of an outage. IoT integration also improves the system's ability to support the automation of energy distribution and accelerate the process of restoring services after a disruption to the power grid (Khan et al., 2021; Moreno et al., 2021).

One of the main components in the implementation of Smart Grid is the Advanced Metering Infrastructure (AMI). AMI is an intelligent metering system that enables two-way communication between electricity service providers and customers through the use of *smart meters*. Unlike conventional meters, *smart meters* are able to record energy consumption periodically, send data automatically, and receive information and commands from the control center. The implementation of AMI provides various benefits, such as increasing the accuracy of recording energy consumption, reducing non-technical energy loss, accelerating the billing process, and improving the quality of service to customers. In addition, energy consumption data obtained from AMI is an important source of information for AI systems in analyzing electricity usage patterns and developing more effective *Demand Response* strategies (Bedi et al., 2018; Radecke et al., 2020).

The results of the study also show that the integration of renewable energy is one of the main factors that encourage the development of Smart Grid. The use of energy sources such as solar and wind power continues to increase as an effort to reduce carbon emissions and dependence on fossil fuels. However, the intermittent characteristics of renewable energy plants cause the stability of the electric power system to be more complex. Therefore, Smart Grids leverage AI, IoT, and digital communication systems to predict energy production, regulate power distribution, and maintain system balance automatically. Various studies show that the application of digital technology is able to increase the reliability of renewable energy integration without reducing the stability of the electric power system. Thus, Smart Grids play a key role as the main infrastructure in supporting the transition to a cleaner, more efficient, and more sustainable energy system (Kumar et al., 2020).

The development of Energy Storage System (ESS) is an important component in supporting the implementation of Smart Grid, especially in electric power systems that integrate renewable energy plants. ESS functions to store excess energy when electricity production exceeds load requirements and redistribute it when there is an increase in consumption or a decrease in energy production. Thus, ESS is able to reduce power fluctuations, maintain frequency and voltage stability, and improve the reliability of the electric power system. The integration of ESS with Artificial Intelligence algorithms allows the system to optimize energy charging and discharging strategies based on load predictions, weather conditions, and storage capacity. The results of various studies show that the combination of ESS and AI is able to increase the operational efficiency of the power grid while increasing the use of renewable energy without reducing system stability (Kumar et al., 2020).

In addition to ESS, the implementation of Demand Response (DR) is one of the important strategies in increasing Smart Grid flexibility. Demand Response is a mechanism for managing energy consumption through changes in electricity usage patterns by customers based on network conditions and electricity price signals. With the support of *Advanced Metering Infrastructure* (AMI), two-way communication, and AI-based data analysis, operators can provide customers with information on system load conditions so that energy consumption can be shifted to periods beyond peak loads. This approach not only improves the efficiency of energy use, but also reduces the need to build new plants and reduces the operating costs of electric power systems. Various studies show that the successful implementation of Demand Response is greatly influenced by the accuracy of load prediction, customer participation, and the ability of communication systems to convey information in real-time (Sarker et al., 2021; Mahmud et al., 2020).

The increasing connectivity between devices on the Smart Grid also poses new challenges in the cybersecurity aspect (Kimani et al., 2019). Unlike conventional power grids, Smart Grids connect various digital devices, sensors, *smart meters*, control centers, and communication systems in one interconnected ecosystem. This condition increases the potential for cyber attacks such as data manipulation, unauthorized access, *malware*, *denial-of-service attacks*, and disruptions to the control system. Such attacks can affect the reliability of grid operations, disrupt the distribution of electrical energy, and even cause large-scale blackouts. Therefore, various studies emphasize the importance of implementing layered security mechanisms, such as user authentication, data encryption, intrusion detection systems, and continuous network monitoring. The use of Artificial Intelligence has also begun to be applied to detect abnormal activities and identify potential cyber threats more quickly so that the risk of disruption to the electric power system can be minimized (Khan et al., 2021; Moreno et al., 2021).

While Smart Grid offers a variety of benefits, its implementation still faces a number of technical and non-technical challenges. One of the main obstacles is the high initial investment required to build communication infrastructure, smart sensors, digital measurement devices, energy storage systems, and data processing centers. In addition, interoperability between devices from various manufacturers is still a challenge because not all components use uniform communication standards. Differences in communication protocols can hinder the process of data exchange, thus reducing the effectiveness of system integration. From the operational side, the availability of human resources who have competence in the fields of power systems, information technology, data analysis, and cybersecurity is also an important factor in the successful implementation of Smart Grid. Therefore, the development of workforce competencies through training and capacity building is an integral part of the transformation process of the electric power system (Bedi et al., 2018; Hussain et al., 2021).

The synthesis of various studies also shows that the development of Smart Grid is increasingly leading to the use of more integrated digital technology. Artificial Intelligence serves as a hub for analysis and decision-making, the Internet of Things provides real-time operational data, Big Data Analytics processes large amounts of data to generate valuable information, while Cloud Computing provides a flexible and efficient computing infrastructure. The integration of these technologies allows operators to monitor network conditions thoroughly, optimize power system operations, improve service quality to customers, and speed up decision-making processes based on actual data. This condition shows that Smart Grid is not only a modernization of the power grid, but also a key foundation in the development of a digital energy ecosystem that is able to adapt to changing societal needs and technological developments (Sarker et al., 2021).

Overall, the results of the study show that research on Smart Grids during the 2018–2022 period has increased significantly with a focus on improving energy efficiency, integrating renewable energy, automating power systems, and strengthening network security. The direction of research has also begun to shift towards the development of a more intelligent, sustainable, and data-centered electric power system through the use of Artificial Intelligence, the Internet of Things, Energy Storage System, and modern communication technology. These developments show that Smart Grid will be the main infrastructure in supporting the global energy transition, increasing the resilience of the electric power system, and realizing a more reliable, efficient, and environmentally friendly electricity system in the future. Therefore, further research needs to be focused on developing more adaptive artificial intelligence algorithms, improving device interoperability, strengthening cybersecurity, and developing implementation standards that are able to support the widespread application of Smart Grid in various electrical power system conditions.

4. | CONCLUSION

Based on the results of the Systematic Literature Review (SLR) on scientific publications for the 2018–2022 period, it can be concluded that Smart Grid is one of the main innovations in the modernization of the electric power system that is able to improve the efficiency, reliability, flexibility, and sustainability of the power grid (Rathor & Saxena, 2020). The transformation from conventional power grid to Smart Grid is supported by the integration of various digital technologies, such as Artificial Intelligence (AI), Internet of Things (IoT), Advanced Metering Infrastructure (AMI), Big Data Analytics, Cloud Computing, and Energy Storage System (ESS). The integration of this technology allows the process of monitoring, control, data analysis, and decision-making to be carried out in real-time so as to improve the quality of service and operational efficiency of the electric power system.

The results of the study also show that the implementation of Smart Grid provides various benefits, including improving the accuracy of electricity load prediction, strengthening the integration of renewable energy sources, optimizing energy management, reducing power losses, and increasing the reliability and resilience of the system to operational disruptions. However, the implementation of Smart Grid still faces various challenges, such as high investment costs, interoperability (Brown et al., 2018). between devices, cybersecurity, technology standardization, and the readiness of human resources to operate digital-based systems. Therefore, the development of Smart Grids in the future needs to be supported by improving communication infrastructure, implementing integrated standards, strengthening information security systems, and developing artificial intelligence algorithms that are more adaptive and efficient. This research is expected to be a reference for academics, researchers, industry, and policymakers in supporting the development of a smarter, more reliable, sustainable electric power system, and ready to face the challenges of energy transformation in the future.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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