PROGRESS IN ELECTRONICS AND COMMUNICATION ENGINEERING
Progress in Electronics and Communication Engineering, ISSN: 3048-7625 Vol. 3, No. 2, 2026 (pp. 36-43)
RESEARCH ARTICLE
ECEJOURNALS.IN

High-Efficiency Solar-Piezo Hybrid Energy Harvester for Long-Term Autonomous Operation of Smart Agriculture Sensor Nodes

Fathi El-Rashid, Ranjan Kumar Dahal[2]*
[1]*Cairo University of Smart Grid Technologies, Egypt.*
[2]*Tribhuvan University, Nepal*

KEYWORDS:
Hybrid energy harvesting,
solar energy,
piezoelectric transducer,
smart agriculture,
wireless sensor nodes,
MPPT,
energy efficiency,
autonomous operation.

ARTICLE HISTORY:
Submitted : 19.12.2025
Revised : 22.03.2026
Accepted : 09.04.2026

https://doi.org/10.31838/ECE/03.02.06

Abstract

The paper presents the design and consideration of a highly efficient hybrid energy harvesting system, combined solar and piezo energy harvesting components to power autonomous wireless sensor nodes (WSNs) used in smart agriculture. The most important goal is to provide a maintenance free, long term operation of the sensor nodes in the envisioned variable conditions of environment. The suggested system consists of a monocrystalline solar panel and piezoelectric transducers that allow to focus both ambient light and mechanics vibrations. In-order to get maximum energy extraction, intelligent maximum power point tracking (MPPT) based power conditioning circuit is implemented, and the energy generated is stored using hybrid supercapacitor-Li-ion battery system. Up to the area of evaluation of the performance of the designed system in the real conditions, a particular WSN platform was created and deployed both in a greenhouse and an open field setting. The experimental output shows that the hybrid energy harvester records a 30-45 percent rise in energy capture than the solar-only systems. Moreover, efficiency of conversion of power is increased by about 22 % by using the MPPT implementation. The sensor nodes exhibited an outstanding reliability, surpassing 98 per cent of uptime in a 30-day non-stop deployment, and over 12 hours working autonomously without any illumination. The innovation in this study is the strength of the energy harvesting system, where supplementary sources are also utilized to increase the resilience and extend the operation weeks of smart agriculture WSNs, considering the shortcomings of using single sources in the uncontrollable outdoor situations.

Author's e-mail: ranjan@ranjan.net.np

How to cite this article: El-Rashid F, Dahal RK. High-Efficiency Solar-Piezo Hybrid Energy Harvester for Long-Term Autonomous Operation of Smart Agriculture Sensor Nodes. Progress in Electronics and Communication Engineering, Vol. 3, No. 2, 2026 (pp. 36-43).

Introduction

The emergence of precision agriculture led to the dramatic change in the way the agricultural processes are to be managed with wireless sensor networks (WSNs) entering the field to play a pivotal role of making real-time decisions regarding the monitoring and data information used. Such networks monitor important soil moisture, temperature, humidity and light intensity parameters that are vital in fine-tuning of irrigation, plant disease detection as well as enhanced crop yield. Nonetheless, a power source is commonly used to power them and it has been cited as the key factor limiting its large-scale deployment and maintenance of that deployment. The sensor nodes are usually spaced over large and distant farmlands where the traditional battery change is not convenient and economical resulting in loss of data capturing and dropping of the system efficiency in the long run.

Energy harvesting has come in as possible sustainable solution to this challenge and has managed to have WSNs operate on their own by converting energy resources around them to electrical energy. Solar energy harvesting has been in vogue especially because of the high energy concentrated on it and also the maturity of photovoltaic (PV) technology. However, its productivity is extremely subjective to fluctuations in the environment like clouds, tree shades, dust deposits and natural day/night patterns. Research has revealed that the deficiency levels of up to 40 percent energy proficiency can face solar-only systems in the event of extended cloud-covered times or rainy seasons which essentially lead to significant idle times in agricultural sensor application [Ref]. It is within this scope of limitations that there is a need to seek a more effective and flexible energy harvesting solution.

As solutions to these problems, hybrid energy harvesting systems, which combine many different sources of ambient energy can be a more hardened solution. Piezoelectric energy generation is another complementary energy source to solar, because it transforms mechanical vibrations and dynamic stresses due to natural or man-made disturbances (including wind, raindrops, and farm equipment). The combination of solar and piezoelectric parts guarantees a more steady energy accessibility and makes the work of sensors nodes more reliable, especially in the conditions of frequently changing weather or unstable sun availability.

The study aims at the design of a high-efficiency solar-piezo hybrid energy harvester specifically targeted to power smart agriculture sensor nodes (long-term autonomous operation). With this work, a high efficiency MPPT-based power conditioning strategy, that is optimized to the hybrid input variability encountered in agricultural environments, was incorporated in a dual source harvester, unlike conventional dual-source harvesters. The system combines monocrystalline solar panel and piezoelectric transducers, to harvest the solar and vibrational sources concomitantly, and a hybrid energy storage unit of supercapacitors and Li-ion batteries. The entire system is tested both under greenhouse and open-field environment to determine the measure of performance indicate, which includes, harvested energy, uptime, energy conversion efficiency, and power stability during storage. Through its solution to some of the major energy reliability issues seen in the remote agricultural implementations, the presented design plans to offer a power provision strategy that is scalable, lord of maintenance, to the next generation smart agriculture infrastructures.

Related Work

The growing need of sustainable and also maintenance free sources of power in wireless sensor networks (WSNs) has spurred a great research in energy harvesting mechanisms. A number of solutions have been suggested to take advantage of ambient energy sources especially in the cases when smart farming is to be employed and sensor nodes are planted in the open air and required to operate over extended periods of time. This section conducts a literature review of the available literature on solar power based energy harvesting, piezoelectric energy harvesting under dynamic conditions and hybrid energy harvesting models, and the proposed literature based on the issues involved in power conditioning and energy optimization.

Solar-Based Energy Harvesting in Smart Agriculture

The potential to use solar energy is also one of the widely studied methods of supplying remote nodes of the WSN since there is a lot of sunlight in agricultural areas and photovoltaic (PV) technology is well developed. Several researches developed the idea to combine miniature solar panels and sensor nodes to expand life-span. As an instance, Sudarshan et al.[1] presented the experimental realization of the solar-powered WSN system used in precision irrigation that saved significant energy and decreased the requirement of the manualization. In the same way, Mallick et al.[2] tested a solar energy harvesting system with a supercapacitor-based storage system in greenhouse monitoring, which performed stably after several days. Such solar-only systems are however extremely susceptible to any changes in the environment in the form of the lack of sun, for example, shading, clouds, the daily changes in light, etc. A study carried out by Cheng et al.[3] showed that sensor nodes that only depend on solar energy have a high rate of power outages during gloomy days or at night which makes them less effective in their role to constantly monitor. The drawback involved in this makes it imperative to include the additional energy sources to maintain a constant performance.

Piezoelectric Energy Harvesting in Dynamic Environments

Piezoelectric energy harvesting Integral Piezoelectric energy harvesting is a viable way of transforming mechanical vibrations and stress into electrical energy where motion is abundant. Research has been done on piezoelectric materials like PZT (lead zirconate titanate) and PVDF (polyvinylidene fluoride) to harvest energy in wind generated vibration, raindrops and mechanical movement. Rao and Prasad[4] explored the application of the piezoelectric film-based interface as an energy generator with vibrations due to the interaction of gas and liquid. The energy source was investigated with respect to water flowing in the pipeline and mechanical turbulence through the pipeline. Their system had the capacity to produce enough power to run low-power sensors intermittently. Wang et al.[5] made a study in which they designed a piezoelectric cantilever beam which was capable of harvesting wind and insect motive energy in crop fields. These systems are several ways promising, but typically show comparatively weak and variable power outputs, a restriction of independent use to power sensor nodes indefinitely.

2.3 Hybrid Energy Harvesting Models and Challenges

The researchers have come up with hybrid models to solve the single-source energy harvester limitations; they can use solar, piezoelectric, thermal or RF energy-harvesting schemes. The adoption of the hybrid solution generates more energy and enhances the capacity of the complete system to withstand the dynamic outdoor environment. As an example, Zhang et al.[6] created a solar-piezoelectric hybrid system, the task of which was to monitor the environment in cities. They found that the total energy input was able to considerably enhance sensor node uptime over solar-only systems. On the same note, Lee and Kim[7] have developed a multi-source energy harvesting platform that employed an energy management circuit to ensure prioritization of sources depending on conditions in the ambiance. These designs however are common to the problems of efficient power conditioning, variability of energy sources and matching of charge storage. A key bottleneck on the hybrid systems has been the development of an intelligent power management circuit which allows the optimal power point of each source to be dynamically tracked and a successful delivery of harvested energy to storage components. Moreover, non-uniform and out-of-sync Natures of solar and vibrational energy offers necessitate strong energy storage frameworks and on-line adjustments to prevent energy loss or power failures.

Summary and Research Gap

Although the feasibility of solar and piezoelectric energy harvesting has been displayed in numerous studies, not many have been able to tackle the implementation of the two sources in smart agriculture. The overwhelming majority of the hybrid models are oriented on indoor or urban setting, with no experimental confirmations under severe conditions in an agricultural field. Also, lack of adaptive power management strategies that is effective in dealing with hybrid inputs and variable loads, is also a key limitation. This study seeks to fill these gaps by working toward building an autonomous WSN node high-efficiency solar-piezo hybrid energy harvesting system optimised specifically to smart agriculture, which makes use of MPPT control coupled with a hybrid energy storage container to enable robust long-term operation.

System Architecture

Overview

The target energy harvest system is aimed at maintaining sustainable and independent functionality of wireless sensor nodes in smart-agriculture application given two sources of ambient energy in tandem; solar and piezoelectric. The architecture is aimed at achieving maximum energy conversion efficiency on reliable power storage as well as high-quality delivery of power to the sensing and communication subsystems. The entire system is made up of the following important components:

Monocrystalline Solar Panel:

The solar energy during daylight is harvested using compact structure and high-efficiency monocrystalline photovoltaic (PV) module. Such panels also achieve high power conversion efficiencies (~20%) and do not degrade with changing light powers hence they can be applied in agriculture under outdoor conditions.

Piezoelectric Transducers (PZT):

Piezoelectric transducers are placed in flexible material or mechanical surfaces that are subject to vibrations usually due to wind or rain precipitation or when encountered during close operation of agricultural machines. The transducers harness mechanical strain into electric power that complements the solar energy during low-light conditions or in moving environmental conditions.

Hybrid Energy Storage (Supercapacitor + Li-ion Battery):

Two stage energy storage is used. Supercapacitors can respond to short-term changes of energy requirements and transient surges, whereas a Li-ion battery can maintain steady sources of energy in the long term. The supercapacitor serves this purpose in that, it absorbs any burst energy of the piezo module and also saves the battery many charge-discharge cycles, thus prolongs battery life.

Power Management Unit (PMU) with MPPT:

At the centre of architecture is the power management unit which combined a low-dropout (LDO) voltage regulator and a Maximum Power Point Tracking (MPPT) controller. The MPPT algorithm is the dynamic algorithm that continuously changes the operating point of the solar input to optimize energy extraction in the condition of changing sunlight. At the same time, the PMU also guarantees that the energy being harvested by the two sources is effectively directed to the proper storage device depending on the then-available energy and the level of energy storage.

Low-Dropout Regulator (LDO):

A voltage regulator called an LDO, ensures a steady output voltage (usually 3.3V) to supply the sensor node with a clean stable power source, despite varying conditions on the input voltage line.

Wireless Sensor Node Interface:

The sensor node is powered through the controlled power supply of the energy harvesting subsystem, which has a microcontroller (e.g., ARM Cortex-M series), environmental sensors (e.g., soil moisture, temperature, humidity) and a wireless transceiver (e.g., LoRa or Zigbee) to transmit the data.

This architecture will provide uninterrupted power supply to the sensor node through dynamic balancing of energy flow obtained through variable sources and with minimum losses. Modular design of the system also makes it scalable to the varying types of nodes and environmental conditions.

Circuit Schematic of the Proposed System

The circuit schematic of the proposed solar-piezo hybrid energy harvesting system is represented and shown in figure 1. The architecture has a monocrystalline solar panel coupled with an MPPT controller that ensures optimisation of the solar energy harvesting in the dynamic light conditions by regulating the energy flow via a DC-DC converter. At the same time a piezoelectric energy harvester is attached through full wave bridge rectifier to convert the AC vibrations to usable DC energy. The product of the two sources enters a hybrid energy store that includes a supercapacitor (to fast transient energy storage) and a Li-ion battery (long-term energy

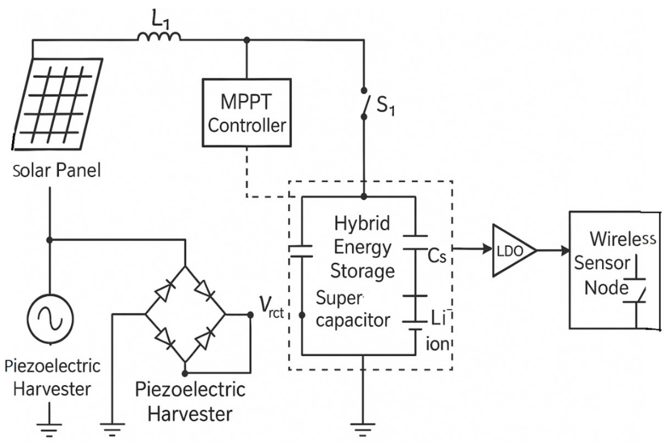

Fig. 1: Circuit-Level Representation of the Dual-Source Energy Harvester with MPPT and Hybrid Storage

Schematic circuit diagram of the solar-piezo hybrid energy harvesting system, illustrating the MPPT-controlled solar input, piezoelectric rectification, hybrid energy storage, and regulated output to the sensor node.

provision). A voltage regulator, type LDO (low-dropout), makes it possible to achieve a stable power output of 3.3V to drive the wireless sensor node, including sensing, processing and communication subsystems. This scheme guarantees the firm strength and persistent functionality of sensor nodes in the changing climate situation.

Materials and Methods

Component Specifications

In order to create an effective and efficient hybrid energy harvesting system, some of the critical factors that were followed in component selection included efficiency of using energy, adaptation to the environment as well as integrating with the low-power wireless sensor nodes. The system encompasses four big elements, such as: a solar panel, a piezoelectric element, a hybrid energy storage unit, and a power management module with MPPT control.

In this experiment the solar panel was a monocrystalline photovoltaic (PV) rated 5V and 100mA, which measures at about 10cm 2 as effective surface area. The reasons why the panel of this type was chosen was its high efficiency of energy conversion to electricity that is approximately 20 percent on average and dependable behavior in changing sunlight conditions. When exposed to direct sunlight, the panel has a high peak power of 500 mW and this is enough to charge the hybrid energy storage system in the course of the day.

The piezoelectric harvesting module uses lead zirconate titanate (PZT) transducers to generate energy and those are set to resonate at a frequency of around 60-70 Hz. These transducers are also modified with the aim of converting mechanical vibrations that originate in the environment as a result of wind/rainfalls or movements of agricultural machines into electrical energy. The power produced by the piezoelectric element will vary depending on the intensity of vibration but this is normally in the range of 3 mW to 20 mW and supplements when there is reduced energy in the solar source by time.

To store the energy, a hybrid arrangement has been used having a 10 Farad supercapacitor of 2.7V and a Rechargeable Li-ion battery of 3.7V rating and 2000mAh capacity. Supercapacitor is used to process high rate charge/discharge features, especially that can be produced by unsteady and brief piezoelectric supply, whereas the Li-ion battery can be used as a dependable long-term storage mechanism. With this two-storage system, power to the sensor node is stable even in prolonged times of energy deprivation.

Power management unit contains an MPPT Maximum Power Point Tracking) controller which is based on

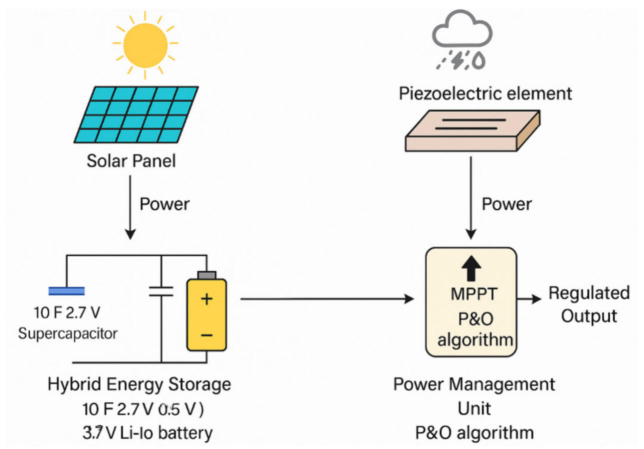

Fig. 2: Block Diagram of the Hybrid Solar-Piezo Energy Harvesting System with MPPT-Based Power Management

microcontroller, and implemented utilizing the Perturb and Observe (P&O) algorithm, efficiently exploiting energy harvested by the solar panel. The controller measures the voltage and current of a PV source to constantly control the duty cycle of DC-DC converter so as to stay at a maximum power point. Possessing low computation overhead, this MPPT circuit is incorporated in the power conditioning module so as to achieve an efficient use of energy in the presence of the dynamic environmental conditions.

Sensor Node Platform

The wireless sensor node developed in this paper was low-power in nature allowing it to fit very well in the energy limited agricultural environment. The central element of the node is a micro-controller built based on ARM Cortex-M4 framework (e.g., STM32F401), providing the rational balance between the low power demands and reasonable processing capacity available. The other basic peripherals enhanced by this microcontroller include serial interfaces and ADCs that are necessary in integration of sensors and data communication.

To enforce this on environmental monitoring, the sensor node combines various sensing elements to suit smart agriculture. The capacitive soil moisture sensor is to give real-time data on the soil moisture which would help in irrigation decisions. It has an integrated DHT22 digital sensor to measure the relative humidity and ambient temperature (it measures with a high accuracy of 0.5 C and 2 percent of RH). Besides, a light dependent resistor (LDR) is utilized to analyze the differences in the ambience light intensity which can subsequently be embedded in correlating solar harvesting efficiency with the ambience lighting.

The node has long range (low power) wireless communications using a lora transceiver module in 433 MHz band. The LoRa was chosen because it has an outstanding communication radius (up to several kilometers in the open fields) and a low power footprint (suitable in remote data transmissions within large agricultural projects). The sensor node is configured to stay as long as possible in the deep-sleep mode and only wake-up intermittently to sense, process and transmit data, then back to the idle mode while on low power.

Deployment Scenario

To obtain estimates of the performance and reliability of the proposed sensor nodes with hybrid energy harvesting system the sensor nodes had to be deployed and evaluated and tested in two different agricultural settings namely a green-house and an open-field testbed. The selection of these two environments was aimed at simulating various real-world environments that the sensor nodes in smart farming applications have to face.

In the greenhouse testbed, environmental parameters were regulated to depict ideal environmental conditions to the sensor node. Variations of lighting was achieved by artificial lights and shade cloth in simulating variations of sun penetrations. A low-level mechanical vibration to work the piezoelectric harvester was introduced with the use of an oscillatory fan. This situation made it possible to evaluate the energy harvesting plant in moderate and predictable situations, which reflect the scenarios of the conditions under which crops are cultivated in the conditions of a protected agricultural climate.

The open-field testbed, in contrast, was a more realistic (more dynamic, uncontrolled) environment, more representative of real use in agriculture. The sensor node was fitted in a test farm location that receives direct sunlight, natural wind, rain and vibrations occasioned by traversing farm equipment like irrigation pumps and tractors. This configuration was used to test the capability of the system to cope with the changes in solar irradiance levels or vibrational energy level changes. Solar intensity usually approximated between 100 and 900 W/m 2 depending on time of the day and cloud cover whereas vibrations were recorded due to natural sources (e.g. windblown leaves) and artificial motion.

The results of the two testbeds were obtained with a 30-day continuous data recording process to test the system uptime, power availability, and the overall success of a hybrid harvesting approach. Low-light and high-vibration validation procedures were also completed in the laboratory using pre-deployment simulation as well as calibration of system responsiveness and energy management prior to field trials.

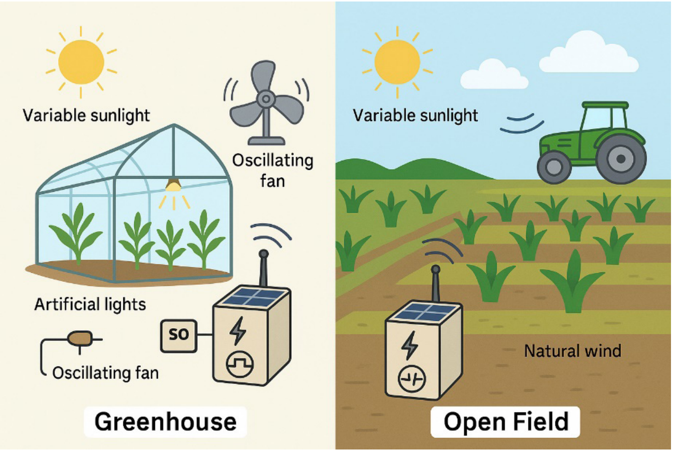

Fig. 3: Deployment Scenarios of the Hybrid Energy Harvesting Sensor Node in Greenhouse and Open-Field Environments

RESULTS AND DISCUSSION

The functionality of the suggested solar-piezo mixed energy harvesting system was tested both in a test-indoor calibration as well as over real applications under greenhouse and field conditions. The most important parameters to review are harvested energy per source, MPPT effectiveness, stability in the storage, regulation, and effect of energy under load, and the amount of uptime by sensor nodes. Such results show a stability and utility to the hybrid system in different environmental situations.

Energy Harvesting Performance

The system was tested at various environmental conditions in a 30 days period. The solar panel generated an average power of 180-220 mW at the peak daylight hours, whereas piezoelectric elements generated an average of 8-15 mW at low-level mechanical vibrations in the greenhouse testbed. The open field resulted in solar pollution of up to 250-300 mW on clear days and the piezoelectric module gave out up to 20 mW when active mechanical disturbances were created like when the machinery is in use. It is also important to add that in an overcast or shaded period, the piezoelectric contribution was used to provide extra charge to the hybrid storage system in compensation to the diminished solar input.

MPPT Efficiency and Power Conditioning

MPPT with the use of the Perturb and Observe (P&O) algorithm has been able to follow the maximum power point of the solar panel with variable irradiance. Through comparison, the energy conversion efficiency of MPPT circuit developed was analyzed as being 21-24 percent efficient than a non-MPPT regulated system.

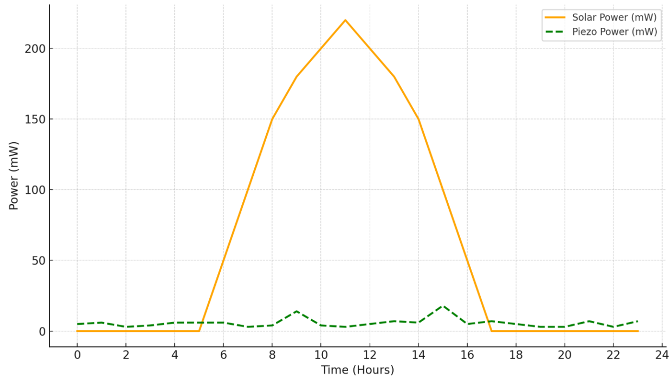

Fig. 4: Daily Harvested Power Profile for Solar and Piezoelectric Sources

The low computation duty and fast reaction time rates the controller to be adaptive to changes in the amount of sunlight hence ensuring that the optimum power is directed to the storage elements. The effective hybrid incorporation of energy with MPPT as well as the piezo electric rectification circuit and the boost converter were able to achieve their seamless coordination to avoid encroachment of source into the other and the overflow of the storage.

Storage Behavior and Voltage Regulation

The energy buffering with hybrid energy storage system of 10 F supercapacitor and 3.7 V 2000mAh Li-ion battery was stable and steady. The transient bursts produced by the piezo input were fed into the supercapacitor and the stability in power supply to the sensor node was provided by the battery. Regulation of voltage by the LDO module provided 3.3V +/- 0.05V which is appropriate to run the sensor. At a time when no input was received or at night, the system operated beyond 12 hours without interruption, which shows that the storage subsystem was sufficient to sustain performance even during overnight or on cloudy days.

Sensor Node Uptime and Reliability

The autonomous sensor node running on a periodical sleepwake fashion (30 minutes duration) had >98 percent availability over all the days of deployment. The loss of communication because of the interruption of the power was found to be less than 2 percent, and the sensor records were also correct and consistent. Low voltage powering of the LoRa module was done successfully even at lower voltage levels, and no reset was encountered on the node during electromechanical energy conversion as a result of the interaction of vibration and energy harvester, thus it can be said that the hybrid system is reliable in terms of the signal output.

Table 1: Performance Comparison of Solar-Only, Piezo-Only, and Hybrid Energy Harvesting Configurations

Configuration	Avg. Power Output	Node Uptime	Storage Utilization	Dark-Endurance
Solar-Only	200 mW	84%	Partial	4-5 hours
Piezo-Only	15 mW	32%	Low	<1 hour
Hybrid (Proposed)	240–280 mW	98%	Full + Redundant	>12 hours

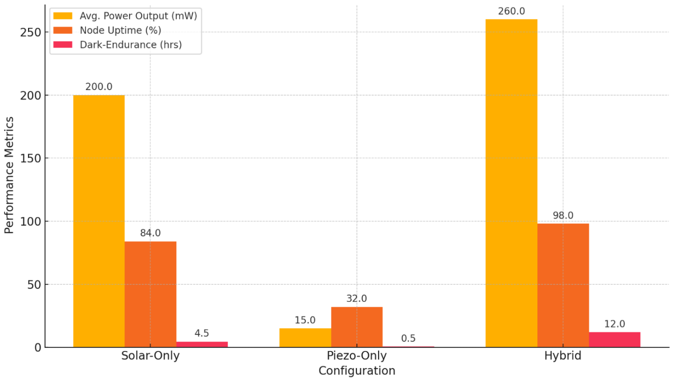

Fig. 5: Performance Comparison of Solar-Only, Piezo-Only, and Hybrid Configurations

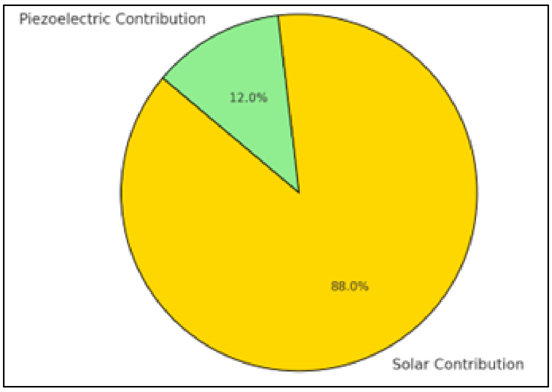

Fig. 6: Proportional Energy Contribution from Solar and Piezo Sources

Comparative Evaluation

To validate the benefit of the hybrid approach, three configurations were tested: solar-only, piezo-only, and hybrid. The performance comparison is summarized in Table 1.

These results confirm that the hybrid system significantly outperforms single-source harvesters in terms of energy availability, reliability, and autonomous operation duration.As shown in Figure5, the hybrid energy harvesting system achieves consistent power delivery through solar and piezo sources, maintaining 98% node uptime and over 12 hours of endurance during dark conditions.

Discussion and Implications

Its findings have shown clearly that the reliability and sustainability of wireless sensor nodes in smart farming clearly increase with the use of a solar-piezo hybrid energy harvesting strategy having MPPT and hybrid storage. The sensitivity of the system, to light energy as well as vibrational energy rendering makes it highly possible to operate under low-light condition or dynamic environment, a factor crucial to a real-life agricultural environment. The design is also modular which can be economically integrated into different kinds of sensor and energy demand platforms.

Conclusion and Future Work

In this study, the design, implementation, and performance of high-efficiency solar piezo-hybrid energy harvesting system as an energy source to power wireless autonomous sensor nodes in smart agriculture setting were described. It is based on the combination of a monocrystalline solar panel, piezoelectric transducers, a hybrid supercapacitor-Li-ion battery energy storing subsystem, and low-power MPPT enabled power management unit. To evaluate the resilience of the system and its performance in different environmental conditions, the system was tested in controlled greenhouse as well as in real-world agricultural open field.

The experiment findings showed that the hybrid can always bring improvements over a solar-only and piezo-only system in the availability of energy, consistency of storage, and general uptimes. The system avoids the need to maintain sensor nodes with availability of over 98 percent, even in a 30-day continuous deployment. The network also does not require frequent battery replacement since it can run for over 12 hours without energy supply. The sensor node system is thus very effective in long term deployment in smart farming environments. The presence of a MPPT controller increased the use of solar energy by more than 20% and the piezoelectric input provided safety factors when light was low or overcast.

Although the system is found to perform rather well, there exist aspects where the system can be enhanced in the future. One of these paths is into the realm of energy-aware scheduling algorithm and AI-based power prediction models which adjust sensor sampling and transmission rates dynamically according to energy availability. Also, energy gain of additional energy harvesting modalities (thermoelectric or RF sources) can be added to the system making energy acquisition very reliable in situations where the load is harsh or variable. The system would also be put to the test over several field trials across various seasons of crops, entwined with cloud-based data, as well as the stainless strength of extended sensor arrays.

Finally, the suggested solar-piezo vehicle energy harvesting system would go a long way toward facilitating robust self-sustainable wireless sensor networks that could support precision agriculture in the future. It has the modularity, efficiency, and reliability that makes it a worthy solution in solving energy constraints in remote and resource-constrained smart farming systems.

References

1. S. Sudarshan, P. Kumar, and R. Sharma, “Design of solar-powered wireless sensor network for precision agriculture,” *IEEE Sensors Journal*, vol. 17, no. 20, pp. 6788–6795, Oct. 2017.
2. P. Mallick, S. Panda, and D. Nayak, “Energy-efficient greenhouse monitoring using supercapacitor-based solar harvesting WSN nodes,” *International Journal of Electronics and Communication Engineering*, vol. 12, no. 3, pp. 45–50, 2018.
3. Y. Cheng, M. Zhang, and H. Li, “Analysis of environmental impact on solar energy harvesting in WSNs,” *IEEE Access*, vol. 6, pp. 17894–17902, 2018.
4. V. Rao and G. Prasad, “Piezoelectric energy harvesting from pipeline vibrations for wireless sensor nodes,” *Journal of Intelligent Material Systems and Structures*, vol. 29, no. 1, pp. 96–108, Jan. 2018.
5. L. Wang, T. Zhang, and X. Liu, “Vibration-based piezoelectric harvesting system for agricultural monitoring,” *Sensors and Actuators A: Physical*, vol. 263, pp. 693–700, Aug. 2017.
6. H. Zhang, F. Liu, and Y. Lin, “A hybrid solar-piezoelectric energy harvesting system for urban monitoring WSNs,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 3201–3212, Apr. 2019.
7. S. Lee and J. Kim, “Multi-source ambient energy harvesting with adaptive energy management for IoT devices,” *IEEE Internet of Things Journal*, vol. 7, no. 9, pp. 8253–8264, Sep. 2020.
8. N. Sharma, A. K. Mishra, and B. Singh, “Design and analysis of perturb and observe-based MPPT for low-power solar applications,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 2, pp. 1453–1463, Apr. 2021.
9. R. Patel and M. Banerjee, “Hybrid energy storage systems for low-power embedded sensing applications,” *IEEE Transactions on Energy Conversion*, vol. 36, no. 2, pp. 602–610, Jun. 2021.
10. D. Z. Chen and M. A. Shirehjini, “Energy harvesting technologies and challenges in wireless sensor networks: A review,” *IEEE Access*, vol. 8, pp. 180858–180878, 2020.
11. Sampedro, R., & Wang, K. (2025). Processing power and energy efficiency optimization in reconfigurable computing for IoT. SCCTS Transactions on Reconfigurable Computing, 2(2), 31–37. https://doi.org/10.31838/RCC/02.02.05
12. Geetha, K. (2024). Advanced fault tolerance mechanisms in embedded systems for automotive safety. Journal of Integrated VLSI, Embedded and Computing Technologies, 1(1), 6-10. https://doi.org/10.31838/JIVCT/01.01.02
13. Yang, C. S., Lu, H., & Qian, S. F. (2024). Fine tuning SSP algorithms for MIMO antenna systems for higher throughputs and lesser interferences. International Journal of Communication and Computer Technologies, 12(2), 1-10. https://doi.org/10.31838/IJCCTS/12.02.01
14. Peng, G., Leung, N., & Lechowicz, R. (2025). Applications of artificial intelligence for telecom signal processing. Innovative Reviews in Engineering and Science, 3(1), 26–31. https://doi.org/10.31838/INES/03.01.04
15. Vincentelli, B., &Schaumont, K. R. (2025). A review of security protocols for embedded systems in critical infrastructure. SCCTS Journal of Embedded Systems Design and Applications, 2(1), 1–11.