Smart Hybrid Energy Management Real-Time Monitoring, Automated Switching & Solar Utilization Mapping

Jayesh Tanga[1], Govradhan Dandi[2], Onkar Punjal[3], Rafiqua Nadaf[4], Shrisiddharth Kardas[5], Prof. A.A. Dhavale[6]
[1,2,3,4,5,6]*Dept. of Electrical Engineering, V. V. P. Institute of Engineering and Technology, Solapur,Maharashtra, India*

Abstract— **The increasing demand for sustainable and reliable energy systems has accelerated the adoption of hybrid renewable energy technologies. This project presents a Smart Hybrid Energy Management System (SHEMS) designed for real-time monitoring, automated source switching, and solar utilization mapping. The system integrates solar energy, battery storage, and conventional grid power to ensure continuous and efficient energy supply.**

An IoT-enabled Espress if Systems ESP32 microcontroller is used as the central controller for monitoring voltage, current, and power parameters from different energy sources. Based on real-time sensor data, the system automatically switches between solar, battery, and grid supply using relay modules to provide uninterrupted power to the load. The system also incorporates IoT-based monitoring through a web/mobile dashboard, enabling users to observe energy usage, battery condition, and source availability remotely.

Index Terms— **Hybrid Energy System, IoT, ESP32, Solar Energy, Automated Switching, Energy Monitoring, Smart Grid, Renewable Energy, Battery Management, Energy Optimization**

I. INTRODUCTION

The rapid growth in energy consumption and depletion of conventional energy resources have increased the need for renewable and intelligent energy management systems. Solar energy is one of the most widely used renewable energy sources because it is clean, eco-friendly, and sustainable.

However, the intermittent nature of solar power creates challenges in maintaining continuous electricity supply [1,2].

To overcome these limitations, hybrid energy systems combine solar energy with battery storage and grid supply. These systems improve reliability and ensure uninterrupted power availability. Modern advancements in IoT technology further enable real-time monitoring, remote control, and intelligent decision-making for energy optimization [3,4,5].

This project proposes a Smart Hybrid Energy Management System (SHEMS) using the ESP32 microcontroller for intelligent energy source management. The system continuously monitors voltage and current values from solar panels, batteries, and grid supply through sensors. Based on energy availability, the controller automatically switches the power source using relay modules [6,7].

The proposed system also includes IoT-based monitoring and solar utilization mapping, allowing users to analyze energy generation and consumption through a dashboard interface. The system enhances renewable energy utilization, improves power reliability, and reduces electricity costs, making it suitable for smart homes and small industrial applications [8,9,10].

II. LITERATURE REVIEW

[1] A. Kumar, S. Basak, and R. K. Maity (2024) proposed an IoT-based smart hybrid power management system with accurate forecasting and intelligent load management. The system monitored solar and grid power in real time and improved energy utilization while reducing unnecessary power consumption.

[2] H. J. El-Khozondar, S. Y. Mtair, K. O. Qoffa, O. I. Qasem, A. H. Munyarawi, Y. F. Nassar, E. H. E. Bayoumi, and A. A. E. B. El Halim (2024) developed an ESP32-based smart energy monitoring system for measuring voltage, current, and power parameters using IoT technology. The system provided remote monitoring and low-cost energy management solutions.

[3] M. T. Shahed, M. M. Haque, and S. Akter (2023) designed an IoT-enabled solar energy management system to improve smart grid reliability and power quality. The study focused on real-time solar monitoring and cloud-based visualization for efficient renewable energy utilization.

[4] G.-L. Huang, A. Anwar, and S. W. Loke (2023) presented an IoT-based smart energy analysis system for monitoring energy consumption patterns and source performance. The research highlighted the importance of real-time data collection and cloud analytics for intelligent energy management.

[5] M. Nikpour, P. B. Yousefi, and H. Jafarzadeh (2023) proposed an intelligent IoT framework for automated energy management in smart cities. The system integrated renewable energy sources with IoT communication technologies to improve energy optimization and system efficiency.

[6] Alniyaz S. (2025) developed a next-generation smart energy system with IoT-based source switching and efficiency analytics. The system automatically switched between solar, battery, and grid supply to ensure uninterrupted power and better energy utilization.

[7] M. Tradacete-Ágreda (2025) introduced a smart residential PV microgrid management system with battery storage and intelligent controllers. The study focused on optimized energy flow control and efficient renewable energy utilization in residential applications.

[8] H. Hartoyo, S. Rosyadi, and U. Nursusanto (2024) proposed an IoT-based electrical power monitoring system for solar power plants. The system provided real-time voltage, current, and power monitoring with graphical visualization through cloud-based dashboards.

[9] Uma (2026) developed a smart hybrid energy switching system with IoT integration for automatic renewable energy prioritization. The proposed system continuously monitored energy availability and shifted the load between solar, battery, and grid supply automatically.

[10] Vallem Ranadheer Reddy (2025) proposed an AI-powered IoT-based smart energy management system for predictive energy control and load balancing. The research used intelligent algorithms for energy analysis, fault detection, and improved system automation.

III. METHODOLOGY

The proposed Smart Hybrid Energy Management System (SHEMS) is developed to provide efficient energy utilization by integrating solar power, battery storage, and conventional grid supply into a single intelligent system. The methodology of the proposed system focuses on real-time monitoring, automated power source switching, and IoT-based remote energy management. The entire system is controlled using the Espressif Systems ESP32 microcontroller, which acts as the central processing unit for monitoring and decision-making operations

Initially, solar energy generated from the photovoltaic panel is supplied to the system and stored in the battery through a charge controller. The solar panel serves as the primary power source because it is renewable, eco-friendly, and cost-effective. However, since solar power availability depends on environmental conditions such as sunlight intensity and weather, a backup energy management mechanism is required to ensure continuous power supply. Therefore, battery storage and conventional grid supply are integrated into the system as secondary and tertiary power sources.

To monitor the condition of all energy sources, voltage and current sensors are connected to the solar panel, battery, and grid supply. These sensors continuously measure electrical parameters such as voltage, current, and power consumption. The sensed analog data is converted into digital signals using the analog-to-digital converter (ADC) of the ESP32 microcontroller. The controller processes this data in real time and determines the availability and efficiency of each energy source

IV. MATHEMATICAL MODEL

The mathematical model of the Smart Hybrid Energy Management System (SHEMS) is used to calculate power generation, energy consumption, battery operation, and system efficiency. The electrical power supplied to the load is calculated by:

1. Electrical power supplied to the load is calculated using:

$P=V\times I$

Where:

- P = Power (W)
- V= Voltage (V)
- I = Current (A)

2. Energy consumed by the load is calculated as:

$E=P\times t$

Where:

- E = Energy (Wh)
- P = Power (W)
- t = Time (h)

3. Solar power generated by the photovoltaic panel is given by:

$P_{solar}=G\times A\times \eta$

Where:

- Psolar = Solar output power
- G = Solar irradiance
- A = Area of solar panel
- η = Efficiency of solar panel

4. System efficiency is calculated using:

$$\eta_{system} = \frac{P_{load}}{P_{input}} \times 100$$

Where:

- η_{system} = System efficiency
- P_{load} = Load power
- P_{input} = Input power

V. BLOCK DIAGRAM

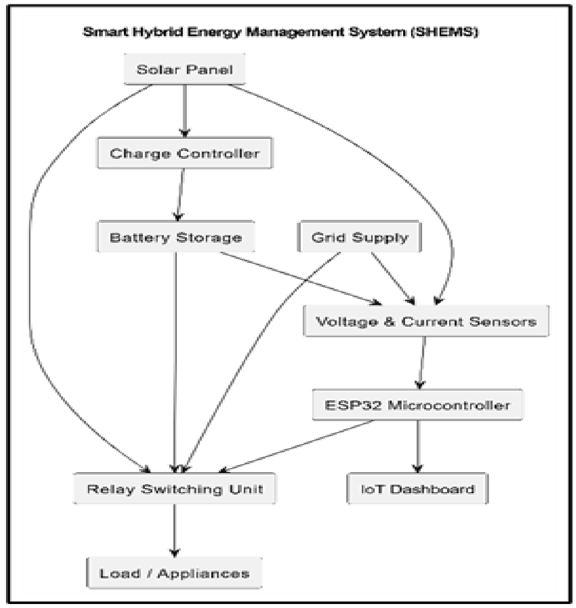

Fig 1 – Block Diagram

VI. RESULTS AND DISCUSION

Table 1 - Performance Analysis and Experimental Results of Smart Hybrid Energy Management System

S.No	Parameter	Observed Result
1	Voltage Monitoring	Accurate real-time voltage monitoring achieved
2	Current Monitoring	Continuous current sensing performed successfully
3	Power Monitoring	Real-time power tracking obtained
4	IoT Connectivity	Sensor data transmitted successfully to cloud dashboard
5	Automated Switching	Smooth switching between solar, battery, and grid supply
6	Solar Energy Utilization	Increased utilization of renewable solar energy
7	Battery Backup Performance	Efficient charging and discharging observed
8	Grid Dependency	Reduced dependency on conventional grid supply
9	Solar Utilization Mapping	Graphical analysis generated successfully

The developed Smart Hybrid Energy Management System (SHEMS) successfully achieved real-time monitoring and intelligent energy management using IoT technology. The ESP32 microcontroller continuously monitored voltage, current, and power parameters from the solar panel, battery, and grid supply through connected sensors. The collected data was processed accurately and transmitted to the cloud dashboard, enabling remote monitoring and visualization of system performance. The IoT-based monitoring platform provided users with real-time information regarding energy consumption, source availability, and battery condition, improving system transparency and accessibility.

The automated relay switching mechanism operated efficiently by automatically selecting the most suitable power source based on energy availability. Solar energy was utilized as the primary source, while the battery and grid supply acted as backup sources during insufficient solar conditions. The switching process was fast and smooth, ensuring uninterrupted power supply to the connected load. Experimental observations showed that the system significantly improved solar energy utilization and reduced dependency on conventional grid electricity, thereby lowering energy costs and promoting renewable energy usage.

VII. CONCLUSION

The proposed Smart Hybrid Energy Management System (SHEMS) provides an efficient and intelligent solution for sustainable energy management by integrating solar energy, battery storage, and conventional grid supply into a single automated platform. The system successfully achieved real-time monitoring of voltage, current, and power parameters using IoT technology and the ESP32 microcontroller. The continuous monitoring capability enabled accurate analysis of energy generation, energy consumption, and source availability, improving overall system efficiency and reliability.

The automated relay-based switching mechanism effectively managed the transition between solar, battery, and grid power sources according to energy availability and load demand. The system prioritized solar energy utilization, thereby reducing dependency on conventional grid electricity and promoting the use of renewable energy resources. The switching process was fast, reliable, and ensured uninterrupted power supply to the connected load without manual intervention.

VIII. FUTURE SCOPE

The future enhancement of the proposed Smart Hybrid Energy Management System can focus on integrating advanced artificial intelligence and machine learning algorithms for predictive energy management and intelligent decision-making. AI-based forecasting techniques can be used to predict solar energy generation, load demand, and battery performance based on weather conditions and historical energy consumption data. This will help improve energy optimization, reduce power wastage, and extend battery life through intelligent charging and discharging control.

The system can also be expanded by integrating additional renewable energy sources such as wind energy and hybrid renewable microgrid technologies. Incorporating electric vehicle charging stations and smart home automation features can further enhance the applicability of the system in modern smart city environments. Future versions of the system may include adaptive energy scheduling, fault detection mechanisms, and automated maintenance alerts to improve reliability and operational safety.

ACKNOWLEDGMENT

We students would like to express their sincere gratitude to the project guide and faculty members of the department for their valuable guidance, continuous encouragement, and technical support throughout the development of this project. Their suggestions and expert advice greatly contributed to the successful completion of the work.

We also thank the institution and laboratory staff for providing the necessary facilities, resources, and equipment required for implementing the Smart Hybrid Energy Management System. Special appreciation is extended to friends and team members for their cooperation, support, and motivation during the design, testing, and documentation phases of the project.

REFERENCES

[1] Kumar, S. Basak, and R. K. Maity, “An IoT-based smart hybrid power management system with accurate forecasting and load strategy,” *Applied Computer Technology*, 2024.

[2] H. J. El-Khozondar, S. Y. Mtair, K. O. Qoffa, O. I. Qasem, A. H. Munyarawi, Y. F. Nassar, E. H. E. Bayoumi, and A. A. E. B. El Halim, "A smart energy monitoring system using ESP32 microcontroller," *Results in Engineering*, vol. 23, 2024.

[3] M. T. Shahed, M. M. Haque, and S. Akter, "IoT-enabled smart solar energy management system for enhancing smart grid power quality and reliability," *SN Computer Science*, 2023.

[4] G.-L. Huang, A. Anwar, and S. W. Loke, "IoT-based analysis for smart energy management," *arXiv preprint arXiv:2311.18643*, 2023.

[5] M. Nikpour, P. B. Yousefi, H. Jafarzadeh, K. Danesh, R. Shomali, S. Asadi, A. G. Lonbar, and M. Ahmadi, "Intelligent energy management with IoT framework in smart cities using intelligent analysis," *arXiv preprint arXiv:2306.05567*, 2023.

[6] S. Alniyaz, "Next-gen smart energy system with IoT-based source switching and efficiency analytics," *International Journal of Creative Research Thoughts (IJCRT)*, 2025.

[7] M. Tradacete-Ágreda, "Smart energy management for residential PV microgrids," *Sensors*, vol. 25, no. 21, 2025.

[8] H. Hartoyo, S. Rosyadi, and U. Nursusanto, "Electrical power monitoring system for solar power plants based on the Internet of Things," *Sustinere Journal of Environment and Sustainability*, 2024.

[9] Uma, "Smart hybrid energy switch optimum energy national energy consumption with IoT integration," *ResearchGate Publication*, 2026.

[10] V. R. Reddy, "Development of an AI-powered IoT-based smart energy management system," *Ballistics Journal*, 2025.

[11] M. F. Ryzaaldy, M. Fikry, and S. F. Anshari, "IoT-integrated home energy management system with real-time monitoring and solar panel optimization," in *Proc. MICoMS*, 2024.

[12] O. Sobhana, G. C. Prabhakar, A. R. Nalamalapu, and R. Kapoor, "A smart IoT-based solar power monitoring system," *Smart Grids and Green Energy Systems*, 2022.

[13] M. Rokonuzzaman, "Artificial intelligence, IoT, and solar PV based smart home energy management systems," *Results in Engineering*, 2026.

[14] P. P. Koumoulos and M. A. Bintoudi, "IoT and AI-driven approaches for energy optimization in smart PV microgrids," *Engineering Proceedings*, 2026.

[15] H. Tasmant, "A review of machine learning and IoT-based energy management systems for microgrids," *Computers & Electrical Engineering*, 2025.

[16] D. O. Njoku, C. Ezeji, C. Osuji, and C. Ofoegbu, "IoT enabled smart energy management system for rural connectivity," *ResearchGate Publication*, 2026.

[17] S. Seenivasan, Gopika Sri, Hemambika, Sasitha, and Wahid, "Smart hybrid solar wind power management system using ESP32," *IRJIET*, 2026.

[18] "IoT-enabled hybrid solar power inverter," *IJNRD*, 2025.

[19] "An IoT and data analytics based smart energy management system with solar grid integration," *Conference Paper*, 2025.

[20] G. L. Huang, A. Anwar, S. W. Loke, A. Zaslavsky, and J. Choi, "IoT-based analysis for smart energy management," *IEEE Smart Systems*, 2023.

[21] M. G. Abeleira, C. S. Pérez, F. J. R. Sánchez, P. M. Sánchez, E. S. Gómez, and J. A. J. Calvo, "Aperiodic two-layer energy management system for community microgrids based on blockchain strategy," *arXiv preprint*, 2024.

[22] V. Barral Vales, O. C. Fernández, T. Domínguez-Bolaño, C. J. Escudero, and J. A. García-Naya, "Fine time measurement for the Internet of Things: A practical approach using ESP32," *arXiv preprint*, 2024.

[23] "EV charging station with solar monitoring and grid integration," *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, 2024.

[24] "IoT-based smart energy management system," in *INSPIRATHON Proceedings*, 2025.

[25] "A comparative study on IoT-based MPPT techniques for solar energy management," *ScienceDirect*, 2026.