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Solar-Assisted IoT-Based Smart Home for Energy Efficiency and Hazard Prevention Toward Sustainable Living

Rahmawati Fitriyan, Syafii*
Department of Electrical Engineering, Faculty of Engineering, Universitas Andalas, Padang, Indonesia
*Corresponding author, e-mail: syafii@eng.unand.ac.id

Abstract—This study presents the development of a solar-assisted smart home system based on the Internet of Things (IoT) that focuses on energy efficiency and hazard prevention as a contribution to sustainable living. The proposed system integrates renewable energy utilization with intelligent monitoring to reduce energy consumption and minimize carbon footprint. A Raspberry Pi microcontroller is employed as the central platform to coordinate multiple sensors, including a DHT11 sensor for temperature and humidity measurement, a gas sensor for leak detection, a vibration sensor for earthquake monitoring, and a PZEM-004T module for real-time energy consumption tracking. The system enables remote supervision and automated responses to environmental hazards while maintaining comfort and security for occupants. Experimental results demonstrate that the prototype enhances early warning capability for potential fire incidents and natural disasters, while significantly improving energy awareness through continuous monitoring. The integration of solar energy further supports the sustainability aspect, making the system a viable smart solution for greener and safer residential environments.

Keywords: Smart home, IoT-Based, Security features, Solar energy, Sustainable

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1. Introduction

The rapid growth of urbanization and global energy demand has accelerated the need for smart and sustainable residential solutions. Conventional households still rely heavily on grid electricity and passive safety systems, which are often inefficient and unable to respond proactively to environmental hazards. At the same time, the integration of renewable energy into smart homes has become a strategic pathway to support long-term carbon reduction goals and enhance energy resilience [1]. Internet of Things (IoT) technologies offer a promising platform for enabling intelligent monitoring, real-time decision-making, and automation within the modern home environment. By combining renewable energy sources, particularly solar energy, with IoT-based sensing and control mechanisms, a sustainable smart home ecosystem can be achieved one that not only improves energy efficiency but also enhances safety and comfort for residents [2]. Moreover, smart home technology plays a crucial role in supporting health and well-being, particularly for the elderly population, by providing health monitoring systems that can reduce care costs and improve quality of life [3], [4]. By leveraging this technology, communities can lower their carbon footprint through more efficient energy use and reduce dependence on non-renewable resources, which is part of the global agenda for achieving sustainability In this context, smart homes serve not only as tools for comfort but also as key drivers in achieving broader sustainable development goals [5].

The integration of smart home technologies with renewable energy systems, such as solar photovoltaics, has become increasingly important to lessen reliance on fossil fuels and promote environmental sustainability. Smart homes equipped with advanced energy management systems are capable of optimizing energy use and utilizing power generated from renewable sources, thereby lowering both electricity expenses and carbon emissions [6], [7]. Studies have shown that incorporating energy management systems in smart homes can lead to significant energy savings, with

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potential reductions in total energy consumption reaching up to 60% when combined with renewable energy technologies [6]. Moreover, the integration of Internet of Things (IoT) technologies allows smart homes to monitor and control energy usage in real time, improving the utilization of renewable energy and enhancing system efficiency [8], [9]. Consequently, linking smart homes to renewable energy production not only helps minimize carbon footprints but also facilitates the shift toward sustainable and energy-independent systems [10], [11].

With the advancement of Internet of Things (IoT) technology, smart homes are able to integrate multiple security components such as surveillance cameras, motion detectors, and fire alarm systems, all of which can be remotely accessed and controlled through smartphone applications [12]. This integration not only enhances user convenience but also improves safety by providing homeowners with instant alerts in the event of suspicious movements or hazardous situations like fire outbreaks [13]. Studies show that incorporating intelligent security systems into smart homes can significantly reduce burglary risks and enhance emergency responses to fire incidents through early detection and warnings [14]. Additionally, smart homes contribute to disaster preparedness by employing sensors capable of detecting seismic activity and issuing early alerts to occupants during earthquakes [15]. In critical situations, these automated systems can cut off gas lines and disable electrical appliances to minimize the risk of secondary fires [16]. Thus, embedding comprehensive security and safety technologies within smart homes not only strengthens protection against criminal and environmental threats but also improves household resilience and comfort for residents [16], [17].

The growing popularity of smart home technology equipped with Node Control Units (NCU) stems from its ability to seamlessly integrate, monitor, and control household devices, providing greater convenience, efficiency, and security for users [18]. Furthermore, this system is often more affordable and easier to implement compared to Raspberry Pi-based solutions, which frequently require deeper technical knowledge and incur higher costs for hardware and software [19]. Consequently, many developers and users prefer Node NCU as the primary solution for building efficient and effective smart home systems. On the other hand, although Raspberry Pi offers greater flexibility and advanced programming capabilities, its relatively high price remains a significant barrier to its adoption as a primary platform for smart homes [20]. Therefore, while Raspberry Pi possesses substantial potential for smart home development, Node NCU continues to be a more common choice among users prioritizing ease of use and lower costs [21].

This study examines the design and implementation of a smart home monitoring system based on the Internet of Things (IoT) using Raspberry Pi, with a focus on strengthening security functions and integrating solar power. By utilizing the flexible and powerful features of Raspberry Pi, the proposed system seeks to deliver an effective and energy-efficient monitoring solution that supports sustainability through the use of renewable energy. This innovative concept responds to the increasing need for intelligent home technologies while highlighting the critical roles of safety and energy efficiency in developing a more secure and eco-friendly living environment.

2. Method

In this research, the development of an IoT-based smart home monitoring system with advanced security features powered by solar energy begins with the design of both hardware and software components. Through the integration of planned security functions and the utilization of solar energy, the proposed system is expected to enhance protection against theft, fire, and earthquake hazards while promoting sustainable energy use. The methodology applied in the design and development of the hardware and software components for this IoT-based smart home monitoring system is described in detail as follows.

2.1 Circuit Design of Smart Home

The smart home monitoring system integrates renewable energy management with a safety and security platform through an IoT-based architecture. Solar energy captured by the photovoltaic (PV) panel is directed to the DC bus and then managed by a hybrid inverter, which converts it into AC power for household loads. The block diagram of an IoT-based solar-assisted smart home system

design is illustrated in Figure 1. The main components used are Raspberry Pi, hybrid inverters, solar panels and sensors. The sensors consist of vibration sensors, KY-026 fire sensors, gas sensors, and PZEM-004T. Data from various sensors is managed through a database and sent to the web monitoring system that has been created to monitor home conditions efficiently and in real time. The output of each sensor can be used to activate the relay and buzzer and read the electrical energy usage.

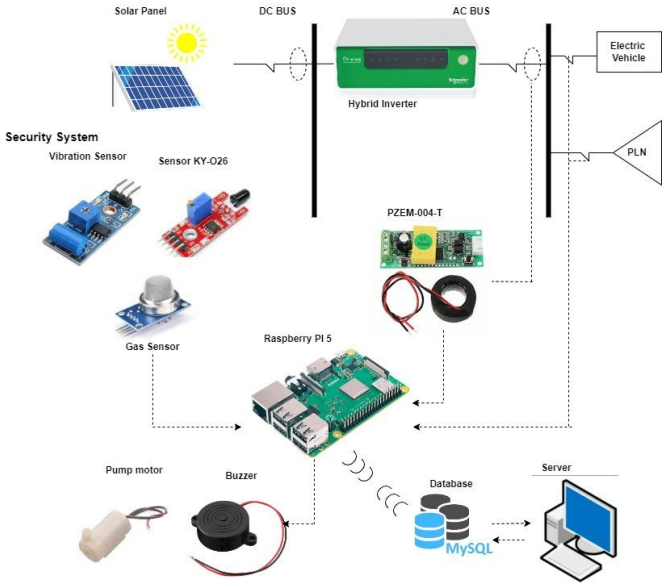


Figure 1. Block diagram of smart home monitoring system

The Raspberry Pi 5 serves as the central controller for the monitoring and security subsystem. It collects data from various environmental and safety sensors, including a gas sensor for leak detection, a KY-026 flame sensor for early fire identification, and a vibration sensor for potential intrusion detection. Upon detecting anomalies, the Raspberry Pi can activate alert mechanisms such as a buzzer or trigger a pump motor for emergency action. All captured sensor data and energy consumption information are transmitted to a MySQL database on a remote server, where they can be visualized and analyzed through a monitoring dashboard. This combination of real-time sensing, automated response, and digital record-keeping makes the system both proactive and highly effective in enhancing home safety and energy awareness.

2.2 Layout of Hardware System Designed

The Figure 2 illustrates the physical placement of the key sensing and actuation components inside a smart home environment. Each sensor is strategically installed in a location that corresponds to its detection function. The fire sensor is mounted at the upper section of the house structure near the roof area, where rising heat and smoke would accumulate first in the event of a fire, ensuring early detection. The gas sensor is positioned at a mid-level location indoors to detect the presence of hazardous gases such as LPG or carbon monoxide, which typically disperse horizontally depending on their density. To enhance emergency mitigation, a pump motor is also installed in proximity to the fire or gas detection zone, which can be activated to provide a response such as water spraying or exhaust ventilation depending on system configuration.

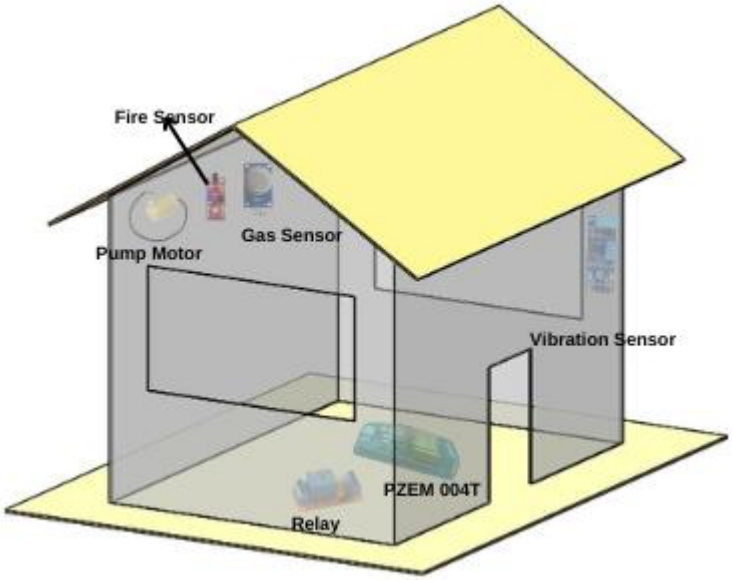


Figure 2. Smart home monitoring system designed

The lower part of the structure houses the PZEM-004T energy meter, which is placed near the main electrical distribution line to measure household voltage, current, and power consumption accurately. A relay module is located adjacent to it, enabling the system to control electrical loads or activate safety mechanisms when necessary. Meanwhile, the vibration sensor is installed near the entrance or wall area where physical disturbances or forced entry attempts are most likely to occur. This layout ensures comprehensive monitoring coverage for both environmental hazards and intrusion detection, and all components work together under coordination of the central IoT controller located externally (Raspberry Pi). The spatial distribution reflected in the figure demonstrates how smart home safety, energy monitoring, and automated actuation are integrated into a single cohesive system.

3. Result and Discussion

Once the overall system development is completed, the subsequent stage involves testing and analyzing the performance of the developed prototype. This evaluation aims to verify that all system components operate correctly in accordance with the predetermined design specifications. The collected measurement data is transmitted to a database and displayed in real time via a web interface. Reliable internet connectivity plays a crucial role in ensuring smooth data transmission throughout this process. The monitoring system testing is conducted through both software and hardware evaluations, using an input voltage of 3.3 V. Specifically, voltage testing is performed on the KY-026 sensor to determine fire detection capability, where the output triggers the relay to activate the pump motor. The test involves exposing the sensor to fire and recording the voltage level at the digital output. The resulting measurements are presented in Table 1.

Table 1. Voltage Measurement Results for the KY-026 sensor and Pump

No	Sensor	Circumstances	Voltage (V)
1.	KY-026 Sensor	Fire Not Detected	0
		Fire Detected	3.142
2.	Pump	OFF	0
		ON	3.2

Table 1 presents the voltage measurement results obtained from the KY-026 sensor along with the corresponding pump operating status. When the KY-026 sensor detects the presence of fire, the recorded voltage reaches 3.142 V, activating the pump. In contrast, when no fire is detected, the voltage reading drops to 0 V, and the pump remains off. The MQ-2 sensor functions as a smoke and gas detector capable of identifying the presence of combustible gases. In this test, the emphasis is placed on analyzing the output response. The results indicate that when gas is detected, the MQ-2 sensor triggers the buzzer alarm. Furthermore, testing of the vibration sensor designed for earthquake detection also produces a buzzer output upon sensing vibrations. The detailed measurement outcomes are summarized in Table 2.

Table 2. Voltage Measurement Results for the Gas sensor and Buzzer

No	Sensor	Circumstances	Voltage (V)
1.	Gas Sensor	Gas Not Detected	0
		Gas Detected	3.1
2.	Buzzer1	OFF	0
		ON	3.2
3.	Vibration Sensor	Earthquake Not Detected	0
		Earthquake Detected	3.274
4.	Buzzer2	OFF	0
		ON	3.2

Table 2 presents the voltage measurement results for the gas sensor with buzzer output 1 and the vibration sensor with buzzer output 2. When the gas sensor detects the presence of gas, the measured voltage is 0 V, causing the buzzer to activate. Conversely, when no gas is detected, the measured voltage rises to 3.1 V, and the buzzer remains off. Similarly, when the vibration sensor identifies seismic activity, the recorded voltage is 0 V, activating the buzzer, while in the absence of vibration, the sensor output voltage is 3.274 V and the buzzer stays off. The accuracy testing and calibration of the PZEM-004T sensor were conducted using a standard Fluke digital multimeter, with the results summarized in Table 3.

Table 3. PZEM 004T Sensor Accuracy

Component	Sensor	Multimeters	Difference	Average
PZEM AC Volt (PZEM Sensor)	222.9	223.1	0.2	0.167
	223.0	222.9	0.1	
	222.8	223	0.2	
PZEM AC Current (PZEM Sensor)	0.423	0.4	0.023	0.028
	0.422	0.39	0.039	
	0.424	0.4	0.024	
PZEM AC Power (PZEM Sensor)	94.0	93.9	0.1	0.2
	93.8	94.1	0.3	
	94.1	94.3	0.2	

Table 3 is the accuracy of the PZEM 004T sensor on solar panels using a hybrid inverter. Where this hybrid inverter has two energy sources, namely PLN as utility grid and PV system. When this hybrid inverter is used, the main source used to take energy is from the PLN grid electricity network. Two test conditions were carried out, namely first, switching from PV to PLN, and second, switching from PLN grid to PV. The results of reading voltage during transition process can be seen in Figure 3.

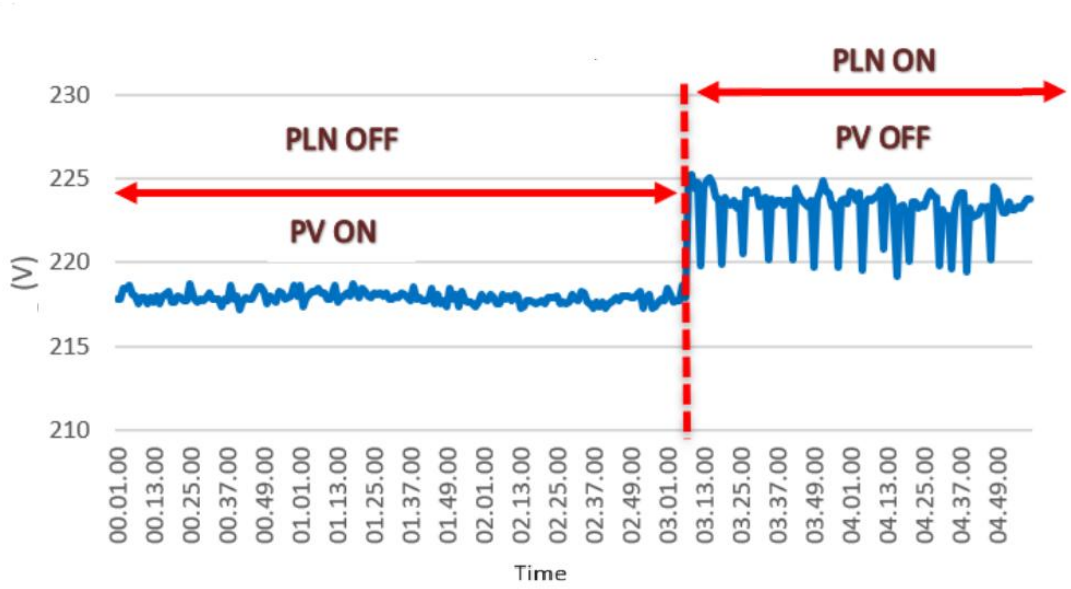


Figure 3. The transition process from PV to PLN grid.

Based on Figure 3, the transition process from PV to utility grid shown in the graph illustrates how the hybrid system switches its power source based on availability and operating conditions. During the initial period, the load is supplied entirely by the PV system, resulting in a relatively stable voltage profile of around 220 V with minimal fluctuations. This indicates that the solar inverter is able to maintain a consistent output while operating in standalone mode. At the point marked by the dashed vertical red line, the system begins switching from PV to the PLN grid, which occurs when the solar generation becomes insufficient or when the system logic prioritizes the grid supply. After the transition, the power supply is taken over by PLN, and the voltage level increases slightly to the range of approximately 225–230 V. The post-transition waveform also shows more noticeable fluctuations, reflecting the inherent variability in public grid conditions compared to the smoother output of the PV inverter. Overall, this graph demonstrates a smooth and uninterrupted power handover between the two sources, confirming the reliability of the hybrid control mechanism in maintaining supply continuity.

The Figure 4 shows the real-time monitoring dashboard of the Solar-Assisted IoT-Based Smart Home System, which integrates energy management with hazard prevention to support sustainable and safe living. The left side of the interface displays environmental and safety-related parameters, including fire detection status, temperature, humidity, and gas concentration. These readings are continuously captured by sensors and transmitted to the IoT gateway, allowing early detection of hazardous conditions such as fire outbreaks, gas leaks, or abnormal vibrations that may indicate attempted intrusion. The status indicator provides immediate visual alerts, enabling users to take preventive action before damage occurs.

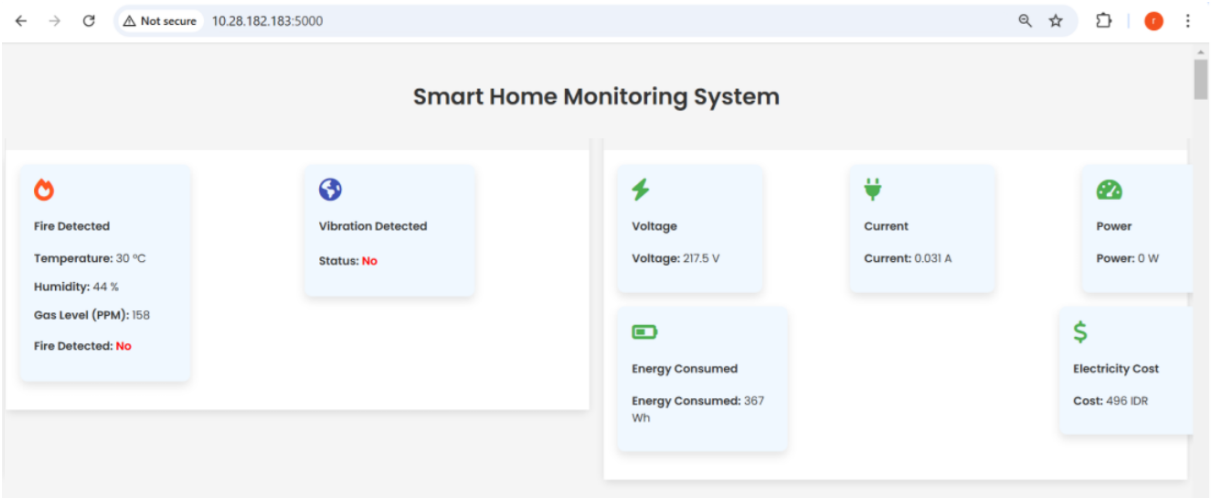


Figure 4. Web-based smart home display

On the right side, the dashboard provides information related to household energy usage. The system displays voltage, current, and instantaneous power consumption obtained from the PZEM-004T energy meter. It also calculates accumulated energy consumption in watt-hours (Wh), and converts it into electricity cost to help users track their usage in economic terms. Since the home is supported by a solar-assisted power supply, this monitoring helps identify when energy is being drawn from renewable sources versus the public grid, encouraging more efficient utilization of solar energy. By combining energy transparency with real-time hazard detection, the system not only improves household safety but also promotes energy-saving behavior, making it an effective solution for sustainable and smart living.

4. Conclusion

The results of this study show that the IoT-based smart home system effectively enhances both safety and energy oversight by enabling continuous real-time monitoring. The performance evaluation of the KY-026 fire sensor, MQ-2 gas sensor, and vibration sensor confirmed their sensitivity and reliability in detecting environmental hazards, while voltage and signal readings validated their accurate responsiveness to abnormal conditions. In parallel, the PZEM-004T sensor demonstrated a high level of accuracy in tracking energy consumption, especially when integrated with solar-based supply systems, allowing a clear comparison between PLN and PV performance. The seamless visualization of all sensor outputs through the web dashboard ensures that users can easily access critical information regarding fire risks, gas leaks, vibration activity, and electricity usage. Overall, the combined hardware-software implementation successfully delivers a comprehensive solution for home safety and renewable energy monitoring, illustrating strong potential for extended deployment within smart and sustainable residential environments.

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