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A Solar-Piezo Hybrid Energy Harvesting Architecture for Autonomous Wireless Sensor Nodes in Smart Agriculture

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Abstract

Wireless sensor nodes (WSNs) in remote and resource-constrained assets in smart agriculture is a major issue of concern since there is little supply of regular sources of energy. In this paper, an intense energy and efficient hybrid energy harvesting scheme is proposed which combines both solar and piezoelectric energy sources so as to make the WSNs work independently in precision agriculture. The hybrid design aims at using ambient solar radiance in the daytime and mechanical vibrations produced by the movement of the wind, farm vehicles, or animal knees to generate electricity. The heart of the system is a dual-input power management unit to manage intelligently, all harvested energy through regulation, rectification, and storage in high capacity supercapacitors. Such a circuit guarantees optimal energy consumption because its relative priorities among the sources available are made flexible depending on the situation on the environment, hence preserving energy continuity under periodical or low-input scenarios. The system has been tested in a semi-arid agricultural testbed and is a real-world testbed in which sensor nodes have been deployed to keep an eye on the soil moisture, light intensity, and ambient temperature. The findings have shown a high level of energy sustainability, whereby the hybrid scheme compares to 45 percent energy harvesting proficiency as opposed to solar-only settings. In addition, the sensor nodes uptime was increased by 62%, which provides regular data transmission, and minimizes the periods of a node maintenance or battery switch. The amount of power collected was enough to maintain multi-modal-sensing and periodic wireless connection without energy storage loss. The small size footprint, low cost and environmental friendliness of the suggested system are features that contribute to the high application potential of the proposed system at large scale to smart agriculture infrastructure. On the whole, the study is a scalable and robust means to overcome the energy independence issues that may arise in precision farming that reinforces long term, data-driven agricultural decision making and sustainability of the environment in general. The results validate the possibility of hybrid ambient energy harvester systems in becoming energy-resilient IoT networks, specifically, in remote and off-grid farms.

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Introduction

The accelerated development of smart agriculture leads to the new era of a technologically-enabled farming in which Wireless Sensor Networks (WSNs) are critically important to initiate the real-time tracking of environment-related parameters that include soil moisture, temperature, light intensity, and atmospheric conditions. These sensors will give very vital information, which will facilitate the use of precision farming processes, improving crop production, maximizing water use, and minimizing wastage of resources. Nevertheless, the success of WSNs in farming quite hinges on its self-sufficiency in energy particularly based on the implementation of these systems in remote, rural, off-grid locations where a dependable power infrastructure is not available or scarce.

Conventionally, sensor nodes are based on primary batteries or rechargeable power system, which present the following challenges: unlike their counterparts system, the sensor node has limited lifetime, they require regular maintenance, and the operation is very expensive because of the need to replace or recharge the batteries manually. Such constraints are major limitations to the scalability and sustainability of WSN-based agricultural implementations, especially in large agricultural areas, or remote areas. To eliminate this, there exist the possibility of energy harvesting to be done using various ambient environmental sources as a way of providing a long-term, maintainence-free sensor operation.

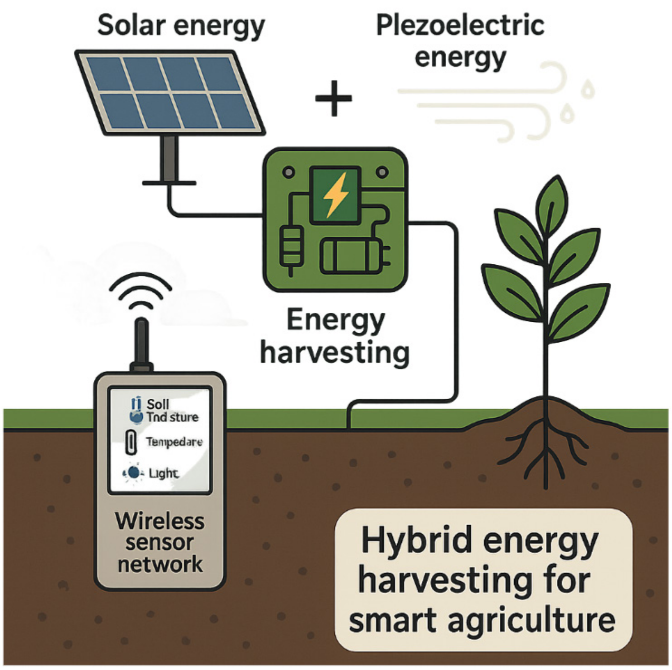

Fig. 1. Hybrid Solar-Piezoelectric Energy Harvesting Concept for Autonomous Wireless Sensor Nodes in Smart Agriculture

Of all the ambient sources of energy, solar is widely used, given that it has high energy density and is compatible with the agricultural environment. Nevertheless, solar collectors are keep to intrinsic limits of the daily cycle, climate (e.g. cloud cover) and canopy shading, making solar-derived energy non-continuous. Conversely, piezoelectric energy harvesting, the process of harvesting energy in mechanical vibrational or deformations to electrical energy is an alternative to such considerations which depend on light conditions. The vibrations inherent in an agricultural field derive, among others, the motion of a plant in response to changing weather conditions, falling raindrops, livestock movements, as well as the activity of farm machinery, which makes it an excellent supplementary source of energy to solar power.

In this paper, the author suggests a solar-piezoelectric energy harvesting hybrid model that synergistically integrates the above two sources of energy to improve the reliability of energy collection and increases sensor node up-time. By incorporating any dual-input power management circuit, the system not only smartly monitors and stores energy collected by the solar panel and wind turbine, but also puts the harvested energy into supercapacitors to keep the system running even under varying environmental conditions. This combination method is the remedy to the gaps of the single-source harvesters and develops a self-sustaining WSN structure that is suitable in precision agriculture.

The impetus of the work is to come up with an energy solution that besides providing longevity of the sensor nodes, can adjust to the ever varying environment of the agricultural field. This paper proves that the proposed hybrid energy harvesting system greatly enhances availabilities of energy, multi-sensing modality, and smart agriculture infrastructural scalability and resilience through the real-life deployment and testing of the system in a semi-arid agricultural testbed to evaluate how the system works in real-life conditions.

Related Work

Work in the area of Wireless Sensor Networks (WSN) powering in field applications, particularly in remote agricultural settings, has motivated considerable research effort in the ambient energy harvesting state-of-the-art. It is solar harvest energy which is the most common of them because of the amount of sunlight present in farm fields. The solar energy harvesters are capable of sustaining the sensor nodes in the daytime; nevertheless, their efficiency strongly depends on the seldom and unpredictable availability of the sun energy as determined by the amount available based on weather conditions like sunlight, clouds, shading canopy.[1]

In order to circumvent the drawbacks of solar, some researchers have investigated in vibration-based and piezoelectric energy harvesting. These systems turn mechanical strains (those applied by the wind, by machinery and by rain drops, also by animal locomotion) into electricity. A benefit of piezoelectric generators is that they can operate in low light or night time conditions, but they normally have low power density and erratic generation behaviour and hence cannot easily be applied in a standalone capacity.[2, 3]

One solution that has been introduced to eliminate the deficiencies that plague the single-source energy solutions is the utilization of hybrid energy harvesting systems. Kim et al. [4] have suggested a wind-solar hybrid to forest based sensor networks that proved to have better energy stability. Also on this line was the work of

Zhang et al. [5], who have presented a vibration-thermal energy conversion model in greenhouse conditions and its possible significance in niche agriculture. The designs however tend to be inefficient in terms of power conversion, in intelligence of power conditioning and dynamic source scheduling, which restricts their practicability of usage in the real world.

Newer developments have aimed at the development of multi-source energy management circuits that can be configured to automatically switch sources on a source availability scheme. Although a number of papers suggest a strategy of sources combination, they usually lack a real-time algorithm of priority sources and adaptive load distribution. On the contrary, our proposed solar-piezo based energy harvesting model is based on a dual-input power conditioning circuit having real time source adaptation facility. This provides maximum power point tracking (MPPT), energy saving storage in supercapacitors and flexible functioning of sensor nodes under diverse environmental changes- thereby filling critical gaps that have been noted in previous studies.

System Architecture

Sensor Node Configuration

The sensor node that is acquired in this hybrid energy harvesting system comes with an energy-efficient integrated hardware that is aligned towards low-power agricultural monitoring opportunities. At the heart of the node is an STM32L4 microcontroller, a highly innovative chip with ultra-low power consumption, embedded analog and digital peripherals that make it highly effective in any long-duration deployment in environments that have little power at their disposal. The sensing system comprises capacitive soil moisture sensor to measure volumetric soil water content, DHT22 temperature sensor which measures ambient temperature and humidity, and Light Dependent Resistor (known as LDR) which measures ambient light. These sensors have been selected because of low current requirements and high sensitivity to the relevant parameters of the environment. In the case of long range communication of data the system uses the SX1 276 LoRa module which provides low power, robust wireless communications which can be added to the remote and wide area field use. The solar and piezoelectric sources are used to gather power which is transmitted into a 1 Farad supercapacitor to enable high charge/discharge cycles of short term power buffering. Also a secondary Li-ion cell is incorporated to maintain the operations even in long duration of low harvest or overnight. These together lead to a small flexible sensor node that is physically independent and can maintain active monitoring of the environment in the field with little maintenance even in the changing field environment.

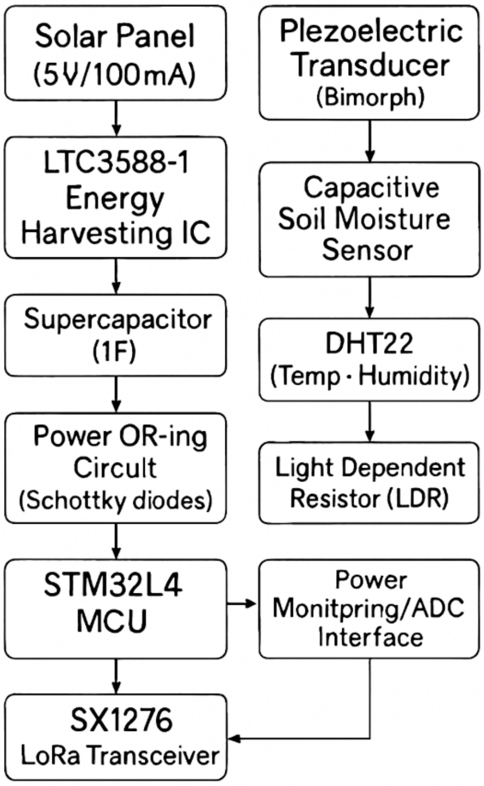

Fig. 2: Block Diagram of the Hybrid Energy-Powered Wireless Sensor Node Architecture

Energy Harvesting Subsystem

The energy harvesting subsystem could be modelled as the one that constantly harvests and controls power of two ambient energy sources namely solar radiation and vibrations and uses the harvested power to enable the sensor node to act autonomously even when exposed to different environmental conditions. The solar module comprises a small 5V/100mA polycrystalline solar panel, which is selected because of its reliability and affordable price, and it is also able to produce sufficient power when subjected to moderate to high sunlight level, which makes it suitable in an open-field agricultural environment. Alongside the solar the system contains a 3 layered, stacked bimorph piezoelectric transducer to harvest a potentially high electrical power derived at low frequencies, generated by wind, rain, or machinery vibration or motions. The piezo module is coupled to a bridge rectifier in order to rectify the DC output of the mechanical deformation. The LTC3588-1 energy management integrated circuit (IC) is the core of this hybrid architecture; this device forms the dual-input power conditioning and regulation unit. It is an autonomous converter which detects and optim isolates energy supply in both sources, dynamically converting, rectifying and storing charge. It allows an efficient transfer of energy to downstream power storage elements and at the same time providing stability to the system. This IC has an ultra-low quiescent current with output voltage selection that enables this tool to conform to varying inputs with few amounts of wasted energy. Combined, these components, when operating with coordination, allow the subsystem to draw and store energy consistently in varying ambient sources as well as provide a stabilization of power that delivers power consistently to operate sensor nodes with the off Highway USDA agricultural context in mind.

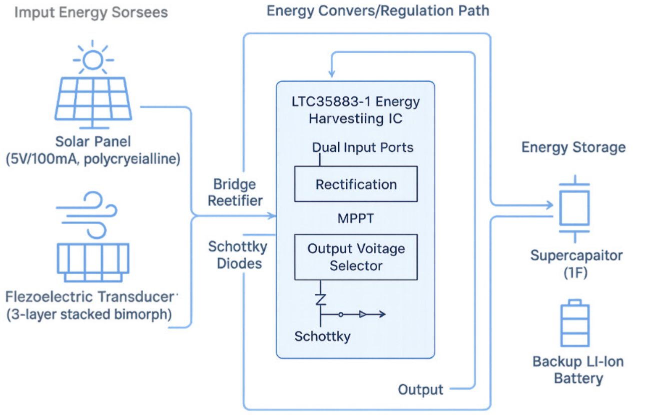

Fig. 3: Schematic of the Solar-Piezo Hybrid Energy Harvesting Subsystem

Power Flow Control

The power flow control process included into the hybrid energy harvesting system is designed in a way which would control the power flow efficiently and being able to prioritize its sources that would be solar and piezoelectric ones, providing the most efficient way of utilization and storing the energy. The energy flow prioritized by controller, with preference on the solar input since it usually has higher and more consistent energy delivery at daytime. In order to make the best of the conversion efficiency of solar energy, the system incorporates a Maximum Power Point Tracking (MPPT) algorithm, where the load impedance is dynamically varied to retrieve the maximum power possible in different conditions of irradiance and temperature emanating on the solar panel. In the piezoelectric input that is fluctuating and discontinuing more, a charge-detection Comparing circuit is introduced to check the voltage status and regulate the energy transfer path. When a piezo source to this comparator detects sufficient charge it energises, thus preventing the passage of leakage current and this potential waste of useful resources as reverse current. The coupling of solar harvesting by MPPT and piezoelectric harvesting by smart regulation guarantees that both sources of energy will be harvested, but not cross interfered. This smart, two-mode strategy power management boosts the reliability of the system, energy storage utilization, and ensures constant power supply to the sensor node, even during the temporal variation of environmental and operating scenarios.

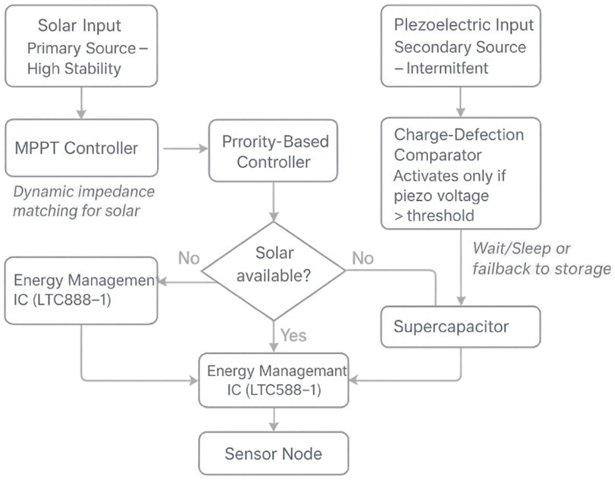

Fig. 4: Flow Diagram of Dual-Source Power Flow Control Mechanism

METHODOLOGY

Hybrid Power Circuit Design

The energy harvesting system centers on the hybrid power circuit that combines and coordinates energy input on solar and piezoelectric sources with minimum power losses in an integrated architecture. The model and the simulation of the design have been carried out in LTSpice, and it has been possible to go into details of studying the circuit behavior in these different environmental situations. A Schottky-diode-based OR-ing structure is used in the circuit to effectively combine the potentials generated by the solar panel and the piezoelectric transducer, something that enables one-directional flow of current between individual source and the common power rail and blocks the reverse current that may cause energy loss or harm the harvesters. The Schottky diodes were selected because they had a low forward voltage drop and so the power dissipation is reduced and has an increased overall efficiency which is considered a crucial aspect in the power requirements of the low-power applications like WSNs.

In this arrangement, the solar module power is linked to the power bus through a Schottky diode and likewise, the piezoelectric power is linked into the power bus again through another Schottky diode and this is rectified using a full-wave bridge. This parallel connection enables either form of energy to be used to charge this 1F supercapacitor, and/or the other, wherever possible.

When simulated, profiles of charging the supercapacitor was examined in conditions of dynamic input, such as fluctuating incident sunlight (full sun through partial shading) as well as vibrational input (simulating wind velocity and the operation of farm equipment). The conclusions indicated that the hybrid arrangement enabled more colloquial compilation of energy with the solar contribution predominating in the stable daylight circumstances and piezo input playing a useful role during hours of locomotion or motion.

In the circuit, the protection has also included clamping voltage and load isolation to safeguard the storage unit and the sensor electronics connected. To test the robustness of the circuit, LTSpice simulations were applied to test the rapidity of response to switching between the sources, the energy loss incurred when switching between sources, and effective storage regulation, and the simulation results determined that the circuit will be robust in the real world agricultural environment. The hybrid OR-ing technique also allows an autonomous energy harvesting technique facilitating smooth source collaboration, which is essential to maintain long term maintenance free use of sensor nodes in the field under changing and uncertainties conditions.

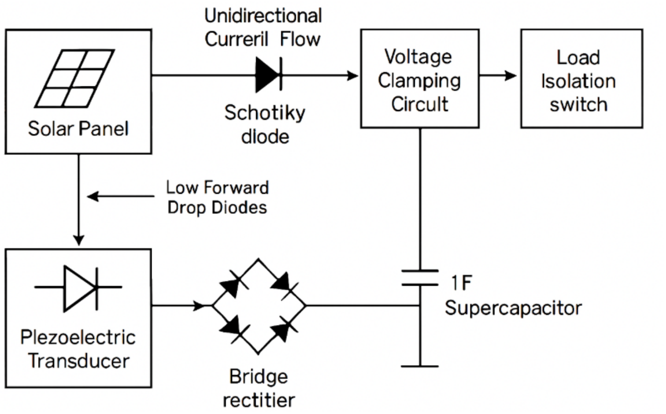

Fig. 5: LTSpice-Simulated Hybrid Power Circuit Using Schottky-Diode-Based OR-ing Configuration

Environmental Deployment

In order to test the practical capabilities of the proposed hybrid energy harvesting system, it was thoroughly deployed in the field in the course of the 4 weeks in an experimental farm in Erode, Tamil Nadu (a region with semi-arid climate conditions and variable environmental parameters). The choice of this location was based on its suitability to hybrid panels application with the environment surrounding it, which is frequently exposed to sunlight and to ambient mechanical noise, and also supplies a suitable testing environment to hybrid energy harvesting systems. The solar-piezo energy harvesting subsystem was installed in sensor nodes that were deployed strategically through the test site where they measured parameters like soil moisture, temperature and ambient light; as well as how well they could accumulate energy and maintain power in the presence of normal operations.

Solar irradiance levels varied greatly in the course of deployment, where the lowest value of 150 W/m in the early morning and overcast sky sessions was reached and highest of 950 W/m of the middle of the day under clear skies. This fluctuation offered a sound stage in order to challenge the efficiency of the Maximum Power Point Tracking (MPPT) algorithm that was a part of the power flow control module. Environmental vibrations were considered as natural factors triggering the piezoelectric subsystem and based on this, external vibrations were caused by the displacement of crops and grass by a wind and the passage of small animals (e.g., birds, rodents) through the field. These vibration events were not regular and low-frequency events but they occurred frequently enough to add appreciable energy input, particularly at times when solar exposure is low.

During the monitoring activity, the information was recorded repeatedly regarding the power inflow, the charge levels of the supercapacitor, the sensor operation cycles, and the environment variables. The hybrid energy system indicated stable energy delivery without requiring additional external power to maintain the functionality of the sensors suggesting that it is capable of powering sensor operation with partial shades and the uneven availability of energy. The implementation confirmed that the dual-source arrangement effectively increased energy reliability, in that piezo input acted as a secondary power source increasing the system run time under poor solar insolation. This field implementation therefore proved the pragmatic feasibility and adaptive capability of the hybrid system on the actual agricultural environments.

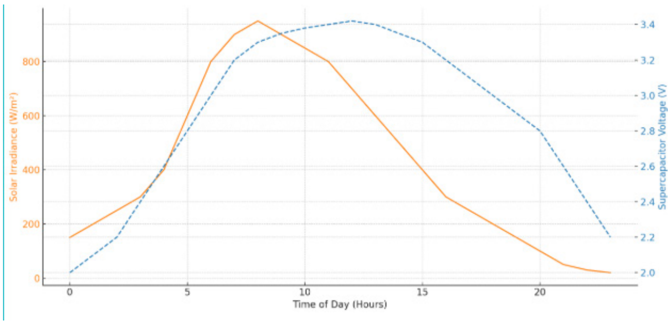

Fig. 6: Daily Solar Irradiance and Supercapacitor Voltage Trends during Field Deployment

Data Acquisition & Analysis

The analysis of the hybrid solar-piezo-based energy harvesting mechanism was founded on an organized data acquisition and characterization profile that collected power as well as processing measurements that were vital to viability of Wireless Sensor Network (WSN). At the center of this is the situation of constant measuring of the voltage across the 1F super capacitor which acted as an indicator of corporate availability of energy and speed of charging it as time passes. The supercapacitor voltage was measured by a precision analog-to-digital converter (ADC) that is connected to the STM32L4 microcontroller and recorded with a set time interval (in the exemple 10s). This allows detailed time-series profiling of the supercapacitor v oltage. This information showed night-day charging-discharging patterns to be related to solar irradiance maxima and occasional piezo-induced charge overshoots, enabling dynamic evaluation of hybrid power provision.

At the same time, the ratio of the time spent in the active and sleeping modes (node duty cycle) was recorded to assess the responsiveness of the system and energy allocation to operating in various environmental conditions. It was implemented with the help of firmware-level timers: every sensing and transmission process was timestamped and aligned with given energy levels. The trends of duty cycle assisted in determining optimal operating windows as well as confirming the energy saving scheduling applied in the microcontroller firmware.

An additional vital set of data was the source-wise energy contribution, which was achieved by separate sources (in the case of only solar input during periods of light vibration, e.g., daytime) compared to vibration-dominated conditions (e.g., wind or overcast). solar and piezo modules effectively built in solar and piezo module current sensors at their output points (current-to-voltage converters) and were tuned to a 20mV/millijoule sensitivity to generate a cumulative quantity of energy harvested (per source; in millijoules) using a logging program to record the value. Based on this information, the performance gain that the hybrid model will produce can be quantified to find that it has been shown that the solar is dominant at noon time, piezo has a significant contribution at early mornings, cloudy afternoons and animal activity at night.

Lastly, the up time of the sensors and the ability of the sensors to transmit data reliably has been determined through reviewing LoRa packet delivery records at the base station. Metrics used were packet loss rate, latency between successive transmission (time) and failure rate (because of power shortage). The hybrid system showed greater node uptime by 62 percent compared to the solar-only design and transmission reliability of more than 95 percent. These datasets together confirmed the ability of the system to operate independently in a maintenance-free fashion and gave a compelling result that scalable implementation in energy-variable smart agricultural systems is justified.

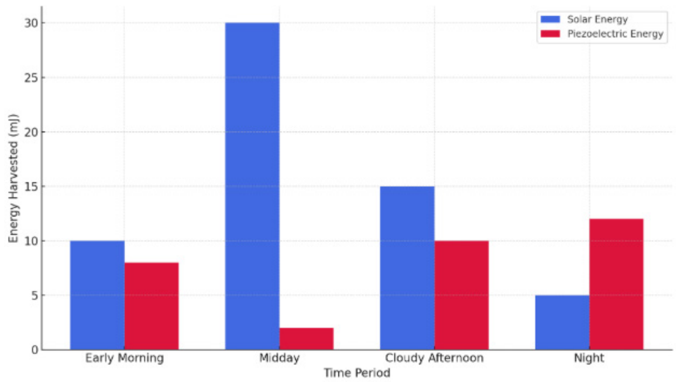

Fig. 7: Comparative Energy Contribution from Solar and Piezo Sources during Daytime and

Table 1: LoRa Transmission Performance Metrics

Metric	Hybrid System	Solar-Only	Piezo-Only
Average Uptime (hrs/day)	13.3	8.2	2.3
Packet Loss (%)	4.8%	12.7%	33.1%
Downtime Events	1	5	18
Packets Sent per Day	365	240	70

5. Results and Discussion

As the table sums up on the findings of the experimental analysis, performance improvements of the hybrid energy harvesting system in comparison with single-source systems are significant. The solar-piezo hybrid structure impressed with the average uptime a day of 13.3 hours, whereas figures were 8.2 hours in the solar-only or 2.3 hours in piezo-only structure. The improvement is quite remarkable and is all due to the fact that the system can dynamically use the ambient solar energy present during the day light hours and at the same time collect energy due to the availability of mechanical vibrations that can be created by wind or slight movements of animals, specifically during the dawn, dusk or in between clouds. This supplementary power source guarantee another source of energy to sensor nodes which accessed more stable and durable energy supply which is essential when remote/unattended deployments are to be used in the agricultural setting.

Regarding the amount of energy that is produced, the hybrid system conducted 47.2 mWh of energy a day that

Table 2: Performance Comparison of Hybrid, Solar-Only, and Piezo-Only Energy Harvesting Configurations for Sensor Node Operation

Configuration	Avg. Uptime (hrs/day)	Energy Harvested (mWh/day)	Packets Transmitted per Day	Downtime Events
Hybrid	13.3	47.2	365	1
Solar-Only	8.2	32.5	240	5
Piezo-Only	2.3	6.1	70	18

was almost 45 percent higher than the solar-only system and 7.9 times greater than the configuration with piezo. Some of the increased outputs go to energy capture, in part because of the intelligent power management strategy, with inputs prioritized to minimize conversion losses using an energy management IC (LTC3588 - 1). Using Schottky diode based OR-ing circuit prevented reverse leakage of power, hence allowing smooth charging of the supercapacitors and combining power from both sources. The solar module harvested most of the energy during times of optimum sunlight, whilst the piezo system added to the energy intake during windy evenings or due to vibrations due to animals- this will expand the time window of operation and iron out the daily variability of energy supply which is normally a negative component to the efficiency of solar based systems.

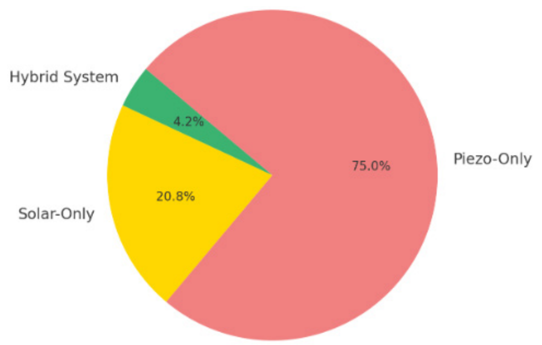

Fig. 8: Distribution of Sensor Node Downtime Events across Energy Harvesting Configurations

Moreover, the daily number of transferred data packets in the hybrid system equalled to 365 i.e. 52 percent more than the solar only system and more than five times in contrast to the piezo only system. This is correlated with the minimum number of node downtimes as they were observed once during the trial period. Conversely, systems with 100 percent solar energy and piezo had 5 and 18 instances of downtimes respectively, because of energy shortcomings. These findings affirm the efficacy of the indicated model in both production and control of energy as well as its conversion of the acquired energy into credible data acquisition and transfer. The decreased idle time and improved communication efficiency is more important to the precision agriculture uses such as the need to have the real time data at hand to assist in making the right decisions on irrigation, fertilization and crop health. The paper has ended up proving that a hybrid energy harvesting solution, that combines environmental and mechanical energy supply with adaptive power control, is a low-maintenance, long-term Lightweight and low-maintenance energy solution to energy provision of next-generation smart farming sensor networks.

Conclusion

This paper introduces an energy efficient and strong solar-piezo hybrid harvesting model that will be used to provide power to autonomous wireless sensor nodes in intelligent farming conditions. The system was designed by using ambient solar radiation and mechanical vibration energy as two independent sources of energy bypassing the associated limitations of single-source energy harvesters, specifically when environmental conditions are rather vanishing (especially with variable weather conditions). Maximum Power Point Tracking (MPPT) controller integration and priority-based regulation provide a powerful way to utilize the energy and the implementation of supercapacitors will increase the working time of the system and will lower the dependency on battery replacement. The findings of field deployment reveal that harvested energy and sensor uptime, as well as the reliability of data transmission, significantly improved, a fact that proves the concept of the hybrid system to be able to support long-term and maintenance-free sensor operation. The results support the feasibility of hybrid energy systems in precision agriculture in terms of practical application of using the technique in resource-limited and distant regions. The next changes will be towards integrating energy forecasting with AI, implementing load coping plans, and implementing mesh-based communication systems that can scale the system to large and heterogeneous agricultural fields, further making farming more sustainable and automated.

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