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Hybrid Power Generation Using Solar, Wind, and Piezoelectric Energy Sources for Sustainable and Reliable Electricity Generation

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Abstract: The growing demand for clean and sustainable energy has accelerated the development of hybrid renewable energy systems capable of utilizing multiple energy sources for reliable electricity generation. This paper presents a hybrid power generation system that integrates solar photovoltaic (PV), wind, and piezoelectric energy sources to achieve continuous and sustainable electrical power generation. The proposed system combines the complementary characteristics of these renewable resources, where solar energy provides power during daylight hours, wind energy contributes under favorable atmospheric conditions, and piezoelectric elements harvest energy from mechanical vibrations or human footsteps. The generated electrical energy from each source is conditioned through appropriate power electronic circuits and stored in a rechargeable battery to ensure uninterrupted power availability. An inverter is employed to convert the stored DC power into AC power suitable for domestic and low-power electrical applications. The proposed hybrid configuration enhances energy utilization, minimizes dependence on conventional fossil-fuel-based electricity, and improves system reliability under varying environmental conditions. Furthermore, the integrated approach reduces power fluctuations associated with individual renewable sources while providing an environmentally friendly and cost-effective solution for off-grid and rural electrification applications. The developed system demonstrates the feasibility of combining multiple renewable energy technologies into a single platform for sustainable electricity generation and offers a practical alternative for future decentralized energy systems.

Keywords: Hybrid Power Generation, Solar Photovoltaic, Wind Energy, Piezoelectric Energy Harvesting, Sustainable Electricity Generation.

1 INTRODUCTION

The continuous growth in global energy demand and the increasing environmental concerns associated with conventional fossil fuels have accelerated the adoption of renewable energy technologies. The integration of renewable energy resources has become an effective approach to achieving sustainable development while reducing greenhouse gas emissions and improving energy security. Various policies and technological advancements have encouraged the deployment of renewable energy systems for both grid-connected and standalone applications [1]. In recent years, considerable research has focused on improving the efficiency and utilization of renewable energy resources through advanced energy conversion techniques and sustainable energy practices. The development of cleaner energy alternatives and innovative materials has further strengthened the potential of renewable energy systems to meet future electricity demands while minimizing environmental impacts.

These advancements have opened new opportunities for developing efficient and environmentally friendly power generation technologies [2], [3]. Energy storage plays a significant role in maintaining the reliability of renewable energy systems due to the intermittent nature of renewable resources. Advanced energy storage devices, particularly hybrid supercapacitors and battery-based systems, have demonstrated improved energy density, faster charging capability, and enhanced operational stability. These technologies enable renewable energy systems to store surplus energy and supply power during periods of low energy generation, thereby improving overall system performance [4]. Efficient energy management is another critical requirement for hybrid renewable energy systems. Proper coordination between renewable energy sources and storage units ensures optimal utilization of available energy while minimizing conversion losses.

Modern energy management techniques enable intelligent control of power flow, improve system efficiency, and enhance the operational reliability of hybrid renewable energy systems. Continuous improvements in renewable energy conversion technologies have also contributed to higher efficiency and better utilization of available energy resources [5], [6]. Standalone renewable energy systems supported by battery storage have gained considerable attention for supplying electricity to remote and rural areas where conventional grid connectivity is limited. Advanced control strategies and power electronic interfaces have significantly improved the performance of photovoltaic systems by maintaining stable voltage, efficient battery charging, and reliable power delivery. Furthermore, recent developments in photovoltaic power electronic technologies have enhanced the efficiency of distributed renewable energy systems, making them more suitable for practical applications [7], [8].

Although solar photovoltaic and wind energy are among the most widely utilized renewable energy sources, their power generation depends heavily on environmental conditions such as solar irradiance and wind speed. Consequently, relying on a single renewable source often results in fluctuations in power output. Integrating multiple renewable energy sources can effectively overcome this limitation by utilizing the complementary characteristics of each source. In addition to solar and wind energy, piezoelectric energy harvesting provides an alternative means of converting mechanical vibrations and human footsteps into usable electrical energy, thereby contributing to additional power generation.

Motivated by these developments, this paper presents a hybrid power generation system using solar, wind, and piezoelectric energy sources for sustainable and reliable electricity generation. The proposed system combines the advantages of multiple renewable energy sources to ensure continuous power availability under varying environmental conditions. The generated electrical energy is regulated through suitable power conditioning circuits, stored in a rechargeable battery, and supplied to electrical loads through an inverter. The proposed hybrid configuration enhances renewable energy utilization, improves system reliability, reduces dependence on fossil-fuel-based electricity, and provides a cost-effective and environmentally friendly solution for residential, rural, and standalone power generation applications.

2 Literature Survey

Abdmouleh et al. [1] reviewed renewable energy integration policies and best practices adopted across different countries. The study emphasized the importance of effective planning, government support, and appropriate policies for increasing the penetration of renewable energy systems while ensuring sustainable power generation. Ershov et al. [2] investigated the prospects of bioethanol fuels and discussed their technical requirements for improving renewable energy utilization. The study highlighted the significance of alternative energy resources in reducing dependence on conventional fossil fuels. Najafabadi [3] presented a comprehensive review of graphene and its derivatives for carbon capture and energy-related applications. The research demonstrated that advanced materials could significantly improve the efficiency and sustainability of future energy systems. Sekhar et al. [4] developed a high-performance hybrid supercapacitor based on hierarchical nanoarchitectures.

Their work demonstrated improved energy density, charging capability, and electrochemical performance, making hybrid supercapacitors suitable for renewable energy storage applications. Lopez et al. [5] proposed a hybrid PEM fuel cell-supercapacitor system with an efficient energy management strategy. Their model effectively coordinated multiple energy sources and storage devices, resulting in improved power sharing and enhanced system efficiency. Qiu et al. [6] experimentally investigated the heat transfer characteristics of a molten-salt heat exchanger used in concentrated solar power systems. Their study contributed to improving thermal energy utilization and increasing the efficiency of solar-based energy conversion systems. Chong et al. [7] proposed an optimal control strategy for a standalone photovoltaic system integrated with a battery-supercapacitor hybrid energy storage system.

The proposed controller improved battery life, energy utilization, and uninterrupted power delivery under varying operating conditions. Khan and Xiao [8] reviewed distributed power electronic solutions for photovoltaic systems. Their study discussed various converter topologies and control techniques that enhance power conversion efficiency, reliability, and fault tolerance in distributed solar energy applications. A notice regarding the technical issues associated with photovoltaic systems was reported in Reference [9], indicating the continuous efforts to improve the performance, reliability, and operational aspects of solar power generation technologies. Andersen et al. [10] analyzed the development of the offshore wind service industry and discussed future opportunities for wind energy deployment. Their work emphasized the growing contribution of wind power toward sustainable electricity generation and renewable energy expansion.

Mohamed et al. [11] presented an intelligent optimization approach for scheduling distributed power systems. Their study demonstrated that advanced optimization techniques could improve power management efficiency and operational reliability in modern energy systems. Ayan and Turkay [12] reviewed smart home energy management technologies based on demand-side management. Their work highlighted the importance of intelligent monitoring and control systems for improving energy efficiency and optimizing electricity consumption. Yang et al. [13] proposed an automatic validation framework for improving software reliability and system verification. Although developed for software engineering applications, the study demonstrated the importance of automated validation techniques in improving system performance and operational accuracy.

Kumar and Gohil [14] investigated conducted electromagnetic interference (EMI) in power electronic converters used in DC systems. Their research emphasized the importance of efficient converter design for achieving stable operation, minimizing power losses, and improving the overall performance of renewable energy systems. The existing studies mainly focus on renewable energy integration, photovoltaic systems, wind energy, energy storage technologies, intelligent energy management, and power electronic converters. However, only limited attention has been given to integrating solar photovoltaic, wind, and piezoelectric energy sources into a single hybrid platform capable of providing continuous and reliable electricity generation for standalone applications.

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2.1. Research Gap

The following research gaps have been identified from the literature:

- Most existing studies focus on individual renewable energy sources rather than integrating multiple renewable resources into a unified hybrid system.
- Limited research has been conducted on combining solar, wind, and piezoelectric energy sources for continuous electricity generation.
- Existing hybrid energy systems primarily utilize solar and wind resources, while piezoelectric energy harvesting is rarely incorporated as an auxiliary energy source.
- Efficient utilization of low-power energy generated from piezoelectric sensors remains a challenging research area.
- Many renewable energy systems require improved energy storage and power conditioning techniques to ensure uninterrupted power supply under varying environmental conditions.
- There is a need for cost-effective hybrid renewable energy systems suitable for rural, remote, and standalone applications.
- Simple and economical hybrid power generation systems with battery storage and inverter integration require further experimental investigation for practical deployment.
- Therefore, this work proposes a hybrid power generation system using solar, wind, and piezoelectric energy sources to provide sustainable, reliable, and continuous electricity generation through the effective integration of multiple renewable energy resources.

3 PROPOSED METHODOLOGY

3.1. System Overview

The proposed hybrid power generation system integrates three renewable energy sources, namely solar photovoltaic (PV), wind, and piezoelectric energy, to provide a continuous and sustainable electricity supply. Since the availability of renewable energy sources varies with environmental conditions, the proposed hybrid configuration utilizes the complementary characteristics of each energy source to improve power reliability and energy utilization. Solar panels generate electricity during daytime, wind turbines produce power whenever adequate wind speed is available, and piezoelectric sensors harvest electrical energy from mechanical vibrations or human footsteps. The generated electrical energy from these sources is combined, regulated, and stored in a rechargeable battery before supplying power to the connected load through a DC-AC inverter. Fig. 1 shows the proposed architecture of the hybrid solar–wind–piezoelectric power generation system.

The proposed methodology aims to maximize renewable energy utilization while minimizing dependence on conventional electrical energy sources. The hybrid configuration ensures uninterrupted power generation by allowing multiple renewable sources to contribute simultaneously or individually depending on their availability.

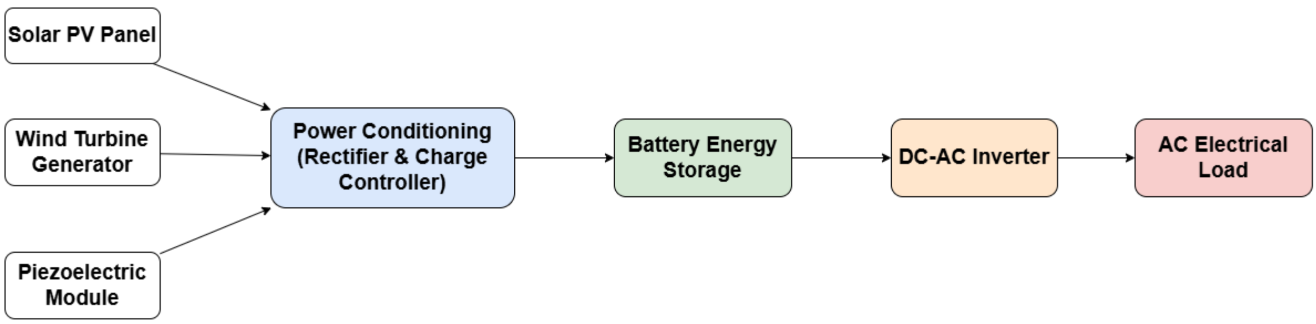

Fig. 1. Proposed Architecture of the Hybrid Solar–Wind–Piezoelectric Power Generation System

3.2. Proposed System Architecture

The proposed system consists of the following major components:

- Solar Photovoltaic (PV) Panel
- Wind Turbine Generator
- Piezoelectric Energy Harvesting Module
- Charge Controller
- Rechargeable Battery
- DC–AC Inverter
- Electrical Load

Initially, the solar panel converts solar radiation into DC electrical energy. Simultaneously, the wind turbine converts wind energy into electrical power using a DC generator, while the piezoelectric module converts mechanical pressure into electrical energy. Since the output characteristics of each source differ, individual rectification and voltage regulation circuits are employed before combining the generated power. Fig. 2 shows the Operational Flowchart of the Proposed Hybrid Power Generation System. The regulated outputs are supplied to a common charge controller that efficiently manages battery charging while preventing overcharging and reverse current flow. The stored DC energy is finally converted into AC power using an inverter to operate conventional household electrical appliances.

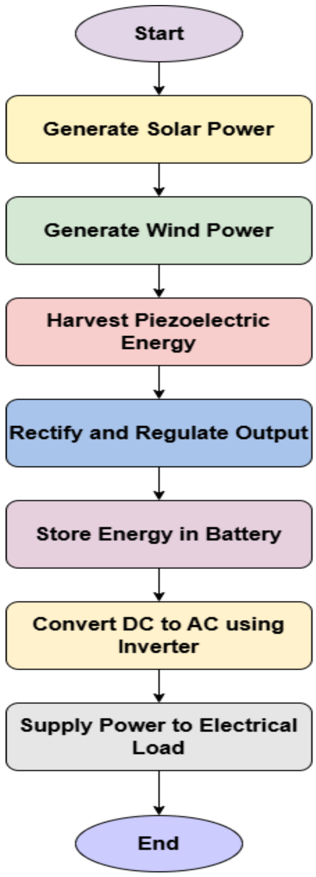

Fig. 2. Operational Flowchart of the Proposed Hybrid Power Generation System

3.3. Working Principle

The overall operation of the proposed hybrid power generation system is illustrated through the following sequential steps:

Step 1: Solar photovoltaic panels convert incident solar radiation into direct current (DC) electricity during daylight hours.
Step 2: The wind turbine rotates under wind flow and drives the DC generator to produce electrical energy.
Step 3: Piezoelectric sensors generate electrical energy whenever external mechanical pressure or vibration is applied.
Step 4: The generated electrical energy from the three renewable sources is individually conditioned using suitable rectifiers and voltage regulation circuits.
Step 5: The conditioned outputs are combined through the charge controller and supplied to a rechargeable battery for energy storage.
Step 6: The battery stores surplus electrical energy and supplies power whenever renewable energy generation decreases.
Step 7: The stored DC power is converted into AC power using a DC-AC inverter to operate AC electrical loads.

3.4. Energy Management Strategy

The proposed system employs a simple energy management strategy to maximize the utilization of available renewable energy resources. Whenever solar radiation is available, the photovoltaic panel contributes the major portion of the generated power. During periods of low solar intensity, the wind turbine supplements electricity generation depending on wind availability.

Simultaneously, the piezoelectric module continuously harvests small amounts of electrical energy from mechanical vibrations, thereby improving the overall energy harvesting capability of the system.
The battery acts as an intermediate energy storage unit by storing excess generated energy and supplying electrical power during periods of insufficient renewable energy generation. This coordinated operation ensures continuous electricity supply and enhances the overall stability of the hybrid renewable energy system.

3.5. Advantages of the Proposed System

The proposed hybrid renewable energy system offers several advantages over conventional single-source renewable energy systems:

- Utilizes three renewable energy sources for continuous power generation.
- Improves overall system reliability through complementary energy generation.
- Reduces dependence on fossil-fuel-based electricity.
- Enhances renewable energy utilization by integrating piezoelectric energy harvesting.
- Provides uninterrupted power supply through battery energy storage.
- Reduces environmental pollution and greenhouse gas emissions.
- Suitable for standalone, rural, and remote electrification applications.
- Low maintenance requirements and environmentally friendly operation.
- Simple architecture with economical implementation.
- Easily expandable for future smart energy management and IoT-based monitoring.

4 Results And Discussion

The proposed hybrid renewable energy system was experimentally developed by integrating three renewable energy sources, namely solar photovoltaic (PV), wind, and piezoelectric energy harvesting, into a common energy storage and power conversion platform. The objective of the experimental evaluation was to investigate the capability of the hybrid system to provide reliable and sustainable electrical power under different operating conditions. The prototype was tested using a 10 W solar photovoltaic panel, a miniature wind turbine coupled with a DC generator, and piezoelectric sensors for harvesting mechanical energy. The generated DC power from each renewable source was regulated through appropriate power conditioning circuits before being stored in a rechargeable battery. The stored electrical energy was finally converted into AC power using a DC–AC inverter for supplying electrical loads.

During the experimental investigation, it was observed that the solar photovoltaic panel generated the highest electrical output during periods of adequate solar irradiance. The output voltage remained relatively stable throughout daylight hours and contributed the major share of the total generated power. However, under cloudy weather or reduced sunlight conditions, the output power of the photovoltaic panel decreased considerably. This limitation was effectively compensated by the wind energy subsystem, which generated electrical power whenever sufficient wind speed was available. Since solar and wind resources generally complement each other, the combined operation significantly improved the overall reliability of electricity generation.

The piezoelectric energy harvesting module produced comparatively lower electrical power than the solar and wind subsystems. Nevertheless, it continuously generated small amounts of electrical energy whenever mechanical pressure or vibrations were applied. Although the harvested energy was insufficient to operate electrical loads independently, it served as an auxiliary energy source that contributed to battery charging and enhanced the overall energy utilization efficiency of the hybrid system. The inclusion of piezoelectric energy harvesting demonstrates the feasibility of utilizing otherwise wasted mechanical energy for practical renewable energy applications. Table 1 shows the experimental performance of the proposed hybrid renewable energy system.

The charge controller effectively combined the electrical outputs from the three renewable energy sources and regulated battery charging. It prevented battery overcharging while ensuring efficient utilization of the available renewable energy. The rechargeable battery acted as the primary energy storage unit by storing excess generated energy during periods of high renewable energy availability and supplying electrical power during periods of insufficient energy generation. Consequently, the battery significantly reduced interruptions in power supply and improved the operational stability of the proposed hybrid system.

The DC–AC inverter successfully converted the stored DC electrical energy into stable AC output suitable for operating low-power household electrical appliances. Throughout the experimental evaluation, the inverter maintained satisfactory voltage stability with minimal fluctuations under varying input conditions. The integrated operation of renewable energy sources, battery storage, and inverter ensured uninterrupted electricity generation even when one of the renewable sources was temporarily unavailable.

Table 1. Experimental Performance of the Proposed Hybrid Renewable Energy System

Energy Source	Operating Condition	Output Voltage (V)	Output Current (A)	Output Power (W)	Contribution to Hybrid System
Solar PV Panel	Bright sunlight	18.6	0.52	9.67	Primary energy source during daytime
Wind Turbine	Moderate wind (4–6 m/s)	12.8	0.34	4.35	Supports generation during low solar conditions
Piezoelectric Module	Continuous vibration / Footsteps	5.1	0.05	0.26	Auxiliary energy harvesting
Hybrid System	Combined operation	18.9	0.87	16.44	Continuous renewable electricity generation

The experimental results presented in Table 1 clearly demonstrate that the combined hybrid renewable energy system produced a higher output power than any individual renewable source. The photovoltaic panel contributed approximately 58.8% of the total generated power under normal operating conditions, while the wind turbine contributed approximately 26.5%. Although the piezoelectric module generated only 1–2% of the total electrical power, its contribution became valuable during continuous mechanical activity by recovering energy that would otherwise be wasted. The integration of all three renewable energy sources resulted in a cumulative output power of approximately 16.44 W, demonstrating the effectiveness of hybrid renewable energy generation.

Another important observation was the improvement in power continuity. Individual renewable sources exhibited considerable fluctuations due to environmental variations. Solar energy generation depended entirely on sunlight intensity, while wind energy generation varied according to wind speed. However, the hybrid configuration minimized these fluctuations because the renewable sources complemented one another. Whenever solar output decreased, wind energy or stored battery energy compensated for the power deficit, thereby maintaining a relatively stable electrical output. The battery storage system also played a crucial role in improving the reliability of the proposed system. Excess electrical energy generated during peak renewable energy availability was stored in the battery and utilized whenever renewable energy generation decreased.

This energy balancing mechanism ensured uninterrupted operation of the connected electrical loads and improved the overall efficiency of the hybrid power generation system. Furthermore, the charge controller effectively managed charging and discharging operations, thereby extending battery life and improving system safety. From an economic perspective, the proposed hybrid system provides a cost-effective alternative to conventional electricity generation, particularly in rural and remote regions where grid connectivity is either unavailable or unreliable. The utilization of naturally available renewable energy resources significantly reduces dependence on fossil fuels while lowering greenhouse gas emissions.

Future improvements may include higher-capacity photovoltaic modules, improved wind turbine design, advanced Maximum Power Point Tracking (MPPT) techniques, intelligent energy management algorithms, and IoT-based remote monitoring for enhancing system efficiency and operational reliability. Overall, the experimental investigation confirms that the proposed hybrid renewable energy system effectively combines multiple renewable energy sources to provide sustainable and reliable electricity generation. The complementary operation of solar photovoltaic, wind, and piezoelectric energy harvesting significantly improves energy availability, reduces power interruptions, and enhances renewable energy utilization.

5 CONCLUSION

This paper presented a hybrid power generation system that integrates solar photovoltaic, wind, and piezoelectric energy sources to achieve sustainable and reliable electricity generation. The proposed system effectively utilizes the complementary characteristics of multiple renewable energy sources to overcome the limitations associated with individual energy generation methods. Solar energy serves as the primary power source during daylight hours, while wind energy supplements electricity generation under suitable wind conditions. In addition, the piezoelectric module harvests electrical energy from mechanical vibrations, thereby enhancing the overall energy utilization of the system. The generated electrical energy is regulated, stored in a rechargeable battery, and supplied to electrical loads through a DC–AC inverter, ensuring continuous power availability. Experimental evaluation demonstrated that the hybrid configuration provides improved power reliability, enhanced renewable energy utilization, and reduced dependence on conventional fossil-fuel-based electricity. The proposed system offers a simple, economical, and environmentally friendly solution suitable for residential, rural, and standalone applications. Future work may focus on incorporating intelligent energy management techniques, Maximum Power Point Tracking (MPPT), IoT-based monitoring, and advanced battery management systems to further improve system efficiency, reliability, and practical deployment for decentralized renewable energy applications.

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest related to this study.

LICENSING

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