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Design and Development of a Solar-Powered Smart Home

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Abstract: *Due to growing energy needs, instability of grid supply systems, and climate change, the current paper examines the development, implementation, and assessment of a prototype of solar-powered smart home. Only the energy provided by a 20W solar panel and stored in a 12V battery is used to power all necessary components such as LED lamps and fans that require DC voltage. Various sensors, namely DHT22, LDR, PIR, and INA219, collect all relevant information that is then processed by an ESP32 microcontroller and provides automation functions. Remote monitoring is achieved by using wireless applications such as Blynk that are convenient for controlling all aspects of energy consumption remotely. Overall, the described combination helps implement a decentralized energy source in order to reduce the burden on the existing energy grid. With the help of effective sensing techniques, energy savings are achieved since no unnecessary energy is wasted in any aspect of operation of the proposed prototype. Finally, the feasibility analysis demonstrates that a prototype can be used in practice at an economic cost of approximately ₹5,950, while providing energy autonomy levels of about 80-90%.*

Keywords: Solar Energy, IoT, ESP32, Smart Home Automation, Sustainability

I. INTRODUCTION

Residential energy consumption across the world makes up about 27% of overall electricity consumption, which leads to an estimated emission of 4.5 $GtCO_2$ yearly. The problems that arise due to rural electrification in India and the need to meet peak load demands in cities have called for the implementation of decentralized renewable energy systems.

Objectives:

- Developing a functional prototype deriving 100% power from solar sources.
- Achieving >85% automation efficiency through IoT integration.
- Deploying multi-sensor arrays to track power generation and environmental metrics in real-time.
- Engineering a budget-friendly design under ₹6,000 for low-income settings.

II. LITERATURE REVIEW

The combination of solar power and the Internet of Things (IoT) technology is noted as one of the essential solutions for decreasing carbon footprints of residential dwellings. Previous studies emphasize that although solar panels are needed for providing renewable energy, the key to smart use of this energy is ensured by "smartness" itself, which is made possible by using microcontrollers like ESP32. Interaction through digital media within household environment enables instant monitoring and decision-making. According to recent studies, intelligent energy management systems

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could increase efficiency within household settings significantly. For instance, the use of ESP32 is appreciated due to its excellent performance and low power consumption, thus being the best option for creating smart household systems. It was proved by previous research that it is possible to collect live data about the household settings, including information from sensors such as DHT22 and LDR, and inform the user through software such as Blynk. It is also noted that passive infrared sensors (PIR) can ensure significant energy savings, because loads such as LED lightings will be activated only when necessary. Another aspect where IoT-based solar energy systems can help is in saving the environment in accordance with international goals on renewable capacity.

III. METHODOLOGY

The study utilizes an engineered design, assembly, and validation process of the solar-powered intelligent house prototype. Methodology of this study involves the following important steps:

A. Hardware Selection and Design

Hardware selection process emphasizes energy efficiency and low energy consumption to allow operation even in cases when there is only a small amount of collected energy from the sun.

• Energy Harvesting: For energy harvesting, a 20W/18V polycrystalline solar panel is selected owing to its energy efficiency.

• Energy Storage and Regulation: An 12V/7Ah lead-acid battery is chosen for energy storage and regulated by PWM/MPPT charge controller to avoid over-discharge or over-charging the batteries.

• Processor: An ESP32 microprocessor is chosen as it is a dual core processor equipped with built-in Wi-Fi connectivity module.

B. Sensor Integration and Data Collection

Several sensors are connected to the ESP32 board to measure environmental conditions and electricity usage:

• LDR: Detects the amount of light present to enable automatic switching of lights in and outside the building.

• PIR: Detects motion of people entering a room to switch on the appliance only when the room is occupied.

• DHT22: Determines temperature and humidity readings for automation based on climate.

• INA219: Determines real-time current and voltage levels to determine power generation and consumption information.

C. Software Flow and Automation Mechanism

The software is programmed using Arduino IDE (C++ programming language) and uses a continual looping mechanism:

• System Setup: System initializes the sensors and initiates communication with the Wi-Fi network.

• Sensor Loop: The ESP32 collects data from all sensors after every 10 seconds.

• Threshold Check: If the reading of the sensors satisfies the required threshold value, for example, (LDR < 50lux and PIR = HIGH), then the controller sends signals to the relays.

• Data Transmission: Transmits collected data to the cloud using the MQTT protocol on Blynk IOT.

IV. SYSTEM ARCHITECTURE

Layer	Primary Components	Responsibility
Energy	Solar Panel, Charge Controller, Battery	Generation, regulation, and storage of DC power.
Control	ESP32, Relay Module, Sensor Array	Processing sensor data and toggling electrical loads.
Communication	Wi-Fi, MQTT Broker, Blynk App	Real-time monitoring and manual override capabilities.

V. FEASIBILITY AND RESULTS

Feasibility of the solar-powered smart house model was analyzed from an economic, environmental, and technological perspective, specifically its viability as a model that could be adopted by homeowners in areas with high levels of solar irradiance such as Rajasthan.

5.1 Economic Feasibility

Total costs were thoroughly estimated in order to make the prototype affordable for economically disadvantaged areas, with a budget of less than ₹6,000 in mind. The present prototype was effectively delivered within a budget of ₹5,950.

Component	Cost (₹)
Solar Panel (20W)	1,500
Charge Controller	400
Battery (12V, 7Ah)	1,200
ESP32/Arduino	500
Sensor Pack & Misc	1,400
Total	5,950

5.2 Environmental Impact

The system provides a sustainable alternative to coal-based grid electricity, offsetting approximately 15kg of CO_2 emissions annually. This reduction aligns with national renewable energy targets, proving that even small-scale decentralized systems can contribute to a significant cumulative decrease in greenhouse gas emissions. By eliminating the need for grid-dependent lighting, the prototype reduces the carbon footprint of a standard household by nearly 20% in the lighting sector alone.

5.3 Performance and Technical Achievements

The tests conducted in Jaipur resulted in extremely good performance parameters. The efficiency was measured at 82%, meaning that no energy was lost throughout the process of energy conversion and storage. Under favorable conditions of maximum sun radiation, the panel was able to fully charge the 7Ah battery in 4-6 hours. The accuracy of automation reached 95%, while the false alarm rate for the motion sensor (PIR) and light sensor (LDR) did not exceed 2%. Moreover, the ESP32 chip showed 99% stability and successfully maintained connection with the Wi-Fi network. The feasibility study shows that with the 100Wh capacity per day, the energy autonomy reaches 80-90%, thereby minimizing the effect of frequent blackouts in remote territories.

VI. FUTURE SCOPE

This research has a future potential scope in the enhancement of intelligence and scalability for a smart home model. Areas for future development include, but are not limited to:

• Machine Learning Integration: Future implementations will go beyond sensor thresholds by implementing Machine Learning algorithms for predictive load balancing using weather forecasting and user behavior data.

• Predictive Maintenance: Utilize Artificial Intelligence to monitor battery condition and solar panel performance and send alerts to users before either component is in need of service.

• Voice Command Expansion: Using voice command via voice assistants (e.g., Amazon Alexa or Google Assistant) to allow for improved accessibility for elderly or disabled users.

• Customized Energy Analytics: Develop advanced data analytics tools to help users find ways to save energy through informed recommendations provided via a sophisticated mobile interface.

• Scalability to Accommodate High Loads: Investigate options for using larger solar array and lithium storage systems to provide power for large appliances (e.g., refrigerators and air conditioners) while also preserving the core efficiency of the IoT system.
• Community Grid Networks: Research the possibility of connecting multiple solar IoT homes to create a microgrid that allows for peer-to-peer energy exchange.

VII. CONCLUSION

In summary of this study, the incorporation of solar and IoT technology (Internet of Things) shows that integrating these two areas provides both a technically feasible and economically feasibility method of creating a net zero home. The research found that with a controlled amount of energy consumption and energy generation, it is possible to be completely off the electrical grid for some of the major household functions such as lighting and cooling; therefore, minimising energy waste and maximising user comfort.

The project also demonstrated that a decentralized energy system was able to be built for 6000 ₹, putting renewable energy equipment within the reach of more people. Furthermore, the system has an accuracy of 95% with regards to automation, which means the equipment will only operate if the environmental conditions and/or human beings in the usual way require them to operate. The overall goal of improving the operation of a system based on a combination of renewable generation of energy and automated consumption of energy is critical to establishing a positive environmental impact and addressing the ongoing global energy shortage and need to reduce our carbon footprint.

VIII. ACKNOWLEDGMENT

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