Monitoring And Performance Analysis of Solar-Piezoelectric Hybrid Energy System

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Abstract

This research presents a hybrid energy harvesting system designed to generate electrical power from both solar and piezoelectric sources. The system utilizes environmental energy such as sunlight and mechanical vibrations to produce usable electricity. Solar panels generate power during daylight, while piezoelectric sensors capture mechanical vibrations or pressure and convert them into electrical energy at any time. Sensors are integrated into the system to monitor parameters such as solar panel voltage, piezoelectric output, and battery charge levels. A microcontroller continuously processes this data and manages the overall system operation. The collected data are transmitted to a cloud platform using Internet of Things (IoT) technology, enabling real-time monitoring of energy production, sensor readings, and battery status through an online dashboard. This remote monitoring capability helps detect system issues quickly, improves energy management, and reduces the need for frequent manual maintenance. By combining renewable energy sources and cloud-based monitoring, the proposed hybrid system provides an efficient, reliable, and eco-friendly solution for sustainable energy generation suitable for both rural and urban applications.

Keywords: Hybrid energy, Solar energy, Piezoelectric, Energy harvesting, Monitoring, Fault detection, Performance analysis, Voltage, Arduino, ESP8266, Thing Speak, Renewable energy.

I. Introduction

The increasing demand for energy and the growing concern over environmental sustainability have accelerated the development of renewable energy technologies. Conventional energy sources such as coal, oil, and natural gas are limited and contribute significantly to environmental pollution, global warming, and climate change. As energy consumption continues to rise worldwide, it has become essential to explore sustainable and eco-friendly alternatives that can meet future energy demands without causing long-term damage to the environment. Renewable energy harvesting technologies have therefore gained considerable attention in recent years [3], [15].

Among various renewable resources, solar energy is one of the most widely utilized sources due to its abundance, availability, and ease of implementation. Photovoltaic (PV) systems convert sunlight directly into electrical energy and are widely adopted for power generation in many applications. However, solar power generation is highly dependent on sunlight availability and environmental conditions, which can reduce its efficiency during cloudy weather or nighttime [4], [15]. These limitations have encouraged researchers to explore hybrid energy harvesting systems that combine multiple energy sources to ensure a more reliable and continuous power supply [1], [2], [3].

Hybrid energy harvesting systems integrate different renewable sources to improve efficiency and reliability. In particular, combining solar energy with vibration-based energy harvesting techniques such as piezoelectric systems has shown promising potential for continuous energy generation [1], [2]. Piezoelectric materials have the ability to convert mechanical stress, vibration, or pressure into electrical energy, making them suitable for harvesting energy from environmental movements or human activities [5], [10], [13]. Studies have demonstrated that low-level vibrations and mechanical forces can be effectively used as alternative power sources for small electronic devices and wireless sensor networks [6], [11], [12].

In this project, a hybrid energy harvesting system is designed and implemented by integrating solar panels with piezoelectric sensors. Solar panels generate electrical energy from sunlight during the daytime and serve as the primary energy source. In addition, piezoelectric sensors are used to harvest energy from mechanical vibrations or pressure generated by human movement. These sensors can be placed in locations such as walkways or public areas where frequent mechanical pressure occurs. When a person steps on the sensor, the applied mechanical force is converted into electrical energy, enabling power generation even when sunlight is not available.

By combining solar and piezoelectric energy sources, the hybrid system ensures continuous energy production under varying environmental conditions. During daytime, solar panels produce the majority of the electrical power, while piezoelectric sensors contribute additional energy through mechanical movements. During nighttime or low sunlight conditions, the piezoelectric system continues to generate electricity, thereby reducing dependency on a single energy source and improving the overall efficiency and reliability of the system [1], [4].

The system also incorporates several sensors and monitoring components to track the performance of each energy source. Voltage sensors measure the electrical output from the solar panels, while piezoelectric sensors convert mechanical forces into electrical signals. The generated energy is stored in a battery storage unit so that it can be utilized whenever required. A microcontroller acts as the central control unit, continuously monitoring system parameters such as voltage levels, current, and battery charge status to ensure efficient system operation. Efficient power conversion and regulation are essential in such systems and are often achieved using power electronic converters [8].

To further enhance system efficiency and monitoring capability, the proposed system integrates Internet of Things (IoT) technology. The microcontroller collects data from sensors and transmits it to a cloud platform, enabling real-time monitoring of system performance through a web interface or mobile application. IoT-based monitoring systems have proven effective in tracking renewable energy systems and improving operational efficiency [9], [17], [18]. Users can observe energy production levels, battery status, and system performance in real time, allowing early detection of faults and improved energy management strategies [16].

In conclusion, the proposed hybrid energy harvesting system provides an efficient and environmentally friendly approach to sustainable energy generation. By integrating solar and piezoelectric technologies with IoT-based monitoring, the system ensures continuous power generation, improved efficiency, and intelligent energy management. Such systems can be effectively implemented in smart cities, public infrastructure, and remote locations, contributing to a cleaner and more sustainable energy future.

II. Literature Survey

[1] Ahsan Ali, "Advancements in energy harvesting techniques for sustainable IoT devices" (Elsevier, 2025). This paper presents a comprehensive review of modern energy harvesting techniques aimed at supporting sustainable and battery-free Internet of Things (IoT) systems. It explores multiple energy sources such as solar, thermal, mechanical, and radio frequency (RF), explaining how each method can be utilized to power low-energy devices. The study emphasizes that relying on a single source of energy may not always be sufficient due to environmental variations. Therefore, it highlights the importance of hybrid energy harvesting systems, where multiple sources are combined to ensure continuous power supply. The paper also discusses advanced power management techniques, including efficient energy storage and conversion methods, which help in maximizing the utilization of harvested energy. Additionally, it focuses on improving the lifetime and reliability of IoT devices by reducing dependency on conventional batteries. The research concludes that integrating hybrid harvesting methods with smart power management can significantly enhance the performance and sustainability of IoT deployments, especially in remote and long-term applications.

[2] Avdhut P. Pawade, "Hybrid footstep power generation: A sustainable approach to energy harvesting" (IJIRT, 2025). This paper introduces a practical hybrid energy harvesting system that combines footstep-based piezoelectric energy with solar power generation. The system is specifically designed for high-traffic public areas such as railway stations, shopping malls, and sidewalks, where mechanical energy from human movement is readily available. The piezoelectric sensors generate electricity when pressure is applied through footsteps, while solar panels provide additional energy during daylight hours. The generated energy is stored in a 12-volt battery, ensuring a continuous power supply even when one source is unavailable. The system is used to power small electrical loads such as LED lighting, demonstrating its practical application. A key feature of the project is its real-time monitoring capability using an LCD display, which shows the amount of energy generated and stored. The study highlights the feasibility, cost-effectiveness, and sustainability of the system, making it suitable for real-

world implementation. Overall, the paper focuses on combining renewable sources to improve efficiency and promote green energy solutions in everyday environments.

III. Proposed System

To achieve sustainable and consistent energy harvesting, this project proposes a hybrid system that combines solar and piezoelectric energy sources along with automated monitoring and power analysis. The primary goal of this system is to ensure continuous energy generation under varying environmental conditions while maintaining a stable and efficient output. By integrating multiple renewable sources and intelligent control techniques, the system aims to overcome the limitations associated with individual energy harvesting methods and improve overall performance. During daytime, the solar panel acts as the main energy source by converting sunlight into electrical energy through the photovoltaic effect. Solar energy is widely used due to its availability, eco-friendly nature, and ability to generate significant power without producing harmful emissions. It provides a dependable and steady power supply when sunlight is present. However, the efficiency of solar panels is affected by environmental conditions such as cloudy weather, seasonal variations, and the absence of sunlight during nighttime. These limitations reduce the reliability of using solar energy alone for continuous power generation. To overcome this issue, the system incorporates a piezoelectric energy harvesting unit. Piezoelectric sensors have the ability to generate electrical energy when mechanical stress or vibrations are applied. In this project, the sensors produce energy from pressure, motion, or disturbances such as human footsteps or moving objects. This enables energy generation even when solar power is unavailable. For instance, in public areas with frequent human movement, the piezoelectric system can continuously generate small amounts of energy. When combined with solar energy, this creates a more balanced and reliable system capable of functioning under different environmental conditions. However, both solar and piezoelectric sources produce variable outputs depending on factors such as sunlight intensity and mechanical activity. These fluctuations can lead to unstable voltage levels, which may affect the performance and safety of connected devices. To address this challenge, a buck-boost converter is incorporated into the system. This converter is responsible for maintaining a stable and acceptable output voltage regardless of variations in input. It can either increase (boost) or decrease (buck) the voltage as required. Additionally, it helps in combining and regulating the energy generated from both sources, ensuring smooth and efficient power flow within the system. The regulated output is then connected to a battery for energy storage. The battery stores excess energy generated from both the solar and piezoelectric units and supplies power to the load whenever needed. This is particularly useful during periods of low energy generation, such as nighttime or low activity conditions. The storage system enhances the reliability and continuity of power supply, making the system suitable for practical applications. For monitoring and user interaction, an LCD display is integrated into the system to show important parameters such as solar voltage, piezoelectric output voltage, and battery voltage in real time. This helps users easily understand the performance of the system. Additionally, the system can be extended to include cloud-based monitoring using IoT technology, allowing users to access real-time data remotely and take necessary actions if any issue occurs.

The Arduino Uno microcontroller serves as the central processing unit of the system. It collects data from sensors, processes the information, and performs analysis to detect any abnormalities or faults. Relays are used for efficient switching and control of the energy sources. Overall, this proposed hybrid system enhances energy efficiency, reliability, and usability, making it a practical solution for sustainable energy generation in modern applications.

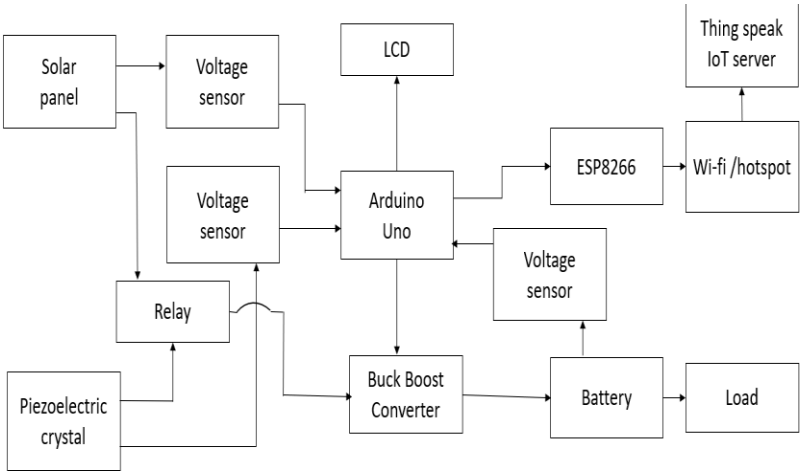

Fig 1: Block Diagram of Proposed Method

The proposed system is designed to generate sustainable energy by combining solar and piezoelectric sources in a hybrid energy harvesting model. Fig 1 shows the block diagram of the project. The methodology begins with capturing energy from two different inputs to ensure continuous power generation under varying environmental conditions. Solar panels are used to convert sunlight into electrical energy during the daytime, while piezoelectric sensors generate electricity from mechanical vibrations such as footsteps or pressure. Both energy sources produce variable outputs depending on environmental factors like sunlight intensity and human movement. To handle this variation, the generated energy from both sources is passed through a buck-boost converter. This converter regulates the voltage by either increasing or decreasing it, ensuring a stable and usable output level. It also helps in combining the energy from both sources into a single regulated output. The regulated power is then stored in a rechargeable battery. This storage unit plays a crucial role in maintaining a continuous power supply, especially during low generation periods such as nighttime or when there is less movement. The stored energy can later be used to power small loads or devices. To monitor system performance, sensors are used to measure parameters such as solar voltage, piezoelectric voltage, and battery level. These values are displayed on an LCD screen for real-time observation. Additionally, a microcontroller processes the data and ensures proper system operation. The methodology also includes an automated monitoring system that helps users track system performance and identify any issues. This improves efficiency, reliability, and ease of maintenance. Overall, the hybrid approach ensures better energy utilization and provides a practical solution for sustainable power generation.

Fig 2: Experimental Setup

Fig 2 shows the Experimental Setup of the project. Automated monitoring and performance analysis of the system is done using ESP8266. The ESP8266 module is connected with the Arduino for collecting the real time data and sent to the IoT server for performance analysis. The Thing speak IoT server is used to display the data. Using wifi/mobile hotspot the data are transferred. The hardware design of the proposed system consists of several key components that work together to achieve efficient energy harvesting and monitoring. The primary components include a solar panel, piezoelectric sensors, buck-boost converter, battery, Arduino Uno microcontroller, LCD display, relays, and necessary supporting circuits.

The solar panel is used to capture sunlight and convert it into electrical energy. It serves as the main energy source during daytime. The piezoelectric sensors are placed in areas where mechanical pressure or vibrations occur, such as walkways. These sensors generate electrical energy when subjected to stress or movement, providing an additional energy source.
Since both sources produce variable voltage, a buck-boost converter is used to regulate the output. This component ensures that the voltage remains stable by stepping it up or down as required. It also helps in combining the outputs from both sources efficiently.

The regulated energy is stored in a rechargeable battery, typically a 12V battery. This battery acts as an energy reservoir, supplying power to the load when generation is low. To control the flow of power between components, relays are used. They help in switching between energy sources and managing the system operation effectively.

The Arduino Uno microcontroller acts as the central control unit. It receives input signals from sensors and controls the overall functioning of the system. Voltage sensors are used to measure the output of the solar panel, piezoelectric unit, and battery.
An LCD display is connected to the microcontroller to show real-time data such as voltage levels and system status. Supporting components like resistors, capacitors, and connecting wires ensure proper circuit functionality. Overall, the hardware design is simple, cost-effective, and suitable for practical implementation.

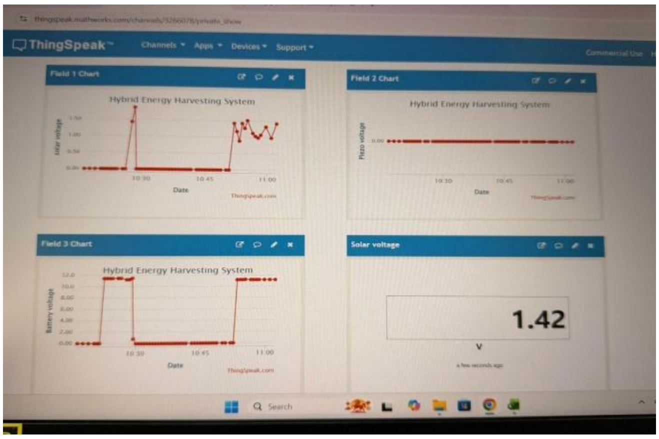

Fig 3: Hybrid Energy Monitoring Dashboard

The software design of the system employs arduino IDE and Thing speak IoT server. Fig 3 shows the graphical representation of the field voltages. The dashboard displays the data of field 1, field 2, field 3 represents the solar voltage, piezo voltage and battery voltage. The data can be exported in excel format, All the data are stored with respect to date and time. The software design of the system is responsible for controlling, monitoring, and analysing the performance of the hybrid energy harvesting setup. The system is programmed using the Arduino Integrated Development Environment (IDE), where the logic for data collection, processing, and display is implemented.

The software begins by initializing all input and output components such as voltage sensors, LCD display, and relays. Once the system starts, the Arduino continuously reads input data from the sensors connected to the solar panel, piezoelectric module, and battery. These readings are taken at regular intervals to ensure accurate monitoring of system performance.

The collected data is then processed within the microcontroller. Basic calculations are performed to convert analog signals into meaningful voltage values. The software also checks whether the values are within acceptable limits. If any abnormal condition is detected, such as low battery voltage or irregular output, the system can be programmed to alert the user or take corrective action.

The processed data is displayed on the LCD screen in real time. This allows users to easily monitor parameters like solar voltage, piezoelectric voltage, and battery level. The display is updated continuously, providing a clear understanding of the system's working condition.

In addition to local monitoring, the system can be extended to include IoT functionality. Data can be transmitted to a cloud platform using communication modules, allowing remote monitoring through mobile or web applications. This enhances user convenience and system control.

The software also manages the operation of relays for switching between energy sources when needed. Overall, the software design ensures smooth operation, accurate monitoring, and efficient control of the hybrid energy harvesting system.

IV. Result And Discussion

The developed hybrid energy harvesting system was successfully designed, implemented, and tested under different environmental conditions to evaluate its performance, efficiency, and reliability. The system integrates solar and piezoelectric energy sources to ensure continuous and optimized power generation. The experimental analysis clearly demonstrates the advantages of combining multiple renewable sources compared to relying on a single energy source.

During the testing phase, the solar panel produced a maximum output voltage in the range of 11–12 V under peak sunlight conditions. This confirms that solar energy serves as the primary and most stable source of power during daytime. However, it was also observed that the output of the solar panel varies depending on factors such as sunlight intensity, weather conditions, and partial shading. In contrast, the piezoelectric sensor generated an average voltage between 2 V and 6 V, depending on the level of mechanical vibrations or pressure applied. Although the energy generated from the piezoelectric module is relatively smaller, it provides an important supplementary power source, especially in the absence of sunlight or during low-light conditions.

Table 1. Field Voltages, Current and Ratings

Field	Voltage(V)	Current(A)	Ratings
Solar	12	0.78	9.36W
Piezo electric	0.7	0.05	0.035W
Batery	12	7	12V7Ah

The table 1 shows the electrical parameters and performance of key components in a hybrid energy harvesting system, namely the solar panel, piezoelectric sensor, and battery. The solar panel operates at 12 V and delivers a current of 0.78 A, resulting in a power output of 9.36 W. This indicates that it is the primary and most efficient energy source in the system, especially under good sunlight conditions. It is mainly responsible for charging the battery and supplying power to the load.

On the other hand, the piezoelectric sensor generates a much smaller output of 0.7 V and 0.05 A, producing only 0.035 W of power. Although its contribution is minimal compared to the solar panel, it plays an important role in harvesting energy from mechanical vibrations, making the system more sustainable by utilizing ambient energy sources.

The battery is rated at 12 V and 7 Ah, which defines its storage capacity. It can supply 7 A for one hour or a lower current for a longer duration. The battery acts as an energy storage unit, ensuring a continuous and stable power supply even when the energy generation from solar and piezoelectric sources is insufficient or unavailable.

A key component of the system is the buck–boost converter, which plays a vital role in regulating the combined output from both energy sources. It ensures that a stable and constant voltage is maintained for efficient battery charging, regardless of fluctuations in input. This regulation improves the safety and performance of the system while preventing voltage-related issues.

The battery charging performance was continuously monitored throughout the experiment. The results indicate that during daytime, the solar panel contributes the majority of the energy, while the piezoelectric module adds additional power when mechanical disturbances occur. This hybrid operation ensures a continuous and reliable energy supply under varying conditions.

The real-time monitoring system, implemented using Arduino Uno and ESP8266, successfully transmitted system data to the Thing Speak cloud platform. Important parameters such as solar voltage, piezoelectric voltage, and battery voltage were displayed graphically, making it easier to analyse system behaviour over time. The system also showed a quick response to voltage variations, enabling early detection of abnormalities such as sudden drops in solar output due to environmental changes.

Furthermore, the relay-based load control mechanism operated efficiently by adjusting according to battery conditions, ensuring optimal energy utilization. Overall, the results confirm that the proposed hybrid system significantly improves energy efficiency, system stability, and operational reliability, making it a practical solution for real-world renewable energy applications. Additionally, the system demonstrated good adaptability to real-time environmental changes, maintaining stable performance under varying conditions. The integration of multiple energy sources reduced dependency on a single input, enhancing overall system robustness. The monitoring system also improved user awareness by providing clear and continuous performance data. These results highlight the potential of the proposed system for scalable and future smart energy applications.

V.Conclusion

The automated monitoring and performance analysis of a hybrid energy harvesting system play a crucial role in improving energy efficiency, reliability, and overall system stability. By combining solar and piezoelectric energy sources, the system is capable of generating power continuously under different environmental conditions. Solar energy provides a steady output during daytime, while the piezoelectric system generates energy from mechanical vibrations such as footsteps or motion. This combination ensures that the system does not depend on a single source, thereby improving consistency in power generation. One of the key advantages of this system is its real-time monitoring capability. By integrating cloud-based platforms and IoT technology, important system parameters such as voltage levels, energy generation, and battery status can be continuously tracked. This allows users to monitor the system from remote locations and gain a clear understanding of its performance. Real-time data also helps in identifying any abnormalities or faults at an early stage, enabling quick corrective actions before the issue becomes serious. The inclusion of automated monitoring reduces the need for frequent manual inspections, thereby minimizing maintenance efforts and operational costs. It also enhances system reliability by ensuring that all components are functioning within safe limits. Additionally, efficient power management techniques help in optimizing the usage of harvested energy, reducing wastage and improving overall system performance. Another important benefit of this approach is the extension of the system's operational lifespan. By continuously analysing performance data and maintaining stable operating conditions, the system experiences less stress and wear over time. This makes it more durable and suitable for long-term applications. Overall, the proposed hybrid energy harvesting system not only improves energy management but also supports the development of sustainable and self-powered solutions. It can be effectively implemented in applications such as smart sensors, remote monitoring systems, wearable devices, and public infrastructure. By promoting the use of renewable energy sources and intelligent monitoring, this approach contributes to building a cleaner, greener, and more energy-efficient future.

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