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Integrating Solar Power System and Smart Home: Energy Efficiency and Sustainability Increase a Review Article

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ABSTRACT

The combination of solar energy systems and smart home technologies offers great potential to improve energy efficiency and support sustainable development. It is urgently needed, particularly in Indonesia, where increasing electricity demand presents both challenges and opportunities. This literature review examines how the integration of these technologies can contribute to reducing energy consumption, promoting sustainable lifestyles, and meeting Indonesia's renewable energy targets. Some key components of integration, namely energy management, automation, and system interoperability, were explored in this review. In addition, the review also highlights the benefits, including financial savings, increased energy autonomy, and reduced carbon emissions. It is believed that implementing solar energy systems and smart home technologies will help change into cleaner energy while improving household energy security.

1. Introduction

As a developing country with rapid economic growth, Indonesia, faces major challenges in meeting increasing energy demand while reducing dependence on fossil fuels [1]. To date, most power plants in Indonesia still rely on coal and natural gas, which contribute to high greenhouse gas emissions and have negative environmental impacts [2]. To meet the net zero emission target by 2060, Indonesia needs to accelerate the transition to renewable energy, namely as solar power [3].

Indonesia, located in the equator area, has abundant sunlight throughout the year, so solar energy has great potential in this country [4]. However, despite this potential, solar energy penetration in the residential sector is still relatively low [5]. Integrating solar power systems with smart home technology offers a way to address energy challenges by increasing efficiency and enabling energy independence at the household level [6].

This literature review aims to explore the potential of integrating solar power systems with smart homes in Indonesia, with a focus on its impact on energy efficiency and sustainability. Some key questions that are the focus of this review include:

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- What are the latest technological developments that support the integration between solar power and smart homes?
- What are the main benefits of implementing such integration, especially in the Indonesian context?

By exploring relevant literature, this review aimed to provide insights into how Indonesia can improve solar and smart home technologies to achieve its future energy and sustainability goals. The results of the analysis are expected to serve as a guideline for stakeholders in designing more effective policies and strategies to support the energy transition.

2. Method

This literature review aimed to explore and synthesize existing research on solar and smart home integration, specifically in the Indonesian context. The methodology used in this review is presented as follows.

• Collecting literature published from 2010 to 2024 to capture the latest developments in solar and smart home technologies

The researchers focused on collecting studies relevant to Indonesia, reviewing local case studies, government policies, and market trends. The aim was to identify how these technologies can be effectively integrated to improve energy efficiency and sustainability in Indonesian households.

• Analyzing the collected studies using the qualitative approach

The analysis aimed to identify common themes, challenges, and solutions related to solar and smart home integration in Indonesia. Key factors being considered were technological innovation, economic viability, environmental impact, and social acceptance. This thematic analysis was expected to provide insights into potential future developments and areas for further research.

3. Results and Discussion

3.1. Results

3.1.1. Solar Power System and Smart Home Technology

Solar Power Generation Systems (SPGS) and Photovoltaic (PV) panels convert sunlight into electricity, providing a renewable energy solution that is in line with Indonesia's commitment to reducing carbon emissions [7]. The Indonesian government has set an ambitious target to increase the contribution of renewable energy to 23% in the national energy mix by 2025 [8]. With a population of over 270 million and abundant sunshine throughout the year, the potential for solar energy utilization in Indonesia is enormous [9].

Fig. 1. Solar power system on the roof of the house, with photovoltaic panels and energy monitoring system

However, the adoption rate of SPGS in the residential sector is still low. The main challenges are high initial investment costs, limited public awareness, and inadequate infrastructure [10]. To overcome these issues, the government has introduced various policies, such as feed-in tariffs and net metering schemes, to encourage the adoption of solar energy among the public [11]. In addition, more technology is developed, such as more affordable PV panels and efficient battery storage systems [12].

The concept of smart homes is also increasingly popular in Indonesia, especially in urban areas such as Jakarta, Bandung, and Surabaya, where the adoption rate of digital technology is quite high [13]. Smart home technology combines Internet of Things (IoT) devices to automate and optimize various household functions, such as lighting, air conditioning, and security systems [14]. Smart meters and energy management systems allow homeowners to monitor energy consumption, providing insights that can lead to significant savings [15].

However, there are still challenges in adopting smart homes in Indonesia [16]. In addition to the relatively expensive cost of devices, low awareness of the benefits of smart homes and limited reliable internet infrastructure are major obstacles [17]. In addition, cultural resistance to new technologies can also affect acceptance in society [18]. Therefore, public awareness campaigns and government incentives are needed to increase public understanding of the benefits of smart homes, especially in the context of their integration with solar power systems [19].

3.1.2. Integration between Solar Power and Smart Homes

The integration of solar power plants with smart home technology in Indonesia offers potential benefits that can improve energy efficiency and sustainability [20]. By utilizing solar energy for household needs, homeowners can reduce dependence on the electricity grid, as well as reduce energy costs and carbon footprints [10]. Smart home systems can optimize solar energy use by setting devices to operate during periods of high solar power production and utilizing batteries efficiently [21].

Fig. 2. The interior of a smart home with IoT devices and energy control through application

As these two sectors grow, collaboration between solar energy providers and smart home technology developers is becoming increasingly important [22]. For example, integrating energy management systems with solar cells can help households maximize renewable energy utilization and ensure a stable electricity supply during blackouts or peak demand periods [23].

3.2. Discussion

3.2.1. Key Aspects of Integrating Solar Power Systems and Smart Homes

The integration of solar power systems with smart home technology includes several key factors that are very relevant to Indonesia. In addition to contributing to energy efficiency, this integration can support sustainability and energy security amidst increasing national energy demand [24]. Several key aspects of this integration process include:

3.2.2. Technology Compatibility

The success of the integration of PV and smart home technology is highly dependent on the compatibility between the systems [25]. In Indonesia, technological developments in both sectors are essential to support effective integration. Devices such as smart meters, energy management systems, and Internet of Things (IoT) devices must be able to operate well with solar inverters and battery storage systems [26]. With this compatibility, users can monitor and control household energy consumption efficiently. Standardization of communication protocols is also needed so that devices from different manufacturers can be interconnected and operate together without any obstacles [27].

3.2.3. Framework of Policies and Regulations

Supportive policies and regulations play an important role in accelerating the integration of solar and smart homes in Indonesia [20]. Currently, the government has introduced various policies, such as the Renewable Energy Law and net metering regulations, to encourage the use of renewable energy [28]. However, additional regulatory frameworks are needed to clarify the rules related to the use of solar-based smart home technology. Policies that focus on energy efficiency, such as energy labeling programs and tax incentives for smart devices, can further increase adoption by the community [29].

3.2.4. Economy

Economic feasibility is an important factor for households in Indonesia in considering the integration of solar power systems and smart homes [26]. Although the cost of solar technology is increasingly affordable, the high initial investment costs remain a significant barrier [30]. To overcome this challenge, financing models such as leasing and power purchase agreements (PPAs) can be a solution for consumers. In addition, the financial benefits of reduced electricity bills and government incentives can make this integration more attractive and economically feasible in the long term [31].

3.2.5. Awareness and Education

Raising public awareness about the integration of solar power systems and smart home technology is critical to improving energy efficiency in Indonesia. Many homeowners remain unaware of how smart homes can optimize energy use, underscoring the need for educational campaigns that leverage public media, workshops, and community programs to spread knowledge about this technology. Collaboration with community leaders and influencers can further strengthen outreach efforts, encouraging greater public engagement [32]. The integration of solar photovoltaic systems in smart homes not only provides a reliable source of energy but also increases automation and control over the home environment, thus leading to significant energy savings [33]. Smart systems can reduce daily energy consumption for lighting and air conditioning, demonstrating the tangible benefits of this technology [34]. Then, by leveraging mobile technology, awareness about sustainable living practices can be raised to ultimately promote a more environmentally friendly lifestyle [35] [36].

3.2.6. Local Market Conditions

A comprehensive understanding of local market conditions is critical to the effective implementation of solar and smart home technologies in Indonesia, especially given the varying energy needs of urban and rural areas. In rural areas, where the electricity grid is often unreliable or non-existent, off-grid photovoltaic (PV) systems present a viable solution, demonstrating

competitive levelized energy costs compared to diesel generators and micro-hydro systems [37][38]. Conversely, urban areas may benefit more from grid-connected solutions that improve energy efficiency and reduce electricity costs [39]. The integration of smart home technologies can further optimize energy consumption, but public awareness remains low, demanding education and community engagement initiatives to foster understanding and adoption [40][41]. Sustainable business models and local participation are critical to overcoming barriers to technology adoption, ensuring that these renewable energy solutions are not only implemented but also effectively maintained [40][41].

3.2.7. Climate Resilience

The integration of solar power systems and smart home technologies significantly improves climate resilience in Indonesia, especially in the face of increasing extreme weather changes. Households equipped with these systems can effectively manage energy needs during crises, leveraging battery storage for backup power during blackouts and energy management systems to optimize usage during shortages [42][43]. For example, the SUNPO (Sun Power) device combines solar power generation with a backup system to ensure reliable electricity supply in disaster-stricken areas, facilitating communication and lighting [44]. In addition, advanced technologies such as smart grids and machine learning can predict energy demand and optimize distribution, reducing reliance on centralized grids and increasing resilience to disruptions [45][46]. This multifaceted approach not only ensures energy availability in remote areas but also contributes to a more sustainable and equitable energy landscape, essential for adapting to the impacts of climate change [42][43].

3.2.8. Benefits of Integration

The integration of solar power systems with smart home technology in Indonesia offers significant advantages, especially in improving energy efficiency and achieving cost savings. Smart home systems, such as those using the ESP32 microcontroller, enable real-time monitoring and control of energy consumption, leading to reduced energy use for lighting and air conditioning [34]. Furthermore, the integration of Internet of Things (IoT) technology facilitates intelligent automation, allowing users to optimize energy use and minimize environmental impact through real-time data analysis [36]. Furthermore, advanced energy management strategies can enhance photovoltaic (PV) self-consumption by rescheduling equipment to operate during peak solar power generation, resulting in substantial reductions in electricity costs and grid dependency [47]. Overall, these innovations not only promote sustainable living but also contribute to broader social and environmental goals in Indonesia [48 [49].

3.2.9. Improved Energy Efficiency

One of the most prominent benefits of this integration is increased energy efficiency [6]. By using solar power for household needs, dependence on electricity from the main grid can be significantly reduced [50]. Smart home technologies, such as Internet of Things (IoT)-based energy management systems, allow real-time energy consumption monitoring and adjusting usage as needed [51] [52] [53]. This is especially relevant in Indonesia, where electricity demand continues to increase every year. The increase in energy efficiency not only reduces the burden on the national electricity grid, but also helps prevent the risk of blackouts [54].

The integration of solar power with smart home technology significantly improves energy efficiency, especially in areas such as Indonesia where electricity demand is increasing. By using IoT-based energy management systems, homeowners can monitor and adjust their energy consumption in real-time, thereby reducing dependence on the main grid and reducing the risk of blackouts [36] [47]. For example, a system using the ESP32 microcontroller allows for lighting and temperature control, leading to substantial energy savings, such as reducing daily lighting consumption from 0.17 kWh to 0.12 kWh [36]. In addition, predictive algorithms can optimize energy distribution by

anticipating fluctuations in solar power generation, further increasing efficiency and allowing users to sell surplus energy back to the grid [47]. This convergence of solar energy and smart technologies not only promotes sustainability but also fosters a resilient energy infrastructure that is able to adapt to a variety of household needs [55][56][57].

3.2.10. Cost Efficiency

In addition to increased efficiency, the integration of solar power and smart homes also provides benefits in the form of cost savings [53]. Amid rising electricity rates in various urban areas in Indonesia, the use of solar energy allows for significant reductions in monthly electricity bills [58]. Smart home systems can further optimize energy use by automating equipment to operate during peak solar power production hours, maximizing the use of renewable energy [59]. In addition, the Indonesian government has introduced various incentives, such as tax breaks and subsidies for renewable energy installations, to increase the economic feasibility of implementing this technology [60].

3.2.11. Environmental Sustainability

Indonesia faces several environmental challenges, including deforestation and air pollution due to high consumption of fossil fuels. Integrating solar power and smart home technology can help reduce greenhouse gas emissions by reducing the use of fossil fuels [61]. By promoting renewable energy, households are supporting the efforts to achieve carbon neutrality and preserve the environment [1] [62]. This step is in line with global initiatives to combat climate change and strengthen Indonesia's position as a leader in sustainable development in the ASEAN region.

3.2.12. Energy Independence

Integrating solar power with smart homes has the potential to increase energy independence for households in Indonesia, especially in rural and remote areas [63]. By producing their own electricity, families can reduce their dependence on the main electrical grid, which is vulnerable to energy price fluctuations and supply disruptions [64]. This energy independence is especially important for communities with limited access to electricity, allowing households to maintain a stable supply for basic needs such as lighting and communications [65].

4. Conclusions

The integration of solar power systems and smart home technologies provide a significant opportunity for Indonesia to improve energy efficiency, promote sustainability, and enhance the quality of life for its people. As the country grapples with rising energy demand, environmental issues, and economic challenges, this integration aligns with Indonesia’s national goals to increase the use of renewable energy and sustainable development. The integration of solar power systems and smart homes has the potential to transform Indonesia’s energy landscape, contributing to a more sustainable, resilient, and prosperous future for all its people. The use of these technologies will be critical in addressing the pressing challenges posed by climate change and energy insecurity.

Conflict of interest

The authors declare no conflict of interest.

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