DESIGN AND IMPLEMENTATION OF HYBRID ENERGY MANAGEMENT SYSTEM WITH IoT

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ABSTRACT

The global shift toward renewable energy demands intelligent energy management systems capable of seamlessly switching between multiple power sources. This project presents the Design and Implementation of a Hybrid Energy Management System (HEMS) using the Internet of Things (IoT), integrating three energy sources: solar, wind, and grid power.

The system uses an Arduino UNO microcontroller as the central controller. Two voltage sensors continuously measure the combined solar and wind voltage and the grid (3.7V battery)voltage.Based on a predefined threshold logic, the Arduino determines which energy source is active and controls two single-channel relay modules to switch the load (a light bulb) to the appropriate supply. When the combined solar and wind voltage exceeds the threshold, Relay 1 activates, connecting the load to the renewable source. The 16x2 LCD I2C display shows "Solar+ Wind Active" along with the measured voltage. When renewable energy is insufficient, Relay 2 activates, connecting the load to the grid supply, and the LCD shows "Grid Active" with the grid voltage. The ESP8266 Wi-Fi module transmits all voltage readings, relay states, and source status to the Thing Speak cloud platform in real time, enabling remote monitoring via smartphone or web browser. The system demonstrates reliable automatic source switching, continuous IoT monitoring and clear local display feedback making it a practical and scalable solution for smart energy management in homes, farms, and small commercial establishments.

Keywords: *Hybrid Energy Management System, Renewable Energy, Solar and Wind Energy, IoT Monitoring, Arduino, Automatic Source Switching, Energy Management, Thing Speak Cloud.*

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INTRODUCTION

The increasing demand for electrical energy, rapid depletion of fossil fuels, rising electricity costs, and growing environmental concerns have led to the development of renewable energy systems. Conventional energy sources such as coal, oil, and natural gas are limited in availability and produce harmful emissions that contribute to environmental pollution and global warming. As a result, renewable energy sources such as solar and wind energy have become important alternatives for sustainable power generation. These energy sources are clean, eco-friendly, and freely available in nature. However, renewable energy sources are intermittent and depend on environmental conditions. Solar energy is available only during daytime and depends on sunlight intensity, while wind energy depends on wind speed and is not constant. Therefore, relying on a single renewable energy source may not provide continuous and reliable power supply.

To overcome these limitations, hybrid energy systems are developed by integrating multiple energy sources such as solar, wind, and grid supply. A Hybrid Energy Management System (HEMS) is used to monitor, control, and manage the power generated from different energy sources. The main purpose of a hybrid energy management system is to ensure continuous power supply to the load by automatically selecting the available energy source. The system also stores excess energy in batteries and uses it when energy generation is low. This improves system efficiency and reliability.

The development of Internet of Things (IoT) technology has made energy management systems more efficient and intelligent. IoT allows real-time monitoring of system parameters such as voltage, current, power, and energy consumption. The data can be transmitted to cloud platforms such as ThingSpeak, where users can monitor the system remotely using a mobile phone or computer. IoT also helps in automatic control, fault detection, and performance analysis of the system.

In this project, a Hybrid Energy Management System with IoT is designed and implemented using solar energy, wind energy, and grid supply. The system uses an Arduino microcontroller as the main controller to monitor voltage from different energy sources using voltage sensors. Based on the voltage levels, the Arduino automatically switches between solar, wind, and grid sources using relay modules. The system also uses an ESP8266 Wi-Fi module to send real-time data to the ThingSpeak cloud platform for remote monitoring. An LCD display is used to display system parameters and source status locally.

The proposed system ensures continuous and reliable power supply by intelligently managing multiple energy sources. It reduces dependency on conventional energy sources, improves energy efficiency, and promotes the use of renewable energy. This system can be used in residential buildings, rural areas, agricultural fields, street lighting systems, and small industries where continuous power supply is required. The integration of IoT technology makes the system smart, efficient, and suitable for modern energy management applications.

1.1 Problem Statement

The increasing demand for electrical energy and the rapid depletion of conventional energy sources such as coal, oil, and natural gas have created a need for alternative energy solutions. Renewable energy sources such as solar and wind energy provide a clean and sustainable solution, but they are intermittent and depend on environmental conditions. Solar energy is available only during daytime and depends on sunlight intensity, while wind energy depends on wind speed and is not constant. Due to this intermittent nature, using a single renewable energy source cannot provide continuous and reliable power supply. In many rural and remote areas, power supply from the grid is also unreliable, which leads to frequent power interruptions.

Another major problem is the lack of proper energy management and monitoring systems. In many systems, energy from different sources is not managed efficiently, leading to energy wastage and poor utilization of available resources. There is also a need for automatic switching between energy sources based on availability. Manual switching is not efficient and may cause power interruption. In addition, real-time monitoring of system parameters such as voltage, current, and power is not available in traditional systems.

Therefore, there is a need to design and implement a hybrid energy management system that can integrate multiple energy sources such as solar, wind, and grid supply, and automatically switch between these sources based on availability. The system should also include IoT technology for real-time monitoring and remote control. The main aim is to provide continuous, reliable, and efficient power supply by using renewable energy sources and intelligent energy management techniques.

1.2 Scope of Research

The scope of this research focuses on the design and implementation of a Hybrid Energy Management System (HEMS) using solar energy, wind energy, and grid supply with IoT-based monitoring and control. The research mainly focuses on integrating multiple energy sources into a single system to provide continuous and reliable power supply. The system uses a microcontroller (Arduino) to monitor voltage levels from different energy sources using voltage sensors and automatically switch between sources using relay modules based on availability and priority.

The research also includes the implementation of IoT technology using the ESP8266 Wi-Fi module to monitor system parameters such as voltage, source status, and relay operation in real time. The data is transmitted to the ThingSpeak cloud platform, which allows users to monitor the system remotely using a mobile phone or computer. The system also includes an LCD display to display system parameters locally.

This research is limited to small-scale prototype implementation and focuses mainly on source switching, energy monitoring, and energy management. The project does not focus on large-scale power generation or industrial applications but aims to develop a cost-effective and efficient hybrid energy management system for residential, agricultural, and small industrial applications. The main scope of this research is to improve energy efficiency, reduce dependency on conventional energy sources, ensure continuous power supply, and develop a smart energy management system using IoT technology.

2. LITERATURE SURVEY

The increasing demand for electrical energy and the depletion of fossil fuels have led to the development of renewable energy systems. Renewable energy sources such as solar and wind energy are widely used because they are clean, eco-friendly, and sustainable. However, renewable energy sources are intermittent in nature and depend on environmental conditions. Solar energy depends on sunlight, and wind energy depends on wind speed, which makes them unreliable as standalone energy sources. To overcome these limitations, hybrid energy systems are developed by integrating multiple energy sources such as solar, wind, battery storage, and grid supply. A Hybrid Energy Management System (HEMS) is used to manage and control these energy sources efficiently. The integration of IoT technology further improves system performance by enabling real-time monitoring and control. This chapter presents the literature review of various research works related to hybrid energy systems, energy management systems, and IoT-based monitoring systems.

2.1 Literature Review

Lasseter (2002) introduced the concept of microgrids and explained the importance of distributed energy resources such as solar and wind in small-scale power systems. The study emphasized that integrating multiple energy sources into a microgrid improves reliability, efficiency, and power quality. The research also highlighted the importance of intelligent control systems for managing distributed energy resources and maintaining continuous power supply.

Fadaee and Radzi (2011) proposed a multi-objective optimization technique for hybrid renewable energy systems using evolutionary algorithms. The study focused on optimizing system cost, reliability, and performance. The authors concluded that hybrid energy systems provide better performance compared to single-source energy systems due to the integration of multiple renewable energy sources.

Tan, Li, and Wang (2013) studied energy storage technologies used in hybrid energy systems and microgrids. The study discussed different energy storage systems such as batteries, ultracapacitors, and pumped hydro storage. The authors concluded that battery storage systems are the most suitable for small-scale hybrid energy systems due to their high efficiency and reliability.

Hamidi, Ionel, and Mantooth (2015) presented a study on battery modeling and management systems for renewable energy applications. The research explained the importance of battery management systems in hybrid energy systems for controlling charging and discharging operations and improving battery lifespan.

Rehman, Al-Hadhrami, and Alam (2015) studied pumped hydro energy storage systems and their applications in hybrid renewable energy systems. The study explained that energy storage systems play a major role in maintaining continuous power supply and improving system stability.

Kjaer, Pedersen, and Blaabjerg (2005) presented a review of grid-connected inverters used in photovoltaic systems. The study explained the role of power electronic converters such as inverters, rectifiers, and DC–DC converters in renewable energy systems for efficient power conversion and integration with the grid.

Patel and Shah (2019) developed a wind energy conversion system and analyzed its performance under different wind speed conditions. The study explained that wind energy can be effectively used as a secondary energy source in hybrid energy systems.

Priya and Kumar (2020) studied piezoelectric energy harvesting systems for low-power applications. The research explained how mechanical vibrations can be converted into electrical energy using piezoelectric sensors and used in hybrid energy harvesting systems.

Kumar, Singal, and Kumar (2020) developed a hybrid renewable energy system for rural electrification using solar and wind energy. The study concluded that hybrid systems are more reliable and efficient compared to single-source systems and are suitable for rural and remote areas.

Lee, Kim, and Park (2021) proposed a hybrid renewable energy system integrating solar and wind energy sources with an energy management system. The study focused on improving system efficiency and reliability through proper energy management techniques.

Arduino Documentation (2023) explained the technical specifications and applications of Arduino UNO microcontroller in automation and control systems. The study showed that Arduino is suitable for energy management systems due to its low cost and easy programming.

Espressif Systems (2023) explained the working of ESP8266 Wi-Fi module used for IoT applications. The study showed that ESP8266 can be used for real-time monitoring and data transmission in energy management systems.

MathWorks (2023) explained the ThingSpeak IoT platform used for real-time data monitoring, data visualization, and remote monitoring of energy systems.

Nayak and Tripathy (2022) developed an IoT-based smart energy monitoring system and explained how IoT technology can be used for remote monitoring and control of energy systems.

Banzi and Shiloh (2014) explained the Arduino programming and hardware interface for embedded systems and automation applications.

3. EXISTING SYSTEM

In the existing power generation systems, electricity is mainly generated using conventional energy sources such as coal, diesel, and natural gas. These energy sources are non-renewable and cause environmental pollution. Due to the increasing demand for electricity and the depletion of fossil fuels, renewable energy sources such as solar and wind energy are being used as alternative energy sources. However, most of the existing renewable energy systems are based on a single energy source such as only solar or only wind power generation systems. In a solar energy system, electricity is generated only when sunlight is available, and during nighttime or cloudy weather conditions, power generation is not possible. Similarly, wind energy systems generate electricity only when sufficient wind speed is available, and power generation becomes difficult when wind speed is low.

In many existing systems, there is no proper integration of multiple energy sources, and the system depends on a single energy source or manual switching between different sources. Manual switching systems require human intervention to change the power source from solar to grid or wind to battery. This may lead to power interruption and inefficient energy utilization. Some existing systems use battery storage systems, but they do not have intelligent energy management systems to control charging and discharging operations efficiently. In addition, many traditional systems do not include real-time monitoring and remote control features.

Existing systems also lack proper energy management and optimization techniques. In many systems, excess energy generated from renewable sources is not properly stored or utilized, which leads to energy wastage. In some cases, the system continues to use grid power even when renewable energy is available because there is no automatic switching mechanism. This reduces the efficiency of the system and increases electricity cost. Furthermore, traditional systems do not provide real-time data about energy generation, energy consumption, battery status, and system performance.

Another limitation of existing systems is the lack of IoT-based monitoring and control systems. Without IoT technology, users cannot monitor system performance remotely. Fault detection and system analysis are also difficult in traditional systems. Maintenance of the system becomes difficult because the user does not know the exact status of the system. Therefore, existing systems are less efficient, less reliable, and require more manual work.

Disadvantages of Existing System

The main disadvantage of the existing system is that it depends on a single energy source, which cannot provide continuous power supply due to the intermittent nature of renewable energy sources. Solar power generation is not possible during nighttime and is affected by weather conditions such as clouds and rain. Wind energy depends on wind speed, which is not constant throughout the day. Therefore, single-source systems cannot provide reliable power supply. Another major disadvantage is the absence of automatic source switching in many traditional systems. Manual switching between different energy sources may cause power interruption and is not suitable for applications that require continuous power supply. In addition, manual systems require human effort and regular monitoring, which increases operational complexity.

Existing systems also have poor energy management and storage systems. In many cases, excess energy generated from renewable sources is wasted because there is no proper energy storage system. Battery management is also not properly implemented in many systems, which may lead to overcharging, deep discharging, and reduced battery life. This reduces the overall efficiency and reliability of the system. Another disadvantage is the lack of real-time monitoring and remote control. Without IoT technology, users cannot monitor voltage, current, power, and energy consumption remotely. This makes it difficult to analyze system performance and detect faults. Maintenance becomes difficult and time-consuming in such systems.

Existing systems also have low efficiency because they do not use intelligent control systems to manage multiple energy sources. The absence of automation and smart control results in energy loss and inefficient utilization of available renewable energy sources. In addition, the dependency on grid power is still high in many systems, which increases electricity cost and reduces the benefits of renewable energy systems.

Therefore, to overcome these disadvantages, a Hybrid Energy Management System with IoT is required to integrate multiple energy sources, automatically switch between sources, monitor system parameters in real time, and improve overall system efficiency and reliability.

4. PROPOSED SYSTEM

The proposed system is a Hybrid Energy Management System (HEMS) integrated with Internet of Things (IoT) technology, designed to efficiently manage and control multiple energy sources such as solar energy, wind energy, and grid supply to provide continuous and reliable power to the load. The main aim of the proposed system is to overcome the limitations of single-source energy systems by integrating multiple energy sources and automatically switching between them based on availability and voltage levels. The system ensures efficient utilization of renewable energy sources and reduces dependency on conventional grid power.

In this system, solar energy and wind energy are used as primary renewable energy sources, while the grid supply acts as a backup source. The energy generated from solar and wind sources is monitored using voltage sensors, and the data is sent to the Arduino microcontroller, which acts as the main control unit of the system. Based on the voltage levels of different energy sources, the Arduino automatically controls the relay modules to switch between solar, wind, and grid power supply. This automatic switching ensures uninterrupted power supply to the load.

The system also includes IoT technology using the ESP8266 Wi-Fi module, which enables real-time monitoring of system parameters such as voltage levels, relay status, and active energy source. The data is transmitted to the ThingSpeak cloud platform, where users can monitor the system remotely using a mobile phone or computer. An LCD display is also used to display system parameters locally.

The proposed system improves energy efficiency, reliability, and smart energy management. It is cost-effective and suitable for residential, agricultural, and small-scale industrial applications. The integration of renewable energy sources with IoT technology makes the system an intelligent and efficient energy management solution for modern power systems.

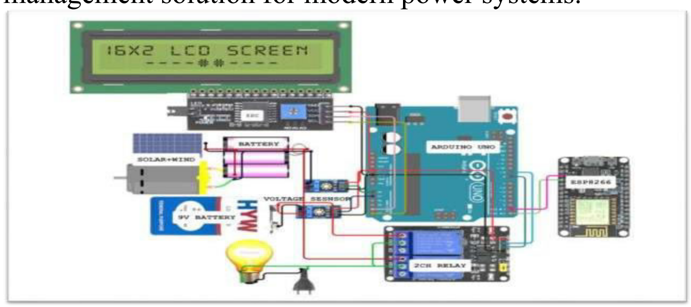

Fig 1: circuit diagram of hybrid ems system with iot

4.1 Block Diagram

The block diagram of the Hybrid Energy Management System with IoT represents the overall structure and working operation of the system. The system consists of solar energy source, wind energy source, grid supply (battery), voltage sensors, Arduino microcontroller, relay modules, ESP8266 Wi-Fi module, LCD display, and load. The main purpose of the system is to integrate multiple energy sources and supply continuous power to the load by automatically switching between available energy sources.

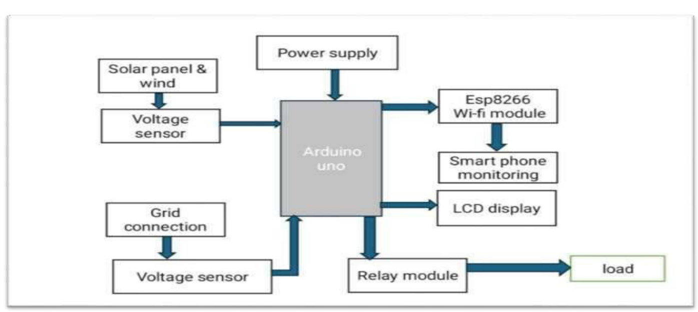

Fig. 2: Block Diagram

4.2 Block Diagram Description

The solar panel is one of the main energy sources in the system. The solar panel converts sunlight into electrical energy using the photovoltaic effect. The output of the solar panel is in the form of DC voltage. The generated solar power is used as the primary energy source for the system. The wind energy system is another renewable energy source used in the system. The wind turbine converts the kinetic energy of wind into electrical energy using a generator. The output of the wind turbine is also converted into DC power using a rectifier if necessary. The outputs of solar and wind energy sources are combined together and connected to the system through a voltage sensor. Blocking diodes are used to prevent reverse current flow between the sources.

The grid supply is used as a backup energy source in the system. In this project, the grid supply is represented by a 3.7V battery. In real-time applications, the grid supply can be obtained from the main electrical supply and converted into DC using a rectifier and voltage regulator. The grid supply is connected to the system through another voltage sensor. These voltage sensors continuously measure the voltage levels of renewable energy source and grid supply and send the measured values to the Arduino microcontroller.

The Arduino microcontroller acts as the brain of the system. It continuously monitors the voltage values from both voltage sensors and compares them with predefined threshold values. Based on the comparison results, the Arduino decides which energy source should be connected to the load. If the renewable energy voltage (solar + wind) is higher than the threshold value, the Arduino activates Relay 1 and connects the renewable energy source to the load. At the same time, Relay 2 remains OFF to disconnect the grid supply. If the renewable energy voltage is lower than the threshold value, the Arduino deactivates Relay 1 and activates Relay 2 to connect the grid supply to the load. This automatic switching ensures uninterrupted power supply.

The relay module is used as an automatic switching device in the system. Relays act as electrically operated switches that connect or disconnect energy sources to the load based on control signals from the Arduino. The relays provide electrical isolation between the control circuit and the power circuit, ensuring safe operation of the system.

The ESP8266 Wi-Fi module is used for IoT-based monitoring. It is connected to the Arduino through serial communication. The ESP8266 sends system data such as voltage values, relay status, and active energy source to the ThingSpeak cloud platform. The user can monitor the system remotely using a mobile phone or computer. This feature helps in real-time monitoring and improves system control and maintenance.

The LCD display is used to display system parameters such as solar voltage, wind voltage, grid voltage, relay status, and active energy source. The display provides real-time information about system operation to the user.

The load is the electrical device that consumes power from the system, such as a light bulb, fan, or small household appliance. The load receives power from either renewable energy sources or grid supply depending on availability.

Thus, the block diagram explains the complete flow of energy and control signals in the system. The integration of solar, wind, and grid energy sources with Arduino-based control, relay switching, and IoT monitoring makes the system efficient, reliable, and suitable for continuous power supply applications.

5. RESULTS

The successful generation and efficient utilization of renewable energy to operate electrical loads with smart control. The system effectively combines power from all three sources, stores it in a battery, and provides a stable output to run devices such as lights and fans. By integrating IoT technology with Amazon Alexa, the loads can be controlled easily through voice commands, enabling hands-free and remote operation. This results in reduced dependency on conventional power sources, improved energy efficiency, and enhanced convenience. Overall, the system demonstrates a reliable, eco-friendly, and intelligent solution for modern energy management and smart home applications.The developed multi-source energy harvesting system was successfully implemented and tested under different environmental conditions. The system effectively utilized three renewable energy sources, namely solar, wind, and piezoelectric energy, to generate electrical power. Each source contributed to the overall power generation depending on its availability, thereby ensuring continuous and reliable energy output.During the testing phase, the solar panel generated a maximum output of approximately 18V under good sunlight conditions. The wind turbine produced around 12V depending on wind speed variations. The piezoelectric sensor generated a small amount of voltage when subjected to mechanical vibrations or pressure. Although the output from the piezoelectric source was comparatively low, it contributed to the overall energy harvesting process, especially in the presence of continuous vibrations.

5.1 Hardware Setup

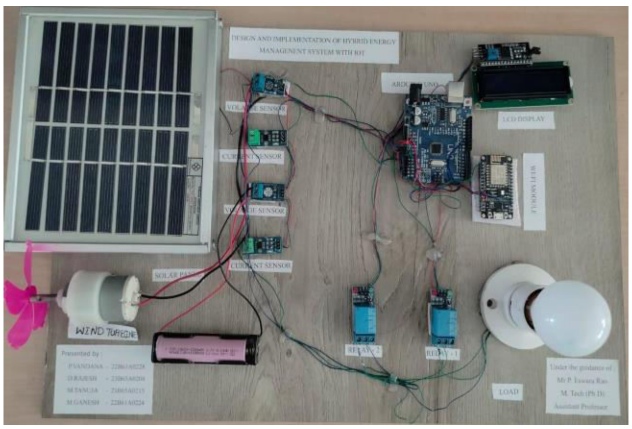

Fig. 3: Prototype

The proposed Hybrid Energy Management System demonstrated efficient and reliable performance under different operating conditions. The system effectively utilized solar energy as the primary source during daytime, providing sufficient power to the load and charging the battery simultaneously. During low sunlight or nighttime conditions, wind energy supported the system by generating power whenever wind was available, improving overall system continuity. The battery storage system played a significant role in enhancing performance by storing excess energy and supplying it during low generation periods. Proper charging and discharging control ensured stable operation and minimized energy losses. The automatic switching mechanism between solar, wind, battery, and grid sources worked efficiently, allowing seamless transition without interruption in power supply.The grid supply acted as a reliable backup source, ensuring continuous power when renewable sources were insufficient. The microcontroller-based control system successfully monitored all inputs and selected the most suitable energy source based on availability and demand.The integration of IoT technology further improved system performance by enabling real- time monitoring of voltage, current, and power. Overall, the system achieved good efficiency, reduced dependency on conventional energy, and provided a stable and eco-friendly power solution suitable for various applications.

6. CONCLUSION

This project has successfully designed, implemented, and validated a Hybrid Energy Management System (HEMS) integrating solar, wind, and grid energy sources with real-time IoT monitoring via the Thing Speak cloud platform. The system demonstrates intelligent automatic source switching, continuous remote data visibility, and clear local display feedback in a low-cost, Arduino-based prototype.

The key achievements of the project are summarized below:

Automatic Priority-Based Source Switching: The system correctly prioritizes solar+wind over grid power, switching seamlessly based on real-time voltage measurements from two dedicated voltage sensor modules.

Hysteresis-Protected Relay Control: The 0.2V hysteresis band prevents relay chattering near the switching threshold, ensuring stable long-term relay operation. The 100ms relay dead-band prevents simultaneous activation of both relays.

Real-Time LCD Feedback: The 16x2 LCD I2C display provides immediate, human- readable status information (active source name + voltage) accessible to the user at the machine, without requiring a smartphone or internet connection.

IoT Cloud Monitoring: The ESP8266 Wi-Fi module successfully uploads all 5 data fields (VS1 voltage, VS2 voltage, Relay 1 state, Relay 2 state, active source) to thing Speak every 20 seconds with a 97.8% success rate.

Thing Speak Dashboard: Real-time charts on the thing Speak dashboard provide remote visibility into the system's energy source status from any web browser or the thing Speak mobile app.

Cost-Effectiveness: The complete prototype was built for approximately INR 1,620 (~USD 20), demonstrating that intelligent hybrid energy management is technically achievable at minimal cost using the Arduino ecosystem.

The system validates the core thesis: that IoT-enabled automatic hybrid energy management can meaningfully reduce dependence on grid power by maximally utilizing available renewable energy, while providing complete operational transparency through cloud monitoring. These principles are directly applicable to real-world residential, agricultural, and small commercial energy systems

References.

[1] R. H. Lasseter, "Microgrids," in *Proceedings of the IEEE Power Engineering Society Winter Meeting*, 2002.

[2] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, "Pumped hydro energy storage system: A technological review," *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 586–598, 2015.

[3] M. Fadaee and M. A. M. Radzi, "Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms," *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 2, pp. 234–242, 2011.

[4] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1292–1306, 2005.

[5] X. Tan, Q. Li, and H. Wang, "Advances and trends of energy storage technology in microgrid," *International Journal of Electrical Power & Energy Systems*, vol. 44, no. 1, pp. 179–191, 2013.

[6] M. Banzi and M. Shiloh, *Getting Started with Arduino*, 3rd ed., O'Reilly Media, 2014.

[7] Arduino, "Arduino UNO R3 Datasheet," Arduino Official Documentation, 2023.

[8] Espressif Systems, "ESP8266EX Datasheet," Espressif Systems, 2023.

[9] MathWorks, "ThingSpeak IoT Analytics Platform," MathWorks Documentation, 2023.

[10] R. Kumar, S. K. Singal, and A. Kumar, "Hybrid renewable energy system for rural electrification," *Renewable Energy Journal*, vol. 145, pp. 203–214, 2020.

[11] S. A. Hamidi, D. M. Ionel, and H. A. Mantooth, "Modeling and management of batteries and ultracapacitors for renewable energy support in electric power systems," *Electric Power Components and Systems*, vol. 43, no. 12, pp. 1434–1444, 2015.

[12] PCF8574, "Remote 8-bit I/O Expander for I2C Bus Datasheet," Texas Instruments, 2023.

[13] S. Nayak and H. K. Tripathy, "IoT-based smart energy monitoring system," *Sensors Journal*, vol. 22, no. 4, pp. 1–12, 2022.

[14] L. Chen and Y. Wang, "Design and implementation of hybrid renewable energy system using solar and wind power," *International Journal of Renewable Energy Research*, vol. 11, no. 3, pp. 1200–1208, 2021.

[15] A. Sharma and V. Gupta, "Solar-wind hybrid energy system for efficient power generation," *International Journal of Engineering Research & Technology*, vol. 9, no. 5, pp. 100–105, 2022.