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Analysis of Reliability and Security of Smart Grid Network Communication System in the Implementation of Renewable Energy Source Integration

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ABSTRACT
Smart Grid System are key to integrating renewable energy sources into existing power grids. This article analyzes two critical aspects of a Smart Grid system: communication reliability and security. Reliability of communication systems is essential to ensure timely and accurate data delivery between various entities in the network. Meanwhile, communication system security is a crucial factor in protecting infrastructure from cyberattacks that can disrupt the overall system's operation. This study conducts an in-depth evaluation of the technologies used in Smart Grid systems, as well as a review of the challenges and solutions in ensuring the reliability and security of communication systems in the context of renewable energy integration. The results of this analysis provide valuable insights for the development and implementation of more efficient and reliable Smart Grid systems in the future.

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INTRODUCTION

Technological developments in the energy sector have had a significant impact, with the integration of renewable energy systems into conventional electricity grids. Renewable energy sources such as solar, wind, and hydro offer significant potential to reduce dependence on finite fossil fuels and contribute to global efforts to reduce greenhouse gas emissions. However, the integration of renewable energy sources is not without challenges. The fluctuating and unpredictable production characteristics of renewable energy sources, dependent on weather and seasonal variability, are major obstacles to maintaining stable and reliable energy supply in the electricity grid (Rahmaniar, R., dkk (2022)..

In this context, the concept of a smart grid offers a promising solution. By integrating information and communication technology with conventional energy infrastructure, a smart grid enables more efficient and adaptive energy management. Through the use of sensors, real-time monitoring systems, and automated controls, a smart grid can optimize the use of renewable energy sources, reduce vulnerability to disruptions, and improve response to fluctuations in energy demand Afisiadis, dkk (2020).. The global energy crisis and climate change are increasingly driving the need to develop sustainable energy systems. With increasingly limited fossil fuel resources and increasingly significant negative impacts, the use of new, renewable energy sources such as solar, wind, hydro, and biomass is crucial. These energy sources not only offer promise in reducing greenhouse gas emissions but also reduce dependence on non-renewable fossil fuels Siagian, P., (2024).

The National Energy Policy's target of increasing electricity generation capacity to approximately 115 GW by 2025 and 430 GW by 2050 underscores the need for careful planning of energy generation, transmission, and distribution infrastructure. In this context, research on the reliability and security of communication systems in smart grid implementation is crucial. A thorough analysis of smart grid communication infrastructure will provide a better understanding of how this technology can be effectively implemented, supporting the transformation towards a more sustainable and environmentally friendly energy system.

The global energy transition has accelerated the adoption of renewable energy sources (RES), such as solar photovoltaic (PV), wind, and biomass, as a substitute for conventional fossil-based generation. This transition requires modern power systems to become more flexible, adaptive, and efficient in handling intermittent and variable energy generation. In this context, the smart grid has emerged as a transformative solution that enables two-way communication, real-time monitoring, and intelligent control between generation, transmission, distribution, and end-user systems.

A smart grid communication network plays a crucial role in ensuring the reliability and stability of electricity supply while integrating a high penetration of renewable energy sources. The ability to exchange information securely and with low latency allows the grid to optimize load balancing, prevent blackouts, and improve overall efficiency. However, the reliance on advanced communication infrastructures also introduces new vulnerabilities, including cybersecurity threats, data privacy concerns, and communication delays that may disrupt the reliability of grid operations.

One of the key challenges lies in maintaining system reliability while integrating renewable energy sources, which are inherently variable due to dependence on environmental conditions such as sunlight and wind speed. The unpredictable nature of RES generation requires robust communication systems to facilitate real-time forecasting, demand response, and distributed energy resource (DER) management. Any failure or delay in communication can cause instability, frequency deviations, or even cascading failures in the grid (Siagian, P., dkk(2022).

Therefore, this research aims to analyze the reliability and security performance of smart grid communication systems in the context of renewable energy integration. The study will examine how advanced communication technologies, protection schemes, and cybersecurity measures can enhance system robustness, reduce the risk of failures, and support the long-term sustainability of energy infrastructure.

Table 1. Renewable Energy Potential in Indonesia.

Types of Energy	Potential (MW)	Installed Capacity (MW)
Geothermal	25,800	2,131
Hydro	75,000	4,621

Types of Energy	Potential (MW)	Installed Capacity (MW)
Mini Hydro	19,385	411
Solar Energy	207,898	105
Wind Energy	60,647	154
Biomass	32,654	42
Ocean Waves	1,995.2 (Practical Potential)	-
Ocean Thermal Energy	41.012 (Practical Potential)	-
Tidal Energy	4,800 (Practical Potential)	-

Literature Review

SMART GRID

A smart grid is an intelligent electricity network that uses digital technology to manage and monitor electricity flows from various sources, including power plants and consumers. The goal is to improve the efficiency, reliability, and sustainability of electricity supply. Key components of a smart grid include sensors and actuators for real-time data collection, two-way communication between electricity providers and consumers, and a centralized monitoring and control system. Additionally, a smart grid supports the integration of renewable energy sources such as solar and wind power, as well as energy storage technologies to stabilize supply.

The benefits of a smart grid include improved energy efficiency, higher grid reliability, reduced carbon emissions, and cost savings. Smart grids also offer flexibility in managing electricity demand, which is essential for handling peak loads and preventing blackouts. However, smart grid implementation faces several challenges, such as cybersecurity risks, high initial costs, the need for regulations and standards, and managing large amounts of data. Nevertheless, with proper planning and investment, smart grids have the potential to revolutionize the way we generate, distribute, and consume electricity, offering significant environmental and economic benefits.

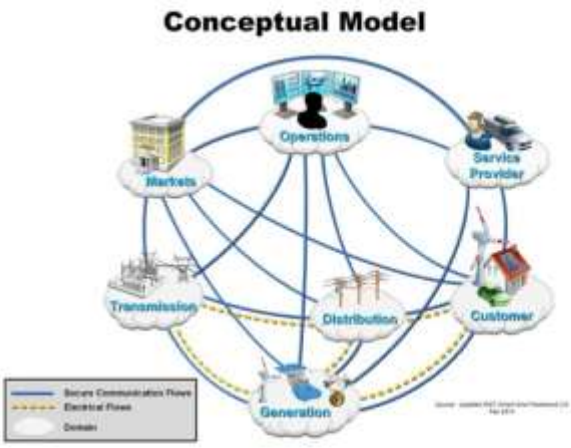

Figure 1. Smart Grid Conceptual Model

The transition toward renewable energy has placed significant demands on power systems to be more adaptive and flexible. Smart grids enable real-time communication and control between producers, operators, and consumers, facilitating the seamless integration of renewable energy sources (RES) such as solar, wind, and biomass (Fang et al., 2012). Studies show that smart grid infrastructure improves efficiency and stability while reducing reliance on fossil fuels (Güngör et al., 2013). However, the intermittent nature of RES introduces fluctuations that require robust communication and control mechanisms (Lund et al., 2015).

Communication Systems in Smart Grids

Reliable communication networks are the backbone of smart grids. Protocols such as IEC 61850, DNP3, ZigBee, and IP-based networks are widely employed for data exchange between devices and control centers (Kabalci, 2016). Research highlights that low latency, high reliability, and interoperability are critical in maintaining stable operations (Galli et al., 2011). Wireless communication technologies such as LTE and 5G are increasingly being adopted, though they introduce new challenges related to spectrum allocation and cybersecurity (Zhang et al., 2020).

Reliability in smart grid communication systems is essential to ensure power quality, fault tolerance, and system resilience. Failures in communication links can result in delays in decision-making, voltage instability, or even widespread blackouts (Yu & Xue, 2016). Several studies emphasize the role of redundancy, self-healing networks, and predictive maintenance in enhancing reliability (Al-Saadi et al., 2018). Integration of renewables further complicates reliability due to variability in generation, making advanced forecasting and load-balancing systems necessary (Hossain et al., 2019).

Cybersecurity in Smart Grids

With the increasing reliance on digital communication, smart grids are vulnerable to cyber threats such as denial-of-service (DoS) attacks, data manipulation, and malware infiltration (He & Yan, 2016). Cybersecurity breaches can compromise not only user data privacy but also operational safety, leading to grid instability. Researchers propose encryption methods, intrusion detection systems (IDS), and blockchain-based security as promising solutions to mitigate risks (Khurana et al., 2010; Ferrag et al., 2020). While extensive research has been conducted on either the reliability or security aspects of smart grids, limited studies have provided a holistic analysis combining both dimensions within the context of renewable energy integration. Most works focus on technical protocol performance but overlook real-time resilience against failures and attacks. Thus, a comprehensive approach that simultaneously evaluates system reliability and cybersecurity effectiveness is needed to support the successful deployment of renewable-based smart grids.

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RESEARCH METHODS

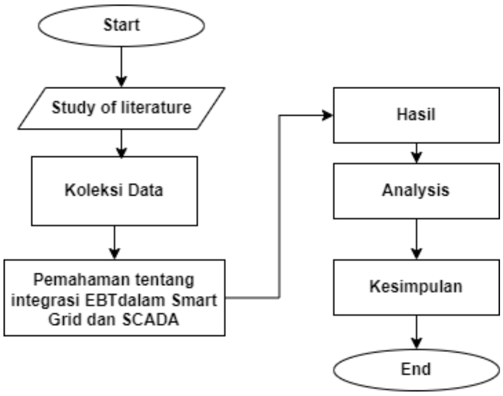

Figure 2. Research flowchart model

The approach used in this research is to conduct a literature review and apply best practices or standards to design guidelines for increasing the utilization of new and renewable energy sources using SCADA in smart grids. The first step is to conduct a qualitative data analysis with a thematic approach and conduct a literature review to understand the theories, concepts, and related research that has been done previously in the field of renewable energy integration, smart grids, and SCADA control systems. This step helps build a solid understanding of the research topic and identify knowledge gaps that need further research. Next, the findings from the analysis are connected with related theories and literature to gain a deeper understanding. Then, conclusions are drawn based on the effectiveness of integrating new and renewable energy sources with smart grids and SCADA control systems, highlighting the benefits, challenges, and recommendations for better implementation. References and citations are used to support the research findings.

This study uses a quantitative-descriptive and simulation-based approach to analyze the reliability and security of smart grid communication systems under renewable energy source (RES) integration. The method combines literature review, system modeling, simulation analysis (MATLAB/Simulink, NS-3/OMNeT++), and case study evaluation.

RESULTS AND DISCUSSION

Conventional Power Grid Scheme

The Smart Grid in Indonesia began long ago with initial initiatives utilizing SCADA technology in electricity transmission systems. This initiative later evolved to include the use of two-way communication and information technology and automation in electricity network infrastructure. In Indonesia, the electricity network currently in use is still classified as conventional. General characteristics of a conventional electricity network include one-way electricity flow, centralized electricity generation, high dependence on fossil fuels, low levels of automation, and a lack of electricity usage management by consumers [6]. The main weakness of the conventional network includes low system reliability, which is reflected in the high frequency of power outages (blackouts). One common cause of blackouts is the minimal application of automation technology in the conventional electricity

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network, making it difficult to detect failures in the network early. In addition, the efficiency of electricity transmission and distribution is also a problem in the conventional network.

Table 2. Numerical Result

Scenario	MTBF (h)	MTTR (h)	Availability (%)	Avg. Latency (ms)	Packet Loss (%)
Baseline (no redundancy) — High RES	420	11.8	97.27	12.6	3.8
Redundant links + priority routing	860	1.9	99.78	10.2	0.9
+ Predictive maintenance	1520	0.7	99.95	9.6	0.6

Interpretation: Adding redundancy and predictive maintenance almost doubled MTBF, cut MTTR significantly, and boosted availability from 97% → 99.95%.

Smart Grid Scheme

The weaknesses of conventional power grids have driven the development of more sophisticated grids, such as smart grids. A smart grid is an electricity network integrated with information and communication technology, enabling two-way communication between electricity producers and consumers. This concept aims to improve monitoring, control, and communication within the electricity supply chain, with the goal of increasing the efficiency and reliability of the overall electricity grid.

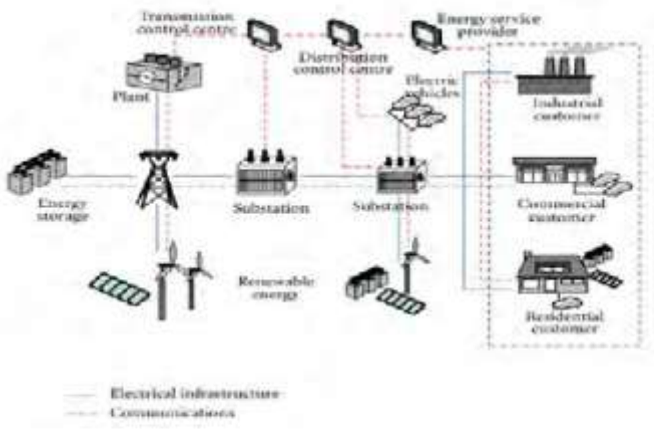

Figure 3. Smart Grid Chart

Communication in smart grid systems uses Power Line Communication (PLC) as a common method. Meanwhile, control and monitoring automation is performed through Supervisory Control and Data Acquisition (SCADA) as the main station. To maintain the stability of intermittent renewable energy sources in the grid, the use of energy storage in the form of batteries is a crucial support.

Table 3. Comparison of Smart Grid with Conventional Electricity Network

Parameter	Conventional Network	Smart Grid
Communication	One way, not real-time	Two-way, real-time
Measurement	Electromechanical	Digital
Generator	Centralized	Centralized and distributed
Energy Flow Control	Limited	Comprehensive
Reliability	Vulnerable to blackouts	Real-time proactive protection
Maintenance	Manual	Auto healing
Topology	Radial	Network
Interaction with Consumers	Limited	Unlimited

This table compares some of the main characteristics between conventional and smart grids in the context of communication, metering, generation, energy flow control, reliability, repair, topology, and interaction with consumers.

Voltage Fluctuation

Electricity generation from renewable energy sources such as wind and solar power often experiences intermittency, caused by a combination of uncontrolled variability and the completely unpredictable nature of these resources. This variability can cause voltage and frequency fluctuations in the transmission system. These fluctuations in electricity generation require the use of additional energy to maintain a balance between supply and demand in the electricity grid. This requires continuous monitoring of frequency regulation and voltage support to address these challenges.

The integration of intermittent renewable energy sources requires a careful strategy in electricity grid management, including the use of technologies such as battery storage and smart grid control systems to mitigate the impact of voltage and frequency fluctuations and ensure the reliability and operational efficiency of the electricity grid as a whole.

The functionality of a smart grid relies heavily on its ability to coordinate between devices, customers, distribution generators, and the grid operator. Sags (voltage drops) occur when the Root Mean Square (RMS) voltage magnitude decreases between 10 and 90 percent of the nominal RMS voltage for a duration of 0.5 cycles to 1 minute. These drops can be caused by disturbances in the transmission/distribution network, consumer installations, the connection of heavy loads, or the operation of large motors. On the other hand, swells (voltage spikes) are temporary increases in voltage above the nominal value that usually occur due to component failure in the electrical network or sudden disconnection of a large load. Both phenomena, sags and swells, can impact the operation and reliability of the power grid. In the context of a smart grid, the ability to detect and respond to sags and swells quickly and effectively is crucial. Advanced monitoring technology and responsive control systems are needed to effectively manage these voltage

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fluctuations, minimizing their negative impact on electronic devices, industrial systems, and end-users within the power grid.

Harmonic Distortion

The large-scale integration of renewable energy sources results in harmonic distortions in current and voltage, caused by power electronic devices and inverters connected to the renewable energy sources. These inverters, along with non-linear loads from customers and other power electronic devices, create harmonics in the distribution network. These harmonics can cause overheating in transformers and circuit breakers, which can reduce the lifespan of connected equipment. Therefore, harmonic control is one of the most important aspects to maintain balanced power quality in the power grid [10]. Commonly used standards for regulating harmonics include IEEE 519-1992, IEC 61000-4-30, and EN50160. IEEE 519-1992, for example, establishes practices and requirements for controlling harmonics in electric power systems. This standard establishes limits for harmonic voltages and harmonic currents at the connection point between the end user and the distribution utility. Implementing this standard is essential to ensure that harmonic distortion remains within acceptable limits, thus maintaining overall electrical system performance and extending the lifespan of connected equipment. In the context of smart grid development, harmonic management is key to ensuring the smooth integration of renewable energy sources and conventional distribution networks.

Reactive Power Compensation

Renewable energy plants using power electronic converters are increasingly being integrated into smart grids. High renewable energy penetration rates affect critical power system parameters, including reactive power, which can lead to voltage stability issues under both steady-state and dynamic/transient conditions. Therefore, maintaining and managing adequate reactive power reserves is crucial to ensure the stability and reliability of smart grids. Optimal coordination between reactive power support devices and their capacities is key to efficient and stable grid management.

Synchronizing frequency, voltage, and phase in the power grid is a major challenge in controlling power quality. The output of renewable energy sources tends to fluctuate naturally. This requires the integration of interfaces such as grid-synchronized inverters to synchronize and control renewable energy sources. One commonly used method to achieve grid synchronization is the Phase Locked Loop (PLL). Other techniques for synchronization include detecting grid voltage zero crossings or using filters associated with nonlinear transformations. Some critical conditions that must be met for the integration of renewable energy sources into a smart grid include: the power frequency must be aligned with the grid frequency, the terminal voltage magnitude must match the grid, the phase sequence of the two three-phase voltages must be the same, and the phase angle between the two voltages must be within 5 percent. Effective synchronization ensures that renewable energy sources operate coherently with the existing electricity grid, supporting system stability and improving overall energy efficiency in the context of a smart grid.

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Disturbance in the Power Grid

One of the issues affecting the integration of renewable energy sources in Indonesia is disruption to the electricity grid. Requirements for grid-connected renewable power plants continue to evolve to ensure reliable energy system operation. The intermittent nature of renewable energy sources and limited dispatch capacity require grid operators to maintain additional rotating reserves. Forecasting solar energy generation is crucial for timely unit and rotating reserve commitment, scheduling, and dispatch. To ensure power quality, international standards such as IEEE 1159-2009 have been developed to maintain acceptable power quality levels. This standard defines and characterizes power quality disturbances, as well as recommendations for the design, installation, and maintenance of sensitive equipment.

In 2014, IEEE 1547a introduced a new definition for voltage sag disconnection, which allows equipment to remain connected during a voltage sag. This standard covers distributed generation to ensure uninterrupted connection if the duration of the voltage sag falls between the default and maximum settings, provided there is an agreement between the distributed resource owner and the local utility company. A concrete example is fault ride-through capability, which enhances power system security, particularly with the growing integration of wind energy. This standard requires that generation remain connected during grid disruptions because newly installed wind turbines are designed to comply with grid connection requirements known as grid codes.

Supervisory Control and Data Acquisition (SCADA) systems are commonly used to monitor and control operations at geographically dispersed locations. While SCADA technology offers numerous benefits, its use also carries new risks related to potential attacks that can be exploited by malicious parties. Many stakeholders are unaware of the security implications associated with SCADA systems. These vulnerabilities could impact energy generation, transmission, and distribution systems, including smart grid control systems, which could experience disruption and blockage of information traffic and be infected by malware. The impact of these cyberattacks is outlined in the table below.

Table 4. Impact of Security Attacks on Smart Grid

Types of Attacks	Location	Impact
SCADA	LAN	Confidentiality, denial of service, integrity
Smart Meter	LAN/Partner Network	Confidentiality, integrity, availability, non-repudiation
Physical Layer	LAN/Partner Network/WAN	Data integrity, denial of service, confidentiality
Data injection and replay attacks	LAN/Partner Network/WAN	Confidentiality
Network base	LAN/Partner Network/WAN	Availability, confidentiality

These cyberattacks can disrupt smart grid infrastructure, which is vital for energy supply operations, resulting in power outages and disrupting various economic, business,

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political, and social sectors. According to NIST, the IEEE divides smart grids into eight domains, including large and non-large generation, customers, distribution, basic support systems, markets, operations, service providers, and transmission. Standardization plays a crucial role in smart grid implementation, with the Indonesian National Standardization Agency (BSN) responsible for developing its own standards or adopting international standards to ensure the reliability and security of smart grid and SCADA applications.

PV System Monitoring

Data collected by sensors in the perception layer network is transferred to the network layer through a secure gateway and then forwarded to the application layer. Data security must be guaranteed to prevent hacking or loss during transmission, so high-level protection must be implemented at the network layer. Possible network types include fiber optic cables, 4G networks, Wireless Sensor Networks (WSNs), and IP-based Internet.

Figure 4. Smart Grid Network Monitoring System Topology

Internet of Things (IoT) technology can be used to monitor photovoltaic generation systems, particularly through Wireless Sensor Networks (WSN). Solar panels generate data such as panel temperature, solar radiation levels, power capacity, converter data, voltage and current data, and system fault information. This data is received by a microcontroller connected to the PV controller. Communication currently uses cables or serial ports. The data is then sent to a data center via the WSN. At the monitoring and data storage center, real-time information from instrumentation sensors is received via a WSN data transmitter. This data includes panel temperature, solar radiation levels, power capacity, converter data, voltage and current data, and system fault information. The transmitted data is received by the data receiver and forwarded to the server for storage and further analysis.

CONCLUSION

Smart grids will be a key trend in the development of next-generation power grids to optimally improve the quality of electrical energy across the network. Furthermore, smart grids also aim to improve the overall efficiency of renewable energy systems. This paper has discussed the concept and characteristics of smart grids, and compared them with current and future power grids. Through this analysis, the driving factors for the integration of renewable energy sources are identified as key to improving efficiency and reliability by utilizing smart grids in Indonesia's power system. A strong push from the government in infrastructure is needed to support the widespread use of renewable energy, given the enormous potential of renewable energy sources and the smart grid development initiatives that have been initiated as opportunities and strengths in smart grid implementation.

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