



ARDUINO-BASED INTELLIGENT HYBRID POWER MANAGEMENT SYSTEM: A MICROCONTROLLER-DRIVEN APPROACH FOR OPTIMIZED MULTI-SOURCE ENERGY UTILIZATION

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Consent for Publication

"All authors have reviewed and approved the final version of the manuscript for publication."

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Abstract

Reliable power supply is essential for modern infrastructure, particularly in regions with unstable grid availability. Hybrid energy systems combining renewable sources, storage devices, and conventional supplies offer an effective solution. This study presents an Arduino-based Intelligent Hybrid Power Management System (IHPMS) integrating five energy sources: solar photovoltaic (PV), wind energy, MSEB utility grid, battery storage, and a diesel generator (DG). A priority-based control algorithm continuously evaluates source availability and selects the most suitable source for the load. Real-time voltage sensing and relay-based switching enable seamless transitions without manual intervention. Experimental testing confirms reliable operation under varying environmental and load conditions, demonstrating the suitability of microcontroller-based hybrid systems for rural and small-scale applications.

Keywords

Arduino Microcontroller, Hybrid Power Management System, Renewable Energy Integration, Automatic Source Switching, Multi-Source Power System.

1. Introduction

Growing energy demand and sustainability goals have increased the need for efficient energy management systems that maximize renewable energy utilization. Although solar and wind energy are environmentally friendly, their intermittent nature limits their ability to supply critical loads independently. Hybrid systems combining renewable sources with batteries, utility grids, and diesel generators provide improved reliability and continuity of supply [2], [4].

Advances in embedded controllers have enabled the development of low-cost intelligent energy management systems. Arduino platforms offer flexibility, ease of programming, and compatibility with sensing and switching devices, making them suitable for real-time power management. This work develops and evaluates an Arduino-driven hybrid system capable of integrating five energy sources while ensuring uninterrupted supply, minimizing operating costs, and prioritizing renewable energy [1], [3].

2. Literature Review

Previous studies show that renewable energy alone cannot guarantee reliable power because of variations in solar irradiance and wind speed. Hybrid systems combining

renewables with batteries or diesel generators improve reliability and reduce operating costs. Most reported systems focus on simulation models or integrate only two or three energy sources [2], [6].

Microcontroller-based energy management systems using Arduino, PIC, and ARM platforms have demonstrated capabilities such as voltage monitoring, battery management, and source switching. However, limited research addresses the integration of solar, wind, battery, grid, and diesel generator sources within a single autonomous platform [1], [3], [7].

Research on source switching highlights the importance of relay-based circuits, voltage threshold detection, and isolation mechanisms for safe operation. [5]. Despite significant progress in renewable integration and control systems, a gap remains in the development of a unified multi-source hybrid management system with real-time autonomous operation. This study addresses that gap through practical implementation and testing [4].

3. System Architecture and Methodology

3.1 System Architecture

The proposed system integrates solar PV, wind energy, battery storage, MSEB grid supply, and a diesel generator under the control of an Arduino UNO. Voltage sensing circuits continuously monitor source availability and send analog signals to the controller. Based on predefined priorities, the Arduino selects the most suitable source and controls relay modules that connect the chosen source to the load. Figure 1 represents block diagram of proposed intelligent hybrid power management system. A transistor-driven relay circuit with flyback protection ensures safe switching, while an LM7805 regulator supplies stable power to the control circuitry.

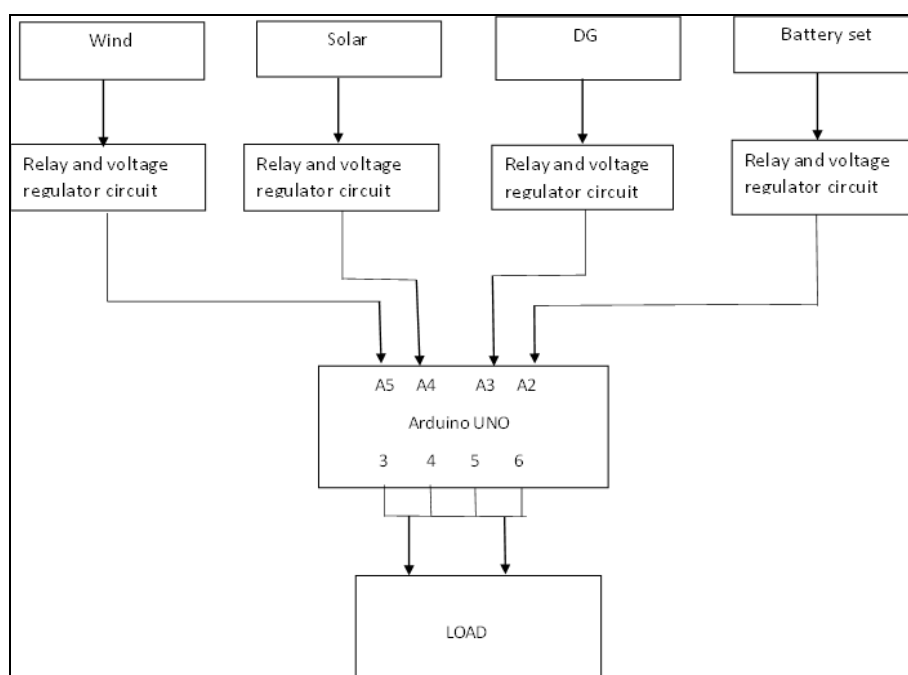


Figure 1 - Block Diagram of Proposed Intelligent Hybrid Power Management System

3.2 Hardware Implementation

The prototype includes voltage sensors, relays, power conditioning circuits, and a battery storage unit. Solar and wind sources provide DC power, while the grid and DG are represented through adapted supplies for testing. The battery serves as an energy buffer and is monitored for charging and discharging conditions. A hardware prototype was assembled on a mounting board with visual indicators to display active power sources and load status. Figure 2 represents a hardware prototype of the Arduino-based hybrid power management system.

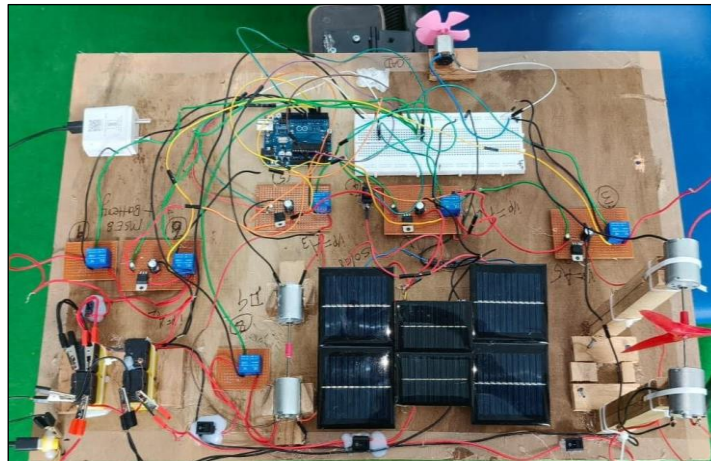


Figure 2 - Hardware prototype of Arduino-based hybrid power management system

3.3 Control Algorithm

The Arduino continuously evaluates source voltages and executes a priority-based decision process. Renewable sources are given highest priority. When solar or wind power is sufficient, the load is supplied directly and the battery is charged. If renewable power decreases, the battery supplies the load.

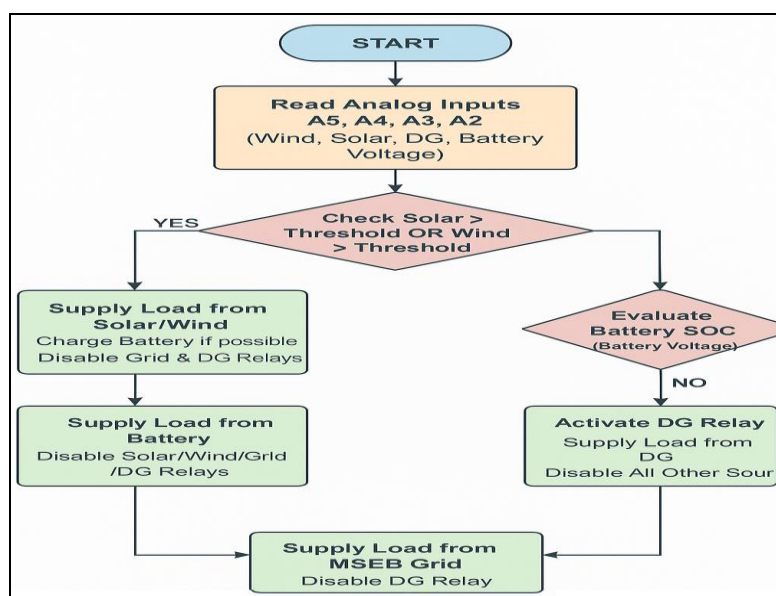


Figure 3 - Flowchart of Arduino-based source selection algorithm

When battery state-of-charge (SOC) falls below a threshold, the system switches to grid power. The diesel generator is activated only when all other sources are unavailable.

Figure 3 represents a flowchart of Arduino-based source selection algorithm. The software includes noise filtering, source-interlocking protection, and switching delays to ensure stable relay operation and prevent simultaneous source connections.

4. Results and Discussion

The prototype was tested under varying renewable and load conditions. Solar variability was simulated using artificial lighting, while wind conditions were created using controlled airflow.

Results demonstrated successful operation of the control system. Under sufficient renewable conditions, the load was powered entirely by solar and wind sources while charging the battery. Figure 4 shows the load operation using solar PV source and Figure 5 shows the load operation using the wind energy source.

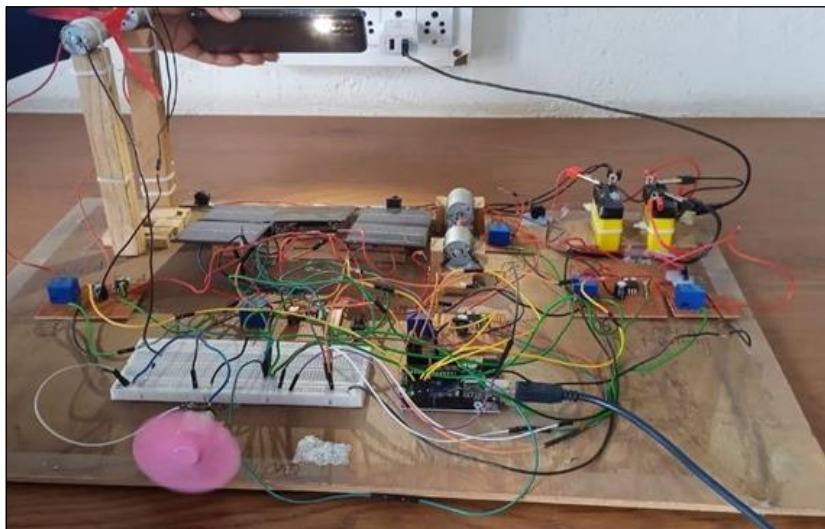


Figure 4 - Load operation using solar PV source

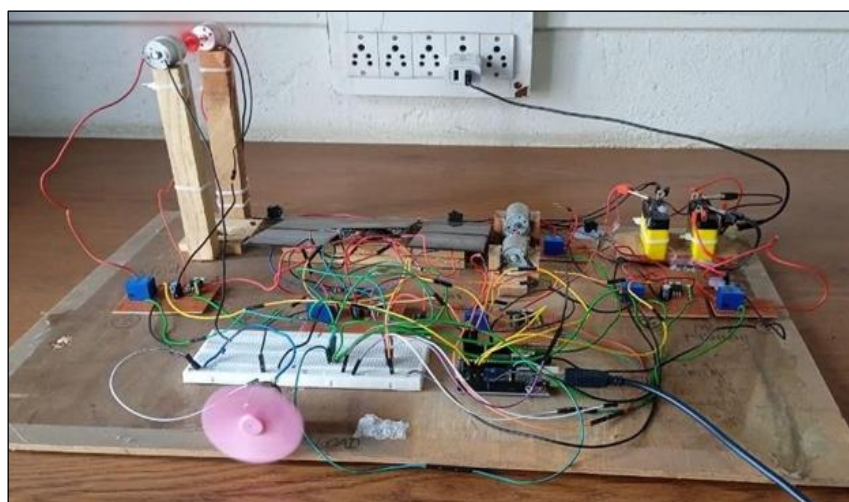


Figure 5 - Load operation using wind energy source

As renewable availability decreased, the controller automatically shifted to battery operation without interrupting the load. Figure 6 shows the load powered by the battery and grid support

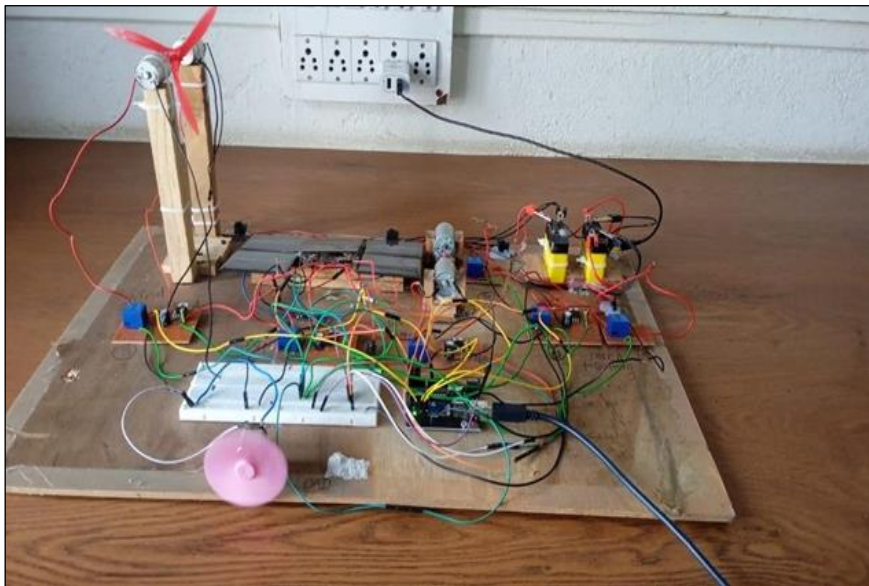


Figure 6 - Load powered by battery and grid support

Grid support was activated when battery SOC reached the minimum threshold, and the DG operated only during simulated grid failure conditions. Figure 7 shows the load powered by diesel generator during emergency operation.

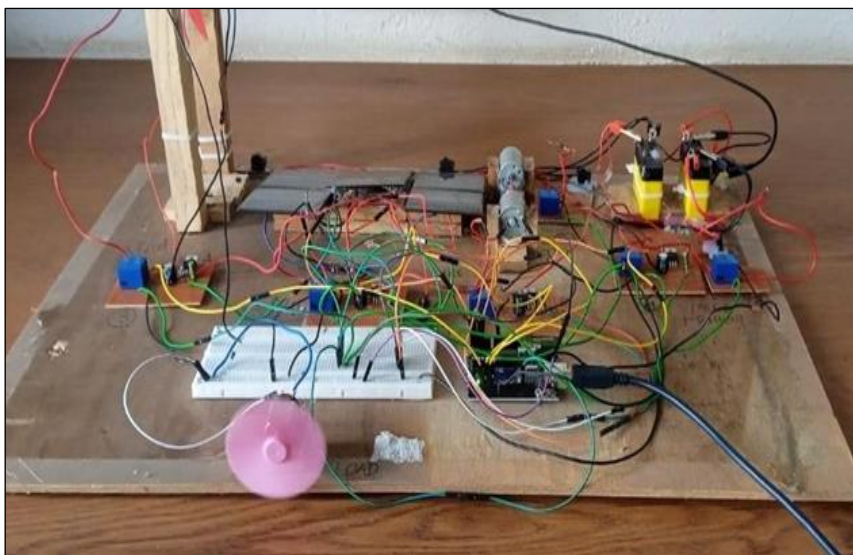


Figure 7 - Load powered by diesel generator during emergency operation

The Arduino controller provided reliable voltage monitoring and accurate relay control. No relay overlap or unsafe source coupling was observed, confirming system safety and operational stability.

4.1 Experimental Test Conditions

Table 1 - Experimental test conditions

Parameter	Test Range	Notes
Solar PV voltage	6–19 V	Artificial light used for variability
Wind generator output	3–15 V	Airflow from table fan
Battery SOC	20%–95%	12 V sealed lead-acid battery
Grid Input	0 or ON	Via 12 V adaptor
DG Output	12 V	Simulated DC generator

4.2 System Performance Metrics

Table 2 - Source selection response time

Operating Condition	Measured Relay Switching Time (ms)	Interpretation
Solar → Battery	142 ms	Fast and seamless transition
Wind → Solar	128 ms	No observable load dropout
Battery → Grid	155 ms	Within acceptable microgrid tolerance
Grid → DG	180 ms	Slightly higher but acceptable
DG → Solar	135 ms	Automatic return to renewables

Table 3 - Load availability across tests

Source Mode	Availability (%) Over 6-Hour Test	Notes
Solar	52%	High irradiance period
Wind	18%	Moderate airflow conditions
Battery	22%	Discharge during low renewable input
Grid	7%	Used only when battery < 20%
DG	1%	Extremely rare; used only in full failure mode

Table 4 - Reliability assessment

Parameter	Measured Value	Requirement	Pass/Fail
Supply continuity	100%	99%+	✓ Pass
Overlap protection	0 occurrences	0 allowed	✓ Pass
Relay misfire	0	<1%	✓ Pass
Sensor noise tolerance	±0.08 V	±0.10 V	✓ Pass

4.3 Comparative Analysis

Compared with existing solar-battery, solar-wind-battery, and solar-grid systems, the proposed IHPMS integrates five energy sources, provides full automatic priority control, achieves faster switching (128–180 ms), supports 70% renewable energy contribution, and includes diesel generator backup for emergency operation. The obtained results are consistent with findings reported in earlier hybrid energy

studies, which indicate that integrating renewable sources with intelligent control strategies significantly improves system reliability and renewable penetration levels.

5. Conclusion

An Arduino-based Intelligent Hybrid Power Management System integrating solar PV, wind energy, battery storage, utility grid, and diesel generator sources was designed and implemented. The system provided automated monitoring, intelligent source selection, and seamless switching for uninterrupted power supply. Experimental results showed reliable operation with switching times below 200 ms and complete load continuity. Renewable sources supplied about 70% of the total energy, while grid and diesel generator contributions were limited to 7% and 1%, respectively. Battery storage effectively supported the load during renewable energy shortages without switching conflicts or safety concerns. Compared with existing systems, the proposed IHPMS offers improved scalability, faster switching, better energy utilization, and enhanced reliability. The system demonstrates strong potential for rural electrification, standalone power systems, educational laboratories, and small-scale microgrids.

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