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Hybrid Grid System as a Solution for Renewable Energy Integration: A Case Study

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Abstract
This article discusses integrating renewable energy technologies and intelligent energy management systems to create efficient and sustainable infrastructure. An analysis is conducted on a microgrid project that combines energy sources such as solar panels, wind turbines, and VRB batteries, which are optimized with SCADA systems and smart grids to improve operational efficiency. In addition, the concept of a net-zero energy home shows how technologies such as heat pumps, efficient lighting, and smart energy management enable homes to produce energy independently. At the commercial building level, smart technologies for HVAC, sensor-based lighting, and electric vehicle charging support energy-efficient and safe operations. In conclusion, renewable energy technologies and intelligent management systems are critical in transitioning to a more environmentally friendly and efficient infrastructure.

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1. Introduction
Renewable energy and smart energy management systems have become a significant focus of global efforts to reduce carbon emissions and increase energy efficiency. As the need for greener energy solutions increases, technological innovations are emerging that enable the integration of renewable energy on a broader scale, whether at the household level, commercial buildings, or electricity distribution networks. With the development of technologies such as smart grids, energy storage systems, and integrated energy monitoring and regulation devices, various sectors can now maximise the use of clean energy more efficiently. One key emerging technology is the concept of microgrids, which allow renewable energy sources such as solar panels and wind turbines to be integrated with energy storage systems to provide a self-sufficient and reliable power supply (Das, Zafar, Sanfilippo, Rudra, & Kolhe, 2024; Erdiwansyah, Gani, MH, Mamat, & Sarjono, 2022; M. Khalid, 2024; SaberiKamarposhti et al., 2024; Tan et al., 2021; Żołądek, Figaj, Kafetzis, & Panopoulos, 2024). Microgrid projects that combine renewable energy sources and storage systems, such as VRB (Vanadium Redox Batteries), demonstrate how decentralized energy management can support grid stability, reduce reliance on fossil fuels, and increase energy security (Fathima & Palanisamy, 2016; Gani et al., 2023; A. Khalid, Stevenson, & Sarwat, 2021).

In addition, the concept of net-zero energy homes has become a leading model in efforts to reduce energy consumption in the residential sector (Erdiwansyah et al., 2023; Ibrahim, Harkouss, Biwole, Fardoun, & Ouldboukhitine, 2024; Wu & Skye, 2021). Homes equipped with solar panels, heat pumps, and intelligent energy management systems can generate energy while managing energy consumption efficiently. Implementing smart meters and efficient lighting allows homeowners to monitor and control energy usage, creating energy-independent and environmentally friendly homes (Abbasi et al., 2024; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; Gani et al., 2025; Krishna Rao, Sahoo, & Yanine, 2024). On a larger scale, implementing intelligent energy management systems is also seen in modern commercial buildings, with operational efficiency and occupant comfort as top priorities. The use of sensors for lighting, air quality monitoring in HVAC systems, and electric vehicle charging are examples of how this technology is being implemented in large buildings (Elmouatamid et al., 2021; Marques, Saini, Dutta, Singh, & Hong, 2020; Zhang & Srinivasan, 2020). Smart technology enables optimal energy management, minimises waste, and provides safety and comfort for its occupants (Amaral et al., 2020; Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Erdiwansyah et al., 2020; Nižetić, Djilali, Papadopoulos, & Rodrigues, 2019).
Not only at the building scale but technologies such as smart grids and smart meters have also enabled more efficient management of electricity flows between energy producers and consumers. With two-way communication, smart grids enable automatic load balancing and integration of renewable energy sources into the primary grid, providing greater flexibility for consumers to manage their energy consumption (Albogamy et al., 2022; Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025; Mohamed, Eltamaly, Farh, & Alolah, 2015; Powell, McCafferty-Leroux, Hilal, & Gadsden, 2024). This is critical to creating an energy system more responsive and resilient to demand fluctuations and disruptions. With the implementation of these technologies, the global energy infrastructure is now on a path to higher efficiency and long-term sustainability (Amir et al., 2023; Gielen et al., 2019; Hassan et al., 2024). This article will explore how renewable energy technologies and smart energy management systems are applied in microgrid projects, net-zero energy homes, and commercial buildings and how each contributes to a more environmentally friendly and reliable energy system.
This study examines integrating renewable energy technologies with intelligent energy management systems to create efficient and sustainable infrastructure. Through a case study on a microgrid project that combines energy sources such as solar panels, wind turbines, and VRB batteries optimised using SCADA systems and smart grids, this study aims to improve the operational efficiency of the energy system. The novelty of this study lies in the holistic approach to integrating various renewable energy technologies with intelligent management systems, which are applied to net-zero energy-based homes and commercial buildings, including optimisation of electric vehicle charging and sensor-based HVAC management to support efficient and safe operations.

2. Methodology

Fig. 1 depicts a schematic of a complex electrical grid, which includes various types of power plants, transmission and distribution networks, and electricity consumers at multiple levels. The schematic shows how electricity is generated from several energy sources, including hydroelectric power plants, wind power plants, solar power plants, and fossil fuel power plants. Each power plant is connected to a transmission network with several voltage levels, from high to low. The power plants on the left side of the figure are shown in their high- to extremely high-voltage classifications, which are systems for transporting electrical energy over long distances with high efficiency. This energy is transmitted through high-voltage power lines before reaching substations or distribution substations that step down the voltage for local use.

This process shows how electricity from large power plants, such as coal-fired or hydroelectric plants, is distributed throughout the electric power system.

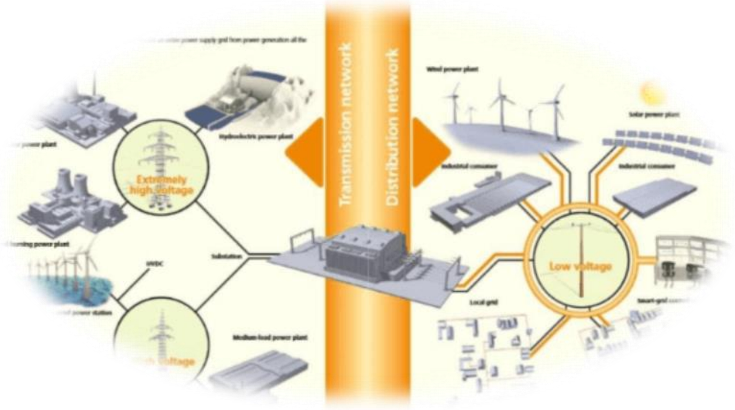

Fig. 1. Schematic diagram of smart grid

On the right side of the figure, you can see various electricity consumers, from large industries and commercial consumers to households, all connected to the low-voltage network. These consumers can also include renewable energy sources such as solar panels and wind turbines directly connected to the low-voltage distribution network. This creates a microgrid system that can support the primary electricity grid or operate independently. This analysis illustrates the importance of integrating different types of energy generation and consumers in an efficient and reliable distribution network. The scheme also describes the critical role of renewable energy in supporting global electricity needs and how innovative grid technologies and decentralized energy distribution are essential elements of the future energy system.

3. Result & Discussion

Table 1 compares conventional and smart grid systems in several aspects: community participation, network form, service products and markets, quality, disturbance handling, and optimization. Overall, the smart grid system shows significant advantages over conventional systems, especially regarding efficiency, flexibility, and community empowerment. Traditional systems are more passive in terms of community participation, where the community only acts as a recipient of the electricity supply. In contrast, in smart grids, the community is actively involved, for example, by providing information related to energy consumption and the possibility of becoming a prosumer (producer and consumer of electricity). This aligns with previous research results showing that community empowerment in energy management, such as in community-based microgrids, increases energy consumption awareness and efficiency.
In terms of network form, conventional centralized systems make the involvement of electrical storage media minimal, making them vulnerable to disruptions at specific points. In contrast, smart grids are decentralized using energy storage technologies such as batteries and more intelligent energy management systems. Previous studies also stated that decentralization can reduce power losses in distribution networks and increase operational stability. Regarding handling disruptions and optimization, smart grids are superior with technology that allows early prediction of disruptions and faster resolution. This system also supports better asset management and operational efficiency compared to conventional systems that are less flexible and tend to be slow in handling disruptions. Previous studies have confirmed that using IoT (Internet of Things) and AI-based technologies in smart grids allows operators to improve network reliability, reducing downtime significantly. Integrating technology in smart grids will

make it a more adaptive and friendly solution for developing dynamic energy markets in the future. This system aligns with the global trend towards greener and more sustainable energy.

Table 1. The difference between conventional electricity networks and smart grids

Characteristics	Conventional	Smart Grid
Community Participation	The community is only a recipient of supply	Communities participate in the provision of information, consumer involvement to meet needs, and decentralization of power generation.
Network form	Centralized and minimal involvement of electrical storage media	Decentralization, and involving electrical storage media for optimization
Service products and markets	Consumers tend to be monotonous and underdeveloped	The products provided in the service can be adjusted to consumer needs so that consumers become diverse.
Quality	Quite difficult to control	Better quality control
Handling disturbances	Disturbance is serviced in a relatively slow time	Accelerate handling and carry out prevention
Optimization	It is quite difficult to scale up and the operation is relatively inefficient.	Asset optimization and operational efficiency can be improved

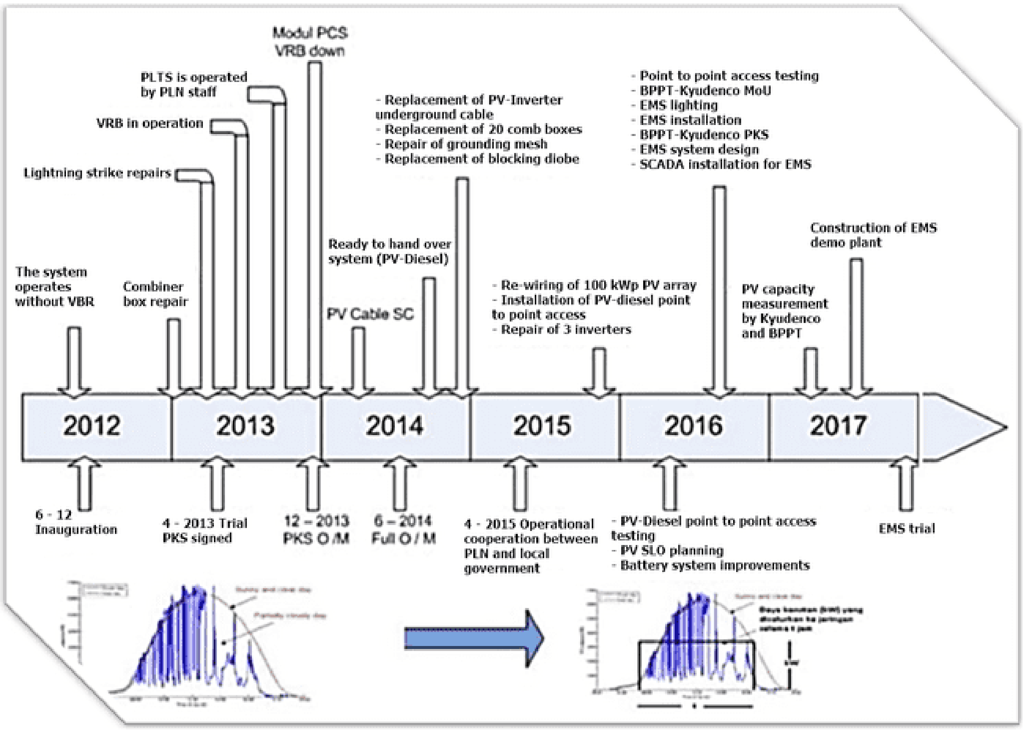

Fig. 2. Capaian smart grid

Fig. 2 displays the progress of a renewable energy project over time. The project seems to be related to a solar power generation system (PLTS) connected to a VRB (Vanadium Redox Battery) type battery storage system. This project ran from 2012 to 2017 and included various installation, repair, testing, and system upgrade activities. In the initial phase in 2012, the project began with the inauguration and operation of the system without using VRB. Staff from PLN operated the solar power plant, and a lightning strike required repairs to the initial system. In 2013, it was seen that the VRB began to operate but experienced several problems, such as damage to the combiner box that required repair. This marked the initial trial phase of the integration between the PLTS system and the VRB. The PKS (Cooperation Agreement) signing for system testing and operational maintenance (O&M) also denoted this phase. This shows coordination between the parties involved in the project, including PLN and the local government.

Entering 2014, the PLTS system with VRB seemed ready to be handed over with the PV-Diesel scheme. This year, repairs to the PV cables and grounding system were also carried out, indicating an evaluation and improvement of the infrastructure to maintain operational stability. 2015, the project underwent further improvements with a 100 kWp PV array rewiring and additional PV-diesel point-to-point access system installations. This phase also included operational cooperation between PLN and the regional government, demonstrating the importance of cross-agency collaboration in operating renewable energy systems. In 2016 and 2017, the project shifted to testing the PV capacity and implementing an energy management system (EMS) integrated with the PLTS. Developing and implementing the EMS and installing SCADA are essential to optimize system performance and real-time monitoring. Finally, in 2017, the EMS system was tested to ensure that the system works according to plan and that the PLTS integrated with VRB can operate effectively and reliably to support energy needs at the project site.

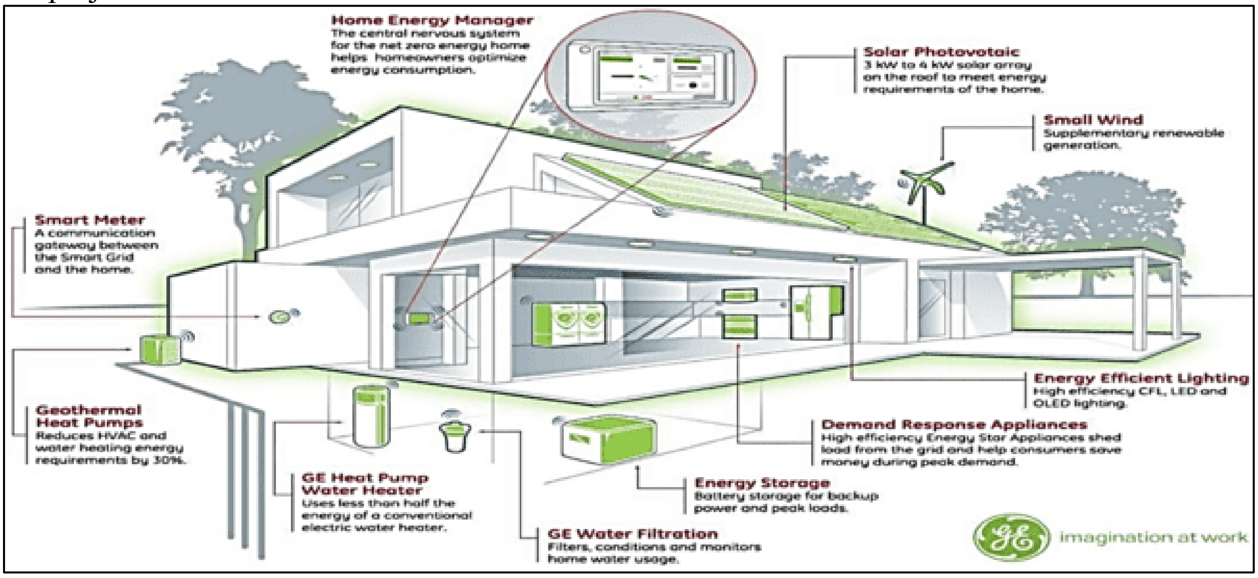

Fig. 3. Smart Grid for House

Fig. 3 above shows a net-zero energy home that utilizes various energy-saving and renewable energy technologies to reduce energy consumption while independently meeting the home's energy needs. At the centre of this system is the Home Energy Manager, which acts as a control centre to optimize energy consumption at home. This system allows homeowners to monitor and manage energy usage efficiently, thereby supporting the achievement of a net-zero energy home. On the roof of the house, there are solar photovoltaic (PV) panels with a capacity of between 3 kW and 4 kW that are used to meet household energy needs. This PV system generates electricity from sunlight, which is the primary energy source for the house. In addition, there is also a tiny wind turbine that functions as an additional renewable energy generator to complement the energy supply from the PV system, especially in locations with good wind potential.

Another technology used in this house is the smart meter, a communication gateway between the house and the smart grid. This intelligent meter allows for more effective energy flow management in and out of the house while allowing homeowners to sell excess energy back to the primary electricity grid. In addition, geothermal heat pumps can reduce energy needs for heating, ventilation, and air conditioning (HVAC) systems and water heaters by up to 30% by utilizing geothermal heat. In addition, this house is equipped with energy storage in the form of an energy storage battery for power reserves and peak consumption needs. In addition, energy-efficient lighting technologies such as CFL, LED, and OLED are installed to reduce energy consumption in the lighting system. These technologies are integrated to create an energy-independent, environmentally friendly, and cost-effective home environment using high-efficiency technology and renewable energy sources.

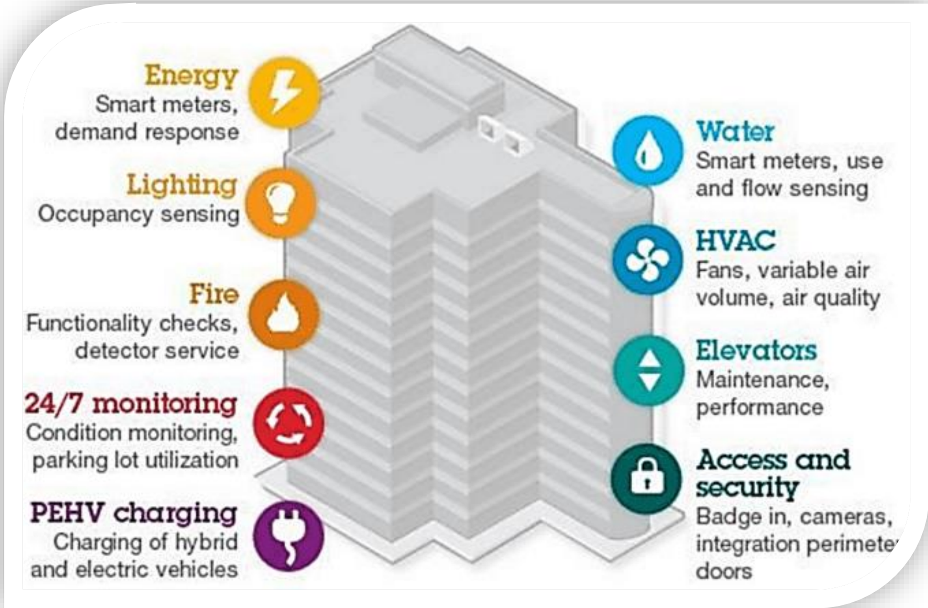

Fig. 4. Smart Grid of Building

Fig. 4 above shows an intelligent building management scheme integrated with various modern technologies to monitor and control several aspects of building operations. The building has intelligent systems for energy, lighting, security, HVAC, and other essential components. Every system in the building is monitored and regulated to optimize energy efficiency, occupant comfort, and safety. The energy system in this building uses smart meters integrated with a demand response system, which allows intelligent management of energy consumption based on current needs. This helps minimize energy use during high demand and maximize overall efficiency. This building can reduce operational costs and environmental impact with suitable energy management.

Furthermore, the lighting system uses occupancy sensing, ensuring that the lights are only on when occupants are in the room. This helps reduce energy waste by ensuring that lighting is used as needed. Smart lighting systems like this are essential for maintaining energy efficiency in large buildings with many spaces that may not always be occupied. The building also has a security and access system, including surveillance cameras, badge access control, and perimeter monitoring. This system ensures that the building is safe for both occupants and visitors. In addition, there is a 24/7 monitoring system that includes monitoring the condition of the building and the use of parking areas. This system allows for better maintenance by detecting problems early before they become more serious. The HVAC (Heating, Ventilation, and Air Conditioning) system is also integrated to monitor air quality, variable air volume, and fan operation to maintain a comfortable environment inside the building. In addition, the building is equipped with an electric vehicle charging facility (PEHV charging), which shows that the building has been designed to support environmentally friendly transportation technology. These features make the building more environmentally friendly, efficient, and comfortable for its occupants.

4. Conclusion

Based on the results of the analysis, it can be concluded that renewable energy technology and intelligent energy management systems are essential in creating efficient, environmentally friendly, energy-independent buildings and infrastructure. First, the concept of microgrids and the integration of renewable energy sources such as solar panels, wind turbines, and battery energy storage, as well as support from SCADA-based energy management and smart grids, enable optimisation of energy consumption while reducing dependence on fossil fuels. This is reflected in the PV and VRB system projects that have been gradually upgraded over several years to achieve better operational efficiency and energy resilience. Second, a net-zero energy house concept shows how energy-saving technologies, such as efficient LED lighting, heat pumps, centralised energy management, and intelligent meters, enable homeowners to control their energy consumption in real-time. With the integration of renewable energy sources such as solar panels and energy storage systems, this house can generate energy while reducing the energy burden from the primary electricity grid. Third, implementing intelligent technology in modern commercial buildings, such as HVAC management systems, sensor-based lighting, and electric vehicle charging facilities, shows that future buildings can be optimized for operational efficiency, safety, and occupant comfort. Real-time monitoring and monitoring technology ensures that building operations are always in optimal condition, minimizing the risk of disruption and supporting a more sustainable lifestyle. Overall, with the increasingly advanced renewable energy technology and the implementation of intelligent energy management on a microgrid scale, homes and commercial buildings can support the transition to a more sustainable and efficient energy system in meeting future energy needs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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