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IoT-Integrated Home Energy Management System with Real-Time Monitoring and Solar Panel Optimization

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Abstract: In this study, an IoT-integrated Home Energy Management System (HEMS) was developed using solar panels as the primary energy source. The system employs an ESP32 microcontroller as the core controller, equipped with DHT22, LDR, and INA219 sensors to monitor temperature, humidity, light intensity, voltage, and current. Real-time sensor data is presented on a web interface, allowing users to monitor system status and control devices like fans and lights either manually or automatically. The system demonstrated stable performance with a control response time of under one second and effective energy management aligned with environmental conditions. However, a key limitation was the limited capacity of the 10 Wp solar panel, particularly during low sunlight periods. To address this, enhancements such as improved load management or increased solar panel capacity are recommended. The system successfully implemented real-time monitoring and automated control, activating the fan at temperatures above 30 degrees Celsius and turning on lights when light intensity is below 1000 lux. This research highlights the potential of IoT technology in achieving efficient and sustainable home energy management.

Keywords: Solar Cell, Internet Of Things, System Control, INA219

1. Introduction

Access to reliable electricity is a significant challenge in many regions of Indonesia, with 236 areas still lacking 24-hour electricity access as of the end of 2022. The Indonesian government has taken steps to address this issue by expanding the electrical grid and increasing power generation capacity. The Ministry of Energy and Mineral Resources set a target to achieve 100% national electrification by 2023, up from 99.63% in 2022, with approximately 318,000 households still lacking electricity access. Despite efforts to expand conventional power sources, Indonesia’s energy infrastructure is heavily reliant on non-renewable, environmentally damaging sources, particularly coal, which dominates the energy mix. The reliance on fossil fuels presents significant challenges for long-term sustainability, as these resources are finite.

Solar power, however, offers a promising alternative. Indonesia, located near the equator, has substantial solar energy potential, yet only 1% of its electricity generation comes from solar power, and current utilization is limited to a mere 0.01% of its total potential [1]. With the rising global demand for clean and renewable energy, expanding the role of solar power in Indonesia's energy mix is essential. Given this context, leveraging innovative technologies, such as the

Internet of Things (IoT), for energy management can play a pivotal role in optimizing solar energy usage and reducing dependence on conventional power sources.

The IoT is a transformative technology that connects physical devices to the internet, allowing real-time monitoring [2], data collection, and automated control over various systems. In the context of home energy management, IoT systems can optimize energy use by monitoring environmental parameters and controlling devices based on real-time data. Sensors such as temperature, light intensity, and current sensors can provide continuous data, enabling more efficient energy usage [3]. IoT systems can also enhance the management of solar power systems by ensuring that devices such as fans and lights are operated based on energy availability, thereby improving energy efficiency and reducing waste.

This study explores the development of an IoT-based Home Energy Management System utilizing solar panels as the primary energy source. The system integrates ESP32 microcontrollers [4], DHT22 sensors for monitoring temperature and humidity [5], LDR sensors for light intensity detection [6], and INA219 sensors [7] for voltage and current measurement. By employing these sensors, the system can manage household energy use efficiently, monitor energy production from solar panels, and enable users to control household appliances remotely via a web interface.

The potential of IoT technology in home energy management systems lies in its ability to provide real-time monitoring, automated control, and energy optimization, leading to more sustainable energy practices. However, challenges such as limited solar panel capacity, particularly during low-light conditions, need to be addressed. This research aims to design and implement a system that not only monitors but also optimizes solar energy usage, demonstrating the feasibility of using IoT technology to create smarter, more sustainable homes and contribute to a greener energy future in Indonesia.

2. Materials and Methods

2.1 Material

The Home Energy Management System (HEMS) developed in this study utilizes various components, each selected to optimize the monitoring and control of energy consumption in a household. The core of the system is the ESP32 microcontroller, chosen for its robust performance, versatility, and integrated Wi-Fi capabilities. This microcontroller serves as the central processing unit, handling data from multiple sensors and controlling connected devices [8]. The ESP32 provides a flexible platform for integrating the sensors and developing the real-time monitoring and control features required [9] for the system's functionality.

For environmental monitoring, the DHT22 sensor is used to measure temperature and humidity. This sensor is highly accurate, providing digital output with a resolution of 0.1°C for temperature and 0.1% for humidity [9], making it suitable for real-time monitoring in the energy management system. The DHT22's stability and resistance to interference make it a reliable choice for maintaining accurate readings over long periods, which is essential for adjusting the system's responses to changing environmental conditions such as temperature and humidity.

To measure light intensity, the Light Dependent Resistor (LDR) is employed. The LDR's resistance decreases with an increase in light intensity, making it an effective tool for monitoring ambient light levels. This sensor's photoconductive properties are utilized to track the amount of sunlight entering a room [10][11], allowing the system to control lighting devices by turning them on or off based on predefined light intensity thresholds. The LDR's cost-effectiveness and simple implementation make it an ideal choice for this application.

The INA219 sensor is utilized to measure the voltage, current, and power consumption of the electrical devices within the home. This sensor can provide accurate readings of the energy consumption, allowing the system to manage energy flow efficiently. The INA219 uses a high-precision shunt resistor to measure current, and its integration with the ESP32 microcontroller ensures seamless communication for real-time energy monitoring. This sensor is essential for determining the energy usage of devices and for optimizing load management within the system [12].

Finally, the system's main energy source is a solar panel. In this study, a 10 Wp solar panel is used to provide renewable energy for the system. The solar panel is connected to a battery, and its performance is closely monitored to ensure that sufficient power is available for operating the system's devices. Although the 10 Wp panel is effective for low energy consumption scenarios, its limited capacity during low sunlight conditions necessitates further optimization, including improved load management or the potential addition of additional panels. This combination of components ensures that the HEMS can efficiently manage energy consumption while leveraging renewable energy sources.

2.2 Method

The development of the IoT-integrated Home Energy Management System (HEMS) was carried out through a systematic approach encompassing hardware design, sensor integration, energy management algorithms, and real-time data visualization (Figure. 1). This section outlines the methodology adopted for the system's design and implementation, covering the various steps from hardware configuration to data processing and system optimization.

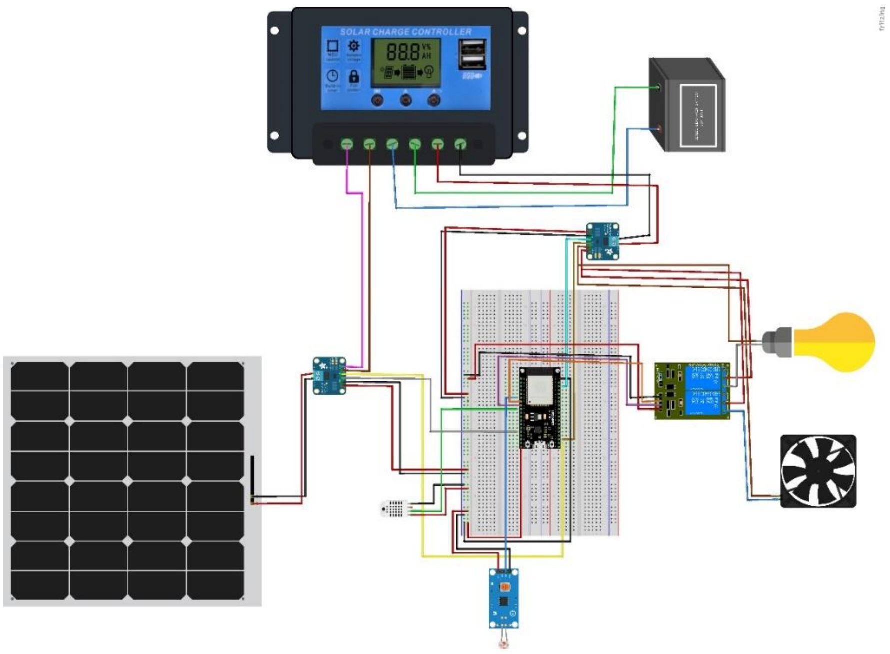


Figure 1. Systematic Apporach

The core of the system is the ESP32 microcontroller, which serves as the main processing unit responsible for collecting and processing data from various sensors. The sensors integrated into the system include the DHT22, which measures temperature and humidity, the LDR (Light Dependent Resistor), which detects light intensity, and the INA219, which monitors voltage and current. These sensors provide essential data that is used to assess environmental conditions and energy consumption within the home. The collected data is then processed and analyzed using rule-based methods, which help in making automated decisions, such as controlling fans and lights based on pre-defined thresholds for temperature, humidity, and light intensity.

To enable real-time monitoring and control, the system was designed with a web-based interface. The data gathered from the sensors is displayed on the web interface, allowing users to track the status of the system, including environmental parameters and energy usage. The interface provides graphical representations of sensor data, including temperature, humidity, light intensity, and the amount of energy generated and consumed. Additionally, users have the option to manually control devices such as fans and lights or set them to operate automatically based on sensor readings. This functionality is achieved through the integration of the ESP32 with the web platform, which processes the sensor data and sends control signals to connected devices.

Energy management within the system is based on monitoring both the energy generated by the solar panel and the energy consumed by the connected devices. The energy generated by the solar panel is calculated using the formula

Input : $\mathbf{Z_1} = \sum \mathbf{y} \leq \mathbf{3200}$

The formula is the total energy produced by the solar panel in watt-hours. Here, y is the energy produced by the solar panel at each specific time period. This formula states that the total energy produced by the $\mathbf{Z_1}$ *solar panel is the sum of the energy y, whose maximum limit is 3200 mAh. This indicates the maximum capacity that the solar panel can produce under certain conditions.*

Output: $\mathbf{Z_2} = \mathbf{x_1} + \mathbf{x_2} + \mathbf{x_3} + \mathbf{x_4}$

The above formula is the total energy used by various devices or loads connected to the system. Here, $\mathbf{x_1}$ *to* $\mathbf{x_4}$ *each represent the energy used by various devices in the system. The sum of energy used by all devices is the total of* $\mathbf{x_1} + \mathbf{x_2} + \mathbf{x_3} + \mathbf{x_4}$.

$$\mathbf{Z} = \mathbf{Z_1} + \mathbf{Z_2}$$

This formula is the total energy in the system, which is the sum of the total energy generated by the solar panels $\mathbf{Z_1}$ *and the total energy used by the devices* $\mathbf{Z_2}$ *. In other words, Z describes the balance between the energy produced and the energy consumed in the system, which gives an idea of the availability and use of energy in the system as a whole.*

Where:

z = Battery
y = Solar Panel
x = Load Out
$\mathbf{x_1}$ = **Fan**
$\mathbf{x_2}$ = **Lamp**
$\mathbf{x_3}$ = **Current and voltage sensors INA219**
$\mathbf{x_4}$ = **Temperature and humidity sensor** *DHT22*

3. Results and Discussion

The IoT-integrated Home Energy Management System (HEMS) demonstrated effective real-time monitoring and control of home energy consumption using solar panels as the primary energy source. The system was able to maintain stable performance with a response time of under one second for control actions, such as turning on fans or lights based on sensor inputs. This quick response time is crucial for achieving efficient energy management, as it allows the system to adjust to changing environmental conditions without delay, ensuring optimal use of the available energy.

One of the key findings of this study was the ability of the system to monitor environmental conditions and control devices based on preset rules. The use of the DHT22 sensor allowed for accurate monitoring of temperature and humidity, while the LDR sensor efficiently detected light intensity levels. The INA219 sensor provided valuable data on the voltage and current used by the connected devices, allowing the system to effectively manage energy consumption. Based on these inputs, the system was able to make automated decisions, such as activating the fan when the temperature exceeded 30°C and turning on the lights when light intensity dropped below 1000 lux. These decisions were crucial for reducing energy wastage, as devices were only activated when necessary.

Despite the system's efficient operation, a significant limitation was identified with the solar panel's energy generation capacity. The 10 Wp solar panel was found to have limited output during periods of low sunlight, which impacted the overall energy supply. This limitation is particularly important for areas with inconsistent sunlight, as the panel's output was insufficient to meet the system's demands during cloudy or rainy weather. Therefore, recommendations for future work include increasing the capacity of the solar panel or incorporating a hybrid energy system that can combine solar power with other renewable energy sources, such as wind or grid power, to ensure a more reliable and continuous energy supply.

Another noteworthy aspect of this study was the implementation of real-time data visualization through a web interface. The user-friendly web platform allowed users to remotely monitor and control the system, providing a convenient and intuitive way to track energy consumption and make adjustments as needed. The integration of IoT technology into the system also facilitated easy access to real-time data, making it possible for users to optimize their energy usage efficiently. Additionally, the system's ability to display data on a web interface made it easier for users to assess energy consumption trends, identify areas of improvement, and take necessary actions to reduce overall energy use.

By leveraging real-time monitoring and automated control, the system demonstrated the potential of IoT technology in optimizing energy usage and reducing reliance on conventional energy sources. Although the limitations related to solar panel capacity during low sunlight periods were noted, the system offers a valuable framework for future research and development in the field of smart home energy management. Future improvements may include enhanced load management strategies, increased solar panel capacity, and the integration of additional renewable energy sources to further increase the system efficiency and sustainability.

The implementation of the IoT-integrated Home Energy Management System (HEMS) demonstrated that a 10 Wp solar panel can generate an average of 40 Wh per day under clear weather conditions, providing sufficient energy to power the system's IoT devices and connected loads such as fans and lights. The use of the INA219 sensor enabled accurate real-time monitoring of battery voltage and current, ensuring efficient energy storage. The integration of the LDR and DHT22 sensors allowed for automatic control of the lights and fan based on light intensity and temperature, respectively. The system successfully activated the fan when the temperature reached or exceeded 30°C, and turned off the fan when the temperature dropped below 29°C. Similarly, the lights were automatically turned on at light levels above 3000 lux and off when the light intensity dropped below 1000 lux. The web-based IoT platform provided real-time monitoring and manual control of the devices, offering users an intuitive interface to manage their home energy consumption.

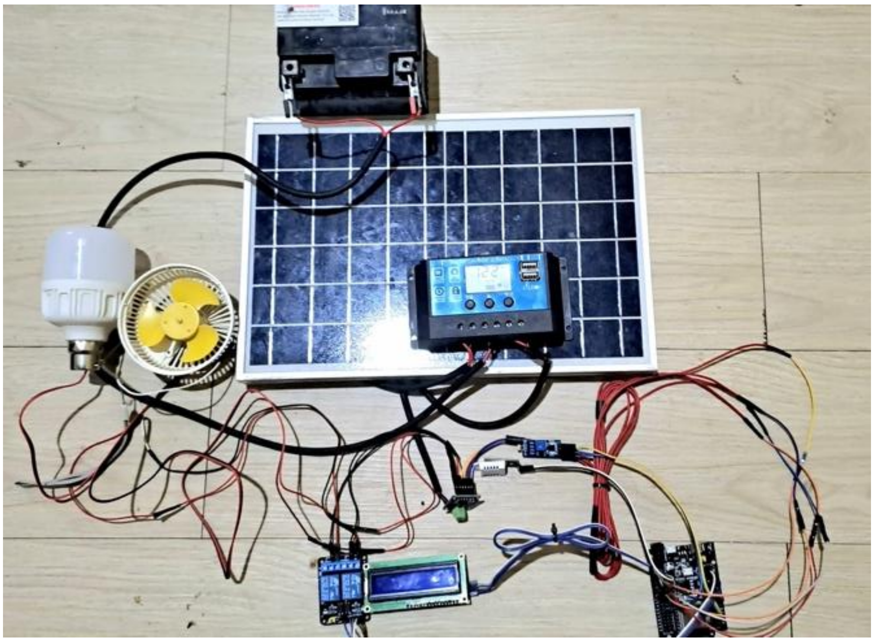
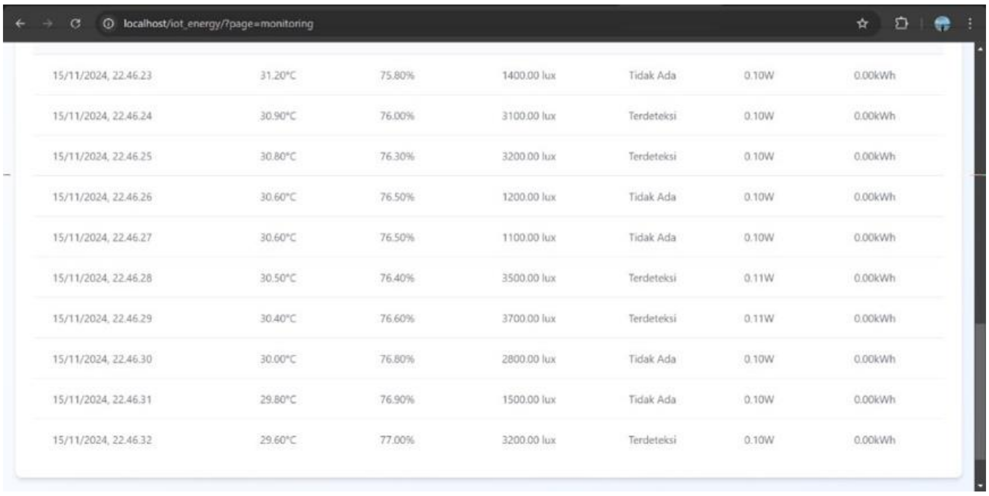


Figure 2. System Implementation

However, the system's performance was limited by the solar panel's energy generation capacity, particularly during periods of low sunlight, which resulted in insufficient power for continuous operation. To address this issue, future improvements could include more efficient load management strategies or the addition of extra solar panels to increase the system's energy capacity. The testing phase showed that the system's real-time monitoring feature, with data updates every 5 seconds, functioned reliably without significant delays or issues. This consistent data display on the web interface allowed users to effectively monitor battery status, energy consumption, and environmental conditions, ensuring that the system operated efficiently and within its energy limits.

Figure 3. Dashbord Website Monitoring



15/11/2024, 22.46.23	31.20°C	75.80%	1400.00 lux	Tidak Ada	0.10W	0.00kWh
15/11/2024, 22.46.24	30.90°C	76.00%	3100.00 lux	Terdeteksi	0.10W	0.00kWh
15/11/2024, 22.46.25	30.80°C	76.30%	3200.00 lux	Terdeteksi	0.10W	0.00kWh
15/11/2024, 22.46.26	30.60°C	76.50%	1200.00 lux	Tidak Ada	0.10W	0.00kWh
15/11/2024, 22.46.27	30.60°C	76.50%	1100.00 lux	Tidak Ada	0.10W	0.00kWh
15/11/2024, 22.46.28	30.50°C	76.40%	3500.00 lux	Terdeteksi	0.11W	0.00kWh
15/11/2024, 22.46.29	30.40°C	76.60%	3700.00 lux	Terdeteksi	0.11W	0.00kWh
15/11/2024, 22.46.30	30.00°C	76.80%	2800.00 lux	Tidak Ada	0.10W	0.00kWh
15/11/2024, 22.46.31	29.80°C	76.90%	1500.00 lux	Tidak Ada	0.10W	0.00kWh
15/11/2024, 22.46.32	29.60°C	77.00%	3200.00 lux	Terdeteksi	0.10W	0.00kWh

Figure 4. History Table

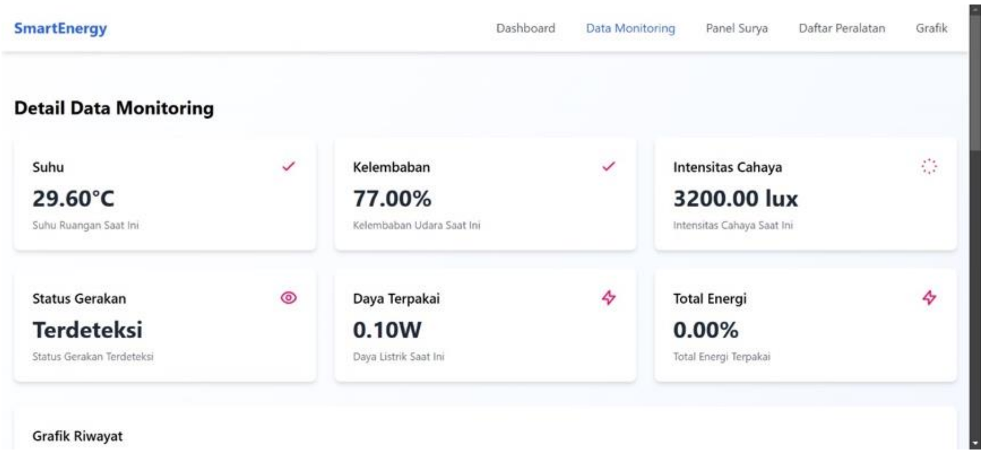


Figure 5. Detail Monitoring Data

The implementation of the IoT-integrated Home Energy Management System (HEMS) demonstrated the system's effective performance in monitoring and controlling home energy consumption based on solar energy. The system was designed to integrate various sensors, including the DHT22 for temperature and humidity, LDR for light intensity, and INA219 for voltage and current measurement. During testing, the system successfully detected changes in temperature and light intensity, automatically activating the fan when the temperature exceeded 30°C and adjusting the lighting based on the ambient light conditions. The sensor-based automation functioned consistently, demonstrating that the system could efficiently manage energy consumption based on environmental conditions.

One of the key highlights of this system was the successful implementation of real-time monitoring through a web interface, which allowed users to view sensor data, including voltage, current, light intensity, temperature, and humidity, in real-time. The system showed a fast response time, with control actions such as turning on the fan or lights taking less than one second, ensuring seamless interaction. Although occasional delays of 3-5 seconds were observed under weak internet connectivity, this did not significantly impact the overall functionality of the system. The manual control feature, allowing users to turn on or off devices through the website, also proved to be effective and user-friendly.

Table 1. DHT22 Sensor Testing

No	Date	Time	Temperature	Humidity	Status Fan
1	15-11-2024	22:46:04	28.8˚C	79.4%	OF
2	15-11-2024	22:46:05	28.8˚C	79.2%	OF
3	15-11-2024	22:46:06	28.9˚C	79.0%	OF
4	15-11-2024	22:46:07	28.9˚C	78.9%	OF
5	15-11-2024	22:46:08	29.0˚C	78.7%	OF
6	15-11-2024	22:46:09	29.1˚C	78.3%	OF
7	15-11-2024	22:46:10	29.3˚C	78.0%	OF
8	15-11-2024	22:46:11	29.6˚C	77.9%	OF
9	15-11-2024	22:46:12	29.8˚C	77.6%	OF
10	15-11-2024	22:46:13	29.9˚C	77.4%	OF
11	15-11-2024	22:46:14	30.0˚C	77.0%	ON
12	15-11-2024	22:46:15	30.4˚C	76.8%	ON
13	15-11-2024	22:46:16	30.4˚C	76.7%	ON
14	15-11-2024	22:46:17	30.6˚C	76.4%	ON
15	15-11-2024	22:46:18	30.8 ˚C	76.6%	ON

The DHT22 sensor, responsible for monitoring temperature and humidity, demonstrated reliable performance throughout the testing phase. The sensor accurately detected the gradual increase in temperature from 28.8°C to 30.0°C and the decrease in humidity from 79.4% to 77.0%. As per the pre-established rules, the fan was activated automatically when the temperature reached 30.0°C, providing a real-time solution to temperature regulation. These results confirm that the systems automated control based on environmental factors was both effective and responsive.

Table 2. LDR Sensor Testing

No	Date	Time	Light Level	Status Lamp
1	15-11-2024	22:46:04	3200	ON
2	15-11-2024	22:46:05	3500	ON
3	15-11-2024	22:46:06	2800	OFF
4	15-11-2024	22:46:07	1500	OFF
5	15-11-2024	22:46:08	1200	OFF
6	15-11-2024	22:46:09	3700	ON
7	15-11-2024	22:46:10	3800	ON
8	15-11-2024	22:46:11	1400	OFF
9	15-11-2024	22:46:12	1300	OFF
10	15-11-2024	22:46:13	3100	ON
11	15-11-2024	22:46:14	3300	ON
12	15-11-2024	22:46:15	1450	OFF
13	15-11-2024	22:46:16	2900	OFF
14	15-11-2024	22:46:17	3500	ON
15	15-11-2024	22:46:18	1300	OF

Similarly, the LDR sensor effectively controlled the lighting system based on light intensity. The sensor responded promptly to changes in light levels, switching the lights on when the intensity exceeded 3000 lux and off when the light intensity fell below 1000 lux. This functionality highlights the system's capability to optimize energy use based on the availability of natural light, ensuring that lights are only used when necessary, contributing to energy conservation.

Table 3. INA219 Sensor Testing

No	Date	Time	Voltage	Current	Power	Status Lamp	Status Fan
1	15-11-2024	22:46:04	0.03v	3200mA	0.096w	OF	ON
2	15-11-2024	22:46:05	0.03v	3400mA	0.102w	OF	ON
3	15-11-2024	22:46:06	0.03v	3200mA	0.096w	OF	OFF
4	15-11-2024	22:46:07	0.03v	3200mA	0.096w	OF	OFF
5	15-11-2024	22:46:08	0.03v	3200mA	0.096w	OF	OFF
6	15-11-2024	22:46:09	0.03v	3550mA	0.107w	OF	ON
7	15-11-2024	22:46:10	0.03v	3750mA	0.113w	OF	ON
8	15-11-2024	22:46:11	0.03v	3200mA	0.096w	OF	OFF
9	15-11-2024	22:46:12	0.03v	3200mA	0.096w	OF	OFF
10	15-11-2024	22:46:13	0.03v	3400mA	0.102w	OF	ON
11	15-11-2024	22:46:14	0.03v	3400mA	0.102w	ON	ON
12	15-11-2024	22:46:15	0.03v	3200mA	0.096w	ON	OFF
13	15-11-2024	22:46:16	0.03v	3200mA	0.096w	ON	OFF
14	15-11-2024	22:46:17	0.03v	3750mA	0.113w	ON	ON
15	15-11-2024	22:46:18	0.03v	3750mA	0.113w	ON	ON

The INA219 sensor, responsible for monitoring the energy consumption of connected devices, performed consistently throughout the testing. The system accurately measured the fluctuations in current and power consumption, providing real-time data on energy usage. In the standby mode, with no active load, the system recorded minimal power consumption. As devices such as the fan and lights were activated, the sensor tracked the changes in current and power, accurately reflecting the system's energy consumption. The data showed significant increases in current and power when the fan and lights were in operation, demonstrating the effectiveness of the INA219 sensor in monitoring and managing energy usage. This accurate energy tracking allowed for a comprehensive understanding of the system's performance and highlighted areas where energy efficiency could be further optimized.

Table 4. System performance Analysis

Testing Aspects	Result	Analysis	Recommendation
Solar Panel Performance	Panel produces 16V at maximum light intensity	Optimal voltage is achieved when the weather is clear; performance decreases significantly when it is cloudy or at night.	Add a battery with a larger capacity for longer energy storage. Or Add solar panel chips.
Solar Charge Controller Efficiency	Stably regulates the input voltage to the battery	The SCC did a good job of keeping the battery voltage at 12V, even though	Ensure that the SCC supports the capacity of the installed solar panels.

		input fluctuations occurred	
Performance INA219	Accurate reading of current and voltage up to ±1%	Sensors provide stable current and voltage data, supporting real-time monitoring of energy consumption.	Use short or shielded cables for sensors.
Performance DHT22	Stable temperature and humidity readings, fast response	Room condition data is accurate, but response is a little slow to drastic temperature changes.	Add calibration routine for accuracy
Performance LDR	The light level reading changes significantly with the light intensity.	LDR is effective in detecting changes in light intensity as an automation control in the system	Avoid LDR from artificial light
Fan and Lamp Load	Fans and lights work well and are stable according to the rules made.	The load is not too heavy for the system, the fan consumes more current than the lamp.	Use low-efficiency fans for energy efficiency.

4. Conclusions

This study successfully demonstrates the feasibility of integrating IoT technology into Home Energy Management Systems (HEMS) using solar panels as the primary energy source. The system effectively monitored environmental parameters such as temperature, humidity, light intensity, voltage, and current in real-time. By employing an ESP32 microcontroller and various sensors, including the DHT22, LDR, and INA219, the system was able to automate the control of home appliances like fans and lights based on environmental conditions. The system's performance was stable, with a rapid response time of under one second for control actions, highlighting its efficiency in managing home energy consumption.

The automated control features of the system, such as activating the fan when temperatures exceed 30°C and adjusting lighting based on ambient light levels, proved to be effective in optimizing energy usage. The real-time monitoring, accessible via a web interface, allowed users to easily track energy consumption and make adjustments as necessary, providing an intuitive and user-friendly solution. These features demonstrate the potential for IoT systems to play a significant role in enhancing home energy efficiency, reducing reliance on traditional energy sources, and supporting the transition to renewable energy.

However, the study also identified limitations related to the capacity of the solar panel used in the system. The 10 Wp solar panel proved insufficient during periods of low sunlight, leading to occasional energy shortages. To overcome this challenge, future improvements such as optimizing load management strategies or increasing the capacity of the solar panel are recommended. This would enhance the system's ability to provide continuous energy supply, particularly during cloudy or low-sunlight conditions, ensuring consistent and reliable operation.

The IoT-integrated presented in this study has the potential to significantly improve energy management in residential settings. By combining renewable energy sources with real-time monitoring and automated control, the system offers a sustainable and efficient solution for reducing energy consumption. Future developments should focus on addressing the limitations related to solar panel capacity and exploring further optimizations to enhance system performance, ultimately contributing to more sustainable and energy-efficient homes.

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