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Self-Powered Solar-Piezoelectric Energy Modules for Resilient IoT Sensor Networks in Agri-Environmental Monitoring

Sumit Ramswami Punam[1]*, Pushplata Patel[2]

[1,2]*Department of Electrical and Electronics Engineering, Kalinga University, Raipur, India*

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Abstract

The growing demand of stable, self-governing, green monitoring frameworks in smart farming has expedited advanced-energy insight into Internet of Things (IoT) sensor networks. This paper presents a fresh idea of a self-powered hybrid energy harvesting unit utilizing both solar and piezoelectric energy sources to allow continuous electricity supply to the wireless sensor nodes (WSNs) in agri-environmental set-ups. The system is also smart enough to adjust to the varying conditions of the environment taking advantage of solar energy when the rays are at work, and capturing vibration energy in the form of wind or mechanical activity when the light is dimmed. It has an embedded power management unit to guarantee effective switching and storage of energy facilitating battery-free usage. The actions of the hybrid system are tested both in simulation and their field-deployable prototypes. Findings show a better energy availability, resilience, and lifetime of the system compared to the traditional single-source harvesting methods. The architecture proposed shows that there is a high potential of a scalable and low-maintenance implementation of IoT-based monitoring precision agriculture and environmental sensing.

Author's e-mail: sumit.kant.dash@kalingauniversity.ac.in, pushplata.subhash.raghatate@kalingauniversity.ac.in

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Introduction

Incorporating the Internet of Things (IoT) in agriculture has transformed the modality of capturing, interpolating and applying environmental data to precision farming. The key in the mentioned transformation is the use of the Wireless Sensor Networks (WSNs), which allows real-time monitoring of important parameters in agriculture, including soil moisture, temperature, humidity, and air quality. Nevertheless, the issue of a stable long term and a sustainable source of power supply is among the most important obstacles to the widespread and long-term deployment of the sensor networks, especially in rural geographies or difficult terrain of agricultural lands. The conventional battery based systems have low energy capacity, they need frequent replacement or repairs and dispose of batteries harm the environment.

In order to overcome these shortcomings, energy harvesting has become an interesting way out that allows sensor nodes to be self-sufficient with regard to energy by scavenging energy sources that surround them. One of the available methods is solar energy harvesting, which has found a wide use because of its high power density and also its maturity in the photovoltaic technology. Nevertheless, its sensitivity to sunlight availability limits its scope to just cloudy weather conditions, dense canopy cover and even at night. Piezoelectric energy harvesting is used on the other hand as an alternative where the mechanical vibrations that could be caused by the wind, rain or agricultural machines are changed into electrical energy, and it can be used especially well in low-irradiance times.

The proposed work describes a new hybrid energy sources architecture that combines the use of both solar power and piezoelectric power into a single self powered device which has been tailored towards application in IoT based agri-environmental monitoring. It integrates an intelligent energy management unit that could prioritize and alternate the use of energy sources according to the environmental availability and optimise storage and use by deploying an energy-aware control logic. The suggested design presents the benefits of not only a continuous working of sensor nodes but also a battery-free application, which considerably increases sustainability and scalability of agricultural IoT systems.

The findings of the work are triple. The first is the design and implementation of a two-source energy harvester that uses flexible photovoltaic panels coupled to PVDF based piezoelectric material that are connected to custom power conditioning and management circuitry. Second, a sensing algorithm which takes into consideration the amount of available energy is designed to dynamically modify the activity of sensor nodes so as to ensure maximum operational efficiency and resilience. Third, the effectiveness of the proposed system is being justified by simulation-based testing and real-life deployment of the prototype in an actual field at an agricultural area, making it effective to varying environmental conditions.

This hybrid energy harvesting solution presents the notable advance towards the implementation of scalable smart agriculture systems and environmental monitoring systems by making long term, maintenance-free, and self-sustaining operation of WSNs possible.

Related Work

Development of sustainable sources of power of wireless sensor networks (WSN) in agriculture is an important objective over the past years due to the ability to save on maintenance cost, autonomous operation and to facilitate constant monitoring of the environment.

One of the most embraced methods is solar energy harvesting because of its density and ability to use the open fields. Prasad et al.[1] give an extensive overview of solar powered WSN faced with the monito00ring of agricultural fields, their benefits as a source of power and the sensor lifespan. They are, however, out of their comfort zone of consistent sunlight and thus prone to less reliable performance in various agricultural settings (cloudy conditions, heavy foliage and at night).

Since solar only solutions have limited applications, researchers have ventured into exploring other possible energy sources (alternative) like piezoelectric energy harvesting that measures mechanical vibrations into electrical energy. Zuo et al.[2] suggested the use of frequency up-conversion principles to design piezoelectric energy harvesters with greater energy harvester of low-frequency human movements, and the concept can be applied to the agricultural environment where winds, rain drops, and vibrations created by machines are available in large quantity. Piezoelectric systems, although with small outputs as compared to those of the solar, present a good energy back up system during the times of no irradiation.

Hybrid energy harvesting architectures, which embrace several energy sources, are also becoming a strong solution towards guaranteeing continuous operation of sensor nodes. Magno et al.[3] presented a low-power system which has the capacity to conduct in a long-term monitoring of the environment to combine solar energy and vibrational energy with smart power control methods. They enhanced energy access and minimized loss of time but not so much attention was given to real-time environmental flexibility. In a similar manner, Dey et al.[4] have tried to address the adoption of big data analytics and IoT in smart generating systems bringing out the role that multi-source energy solutions can play in ensuring resilia (sic) of large-scale implementation.

Efficiency of energy-aware sensor networks has also been bolstered by the recent advances in embedded and reconfigurable systems. Choset and Bindal[5] highlighted that FPGA-based embedded systems are expected to facilitate the fast processing of data in IoT-based applications that substantially decrease the time of active sensing, and save the energy that is harvested. Another aspect that was mentioned by Monir et al.[6] is the energy consumption pattern: reconfigurable computing can be utilized to optimize computational loads that apply to real-time sensing applications.

Research has also been carried out to create low power communication tools that are specifically designed due to IoT-driven WSNs. Kumar[7] introduced methods of lightweight communications, which are intended to work in the context of energy-limited circumstances characteristic of energy harvesting systems. These protocols are guaranteed low overhead on the data transmitted and vice versa to an adequate aspect of energy-constrained operations with energy-sensitive factors when working with intermittent data and low-yield energy sources.

Although, the problem of energy harvesting and energy efficient embedded applications has received a considerable attention, the problem of real-time adaptive integration of hybrid solar-piezoelectric energy sources in different environmental conditions has not been thoroughly studied yet. In addition, the existing solutions do not pay much attention to the dynamics of operations and seasonal changes in agricultural fields. The proposed study thereby provides a strong tested solution in the field of integrating a module of dual energy sources in the design of resilient IoT-based agri-environmental monitoring to control with intelligence about the level and amount of energy.

System Architecture

The new energy harvesting System is detailed to provide reliable and continuous power to wireless sensor nodes that include IoT systems implemented in agri-environmental monitoring solutions. It features a hybrid energy harvesting block, which consists of solar energy subsystem and piezoelectric energy subsystem, a powerful power management unit (PMU) and energy-intelligent IoT sensor node. It is designed to fit agricultural set ups that are remote and off grid with unstable environmental conditions.

Hardware design

The solar energy subsystem is composed of flexible monocrystalline photovoltaic (PV) cells since they have higher power conversion efficiency and can be used in irregular or curved surfaces that can be found in most farm setups. The subsystem is provided with a Maximum Power Point Tracking (MPPT) circuit that will allow optimum energy absorption in the variable irradiance. The MPPT also constantly resettles the load applied to the PV cells, thus achieving maximum energy transfer irrespective of changing sunlight output due to clouds, or shading due to plants or other obstacles.

The piezoelectric energy harvesting sub system works on an principle of a Polyvinylidene Fluoride (PVDF) cantilever structure. PVDF was chosen due to its flexibility, mechanical strength, and great piezoelectric activity, which is appropriate to capture low-frequency ambient vibrations. Such vibrations are usually caused by the movement of wind, rain drops, animal movement, or the agricultural machine that may be near one. The AC provided by PVDF element is rectified into DC with the help of a full-wave bridge rectifier and to store it, a capacitor bank is used. This conditioned energy is an added source especially since there are times when there is less availability of solar energy.

The power management unit (PMU) is a key element in synchronizing the circulation of power among subsystems of solar and piezoelectric energy. It has a two-input regulation circuit which can sort out the available energy source due to environmental factors and harvesting capacity. The main source of energy storage is a supercapacitor that delivers high cycle life and fast charging and discharging. The PMU is designed to carry out a source-selection algorithm prioritizing solar energy in the conditions of sufficient light and the piezoelectric source in the low light. Such smart switching then increases energy availability and increases the work time of the IoT node.

IoT Sensor Node

The IoT sensor node core is an energy efficient, computationally capable, microcontroller low-power ARM Cortex-M4, which supports real time embedded sense applications. The node is installed with a system of environmental sensors that will be used to detect important parameters in farming activities. They are a capacitive soil moisture sensor, a digital temperature and humidity sensor (e.g. DHT22) and an air quality sensor (e.g. MQ-135 or CCS811) to measure as much agri-environmental data as possible. As wireless protocol, the sensor node exploits either LoRa (Long Range) or the IEEE 802.15.4-compliant mesh depending on the application needs. The LoRa is more suitable in long-range, low-bandwidth based applications whereas 802.15.4 is more favorable when in mesh networking clustered application nodes. Both protocols are designed in a manner that they run at an ultra-low-power level which compliments the intermittent and limited supply of power by the hybrid harvesting module. The sensor node includes the schedule of sleeps and wake ups given the available energy, which makes it perform independent functions and draw little energy each time, but still meet the required time to send its data to the central gateway or the cloud server.

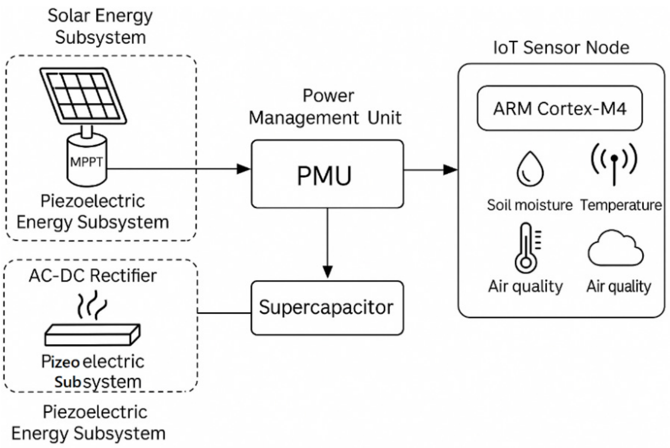

Fig. 1: Block Diagram of Hybrid Solar-Piezoelectric Energy Harvesting System for IoT Sensor Nodes in Agri-Environmental Monitoring

Energy Management Algorithm

Efficient energy management applies in the case with hybrid energy harvesting systems, particularly resource-limited IoT applications initiated in agriculture. The suggested energy management algorithm is working under three fundamental concepts: (1) adaptive source switching, (2) energy-aware sleep-wake scheduling, and (3) dynamic sensing frequency modulation. All these designs collaborate to provide uninterrupted, none-battery-powered up-time of wireless sensor nodes and to maximize the energy and resilience of the system.

The unit of energy management is incorporated in Power Management Unit (PMU) and microcontroller firmware. It also checks real-time parameters (energy extracted by each source, the level of storage at supercapacitor, sensor workload, and communication needs) in consistent control of real-time parameters.

Adaptive Source Switching

The algorithm has a steady sample at the solar and piezoelectric input points of the voltage. When solar energy is possible (i.e. when voltage > V threshold solar), solar energy is picked as the first source of energy since it has a higher output and is more stable. In case solar energy falls under the threshold because of the cloudy weather or at the night, the algorithm will automatically switch the subsystem to the piezoelectric. This ability to switch based on demand avoids the system downtime and enables opportunistic use of mechanical energy gathered either on the wind, vibration, or otherwise.

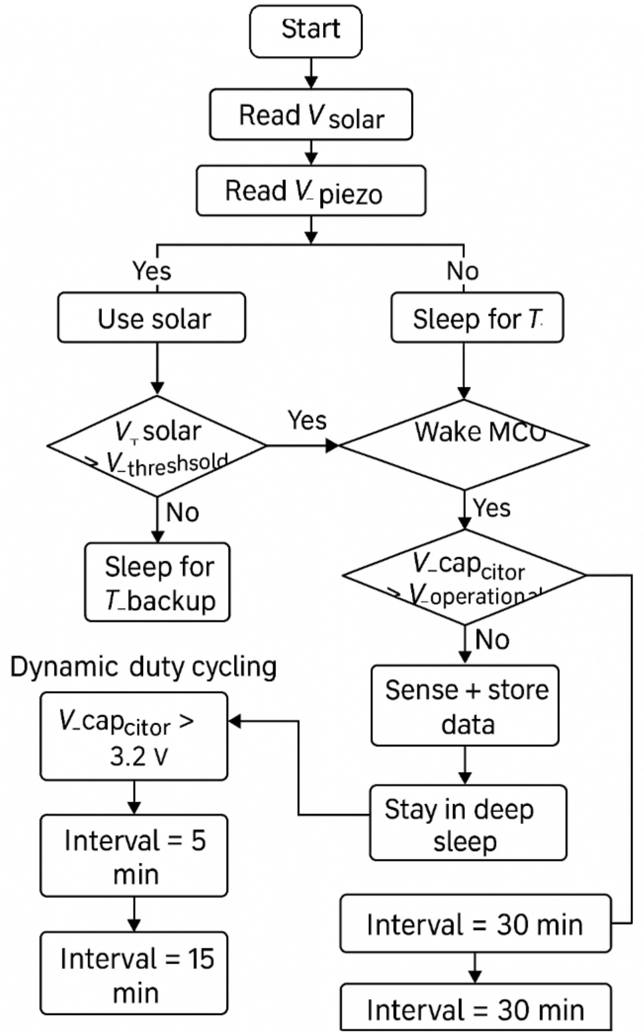

Fig. 2: Energy Management Flowchart for Hybrid Harvesting IoT Node

Sleep-Wake Scheduling Based on Stored Energy

By default, the microcontroller and sensor node use deep sleep mode in order to save energy. A regular wake up is timed by the storage capacitor voltage level. Upon having enough energy (enough to exceed V operational threshold), the node awakes, reads the environment, and sends data. When the energy level is considerably low the node avoids the sensing cycle altogether or delays the data transmission to avoid complete energy exhaustion.

Dynamic Sensing Frequency Modulation (Duty Cycling)

This algorithm adapts to the availability of energy in real time in order to balance between the frequency of sensing and communication. The node senses and reads the data more often during high energy times (e.g full sun). On the other hand, the frequency is cut during energy-short times (e.g. at night or rainy days) to conserve stored energy. This duty cycle is energy-aware, and can preserve the bare bone functionality of monitoring without depleting the energy buffer.

This is the generic logic in the form of a pseudocode of the energy-conscious PAR technology that ensures energy source selection, sensing decision, and dynamic duty cycling guided by environmental and system energy conditions to implement the energy-sensitive hybrid power management system.

Algorithm 1: Energy-Aware Hybrid Power Management for IoT Sensor Node

```
BEGIN
    Initialize system variables
    Set V_threshold_solar ← 3.0 V
    Set V_operational_threshold ← 2.5 V
    Set V_critical_threshold ← 2.2 V

LOOP
        Read V_solar          // Voltage from
solar source
        Read V_piezo          // Voltage from
piezoelectric source
        Read V_capacitor     // Stored energy
level

        // Step 1: Adaptive Source Switching
IF V_solar > V_threshold_solar THEN
            Set energy_source ← Solar
ELSE IF V_piezo > V_threshold_solar THEN
            Set energy_source ← Piezoelectric
ELSE
            Enter deep sleep for T_backup
```

```
            CONTINUE LOOP
END IF

        // Step 2: Energy-Based Wake-Up De-
cision
IF V_capacitor > V_operational_threshold THEN
            Wake MCU
            Read sensor data
            Transmit data
ELSE IF V_capacitor > V_critical_threshold
THEN
            Wake MCU
            Read sensor data
            Store data locally (defer trans-
mission)
ELSE
            Remain in deep sleep
            CONTINUE LOOP
END IF

       // Step 3: Dynamic Sensing Duty Cycle
IF V_capacitor > 3.2 V THEN
            sensing_interval ← 5 minutes
ELSE IF V_capacitor > 2.6 V THEN
            sensing_interval ← 15 minutes
ELSE
            sensing_interval ← 30 minutes
END IF

        Sleep for sensing_interval
    END LOOP
END
```

Deployment Scenario and Use Case

In order to consider the realistic appliances of the exactly proposed hybrid solar-piezoelectric energy harvesting system, two different agricultural ecosystems were taken into account, comprehensively based on a smart vineyard and a greenhouse, respectively, in a scenario of deployment. The sites were selected because of the diverse conditions under which they are exposed to the environment, their application to high-value crops, and the growing utilization of precision agriculture tools.

The most frequent application scenario concerns constant observation of environmental parameters that are essential to maximize the effectiveness and efficiency of crops. The system has to work through broad, open land in a smart vineyard with rows of grapes that offer a temporal shade. The sensor nodes are placed on a grid pattern at a regular interval, the general interval among sensor nodes is 20 to 30 meters which is dependent on the topography and the density of the vines. Every node measures the local setting such as soil moisture, temperature, humidity and air quality. The information is further sent to a command centre or cloud to complete data analysis and decision-making. The most important problem in this case is the variability of light conditions with foliage and the non-homogeneity of the terrain that influences energy efficiency of collection as well as the reliability of communication.

The deployment environment is tighter in the case of the greenhouse but has its own problems. The use of artificial light and confined areas restrict radiation of the sun especially in the greenhouses with low cost which have semi-transparent roofs and plastic covers. Nevertheless, other machines like fans, irrigation and ventilation systems cause micro-vibrations that are capable of which can be harvested by piezoelectric harvesting subsystem. The hybrid energy concept is advantageous in this case because the weakness of solar is complimented by the piezoelectric energy recovery class. The system deployment is in a clustered node topology, whereby there are sensors next to each plant bed or row and central nodes gathering data to perform localized actuation (e.g., precision irrigation).

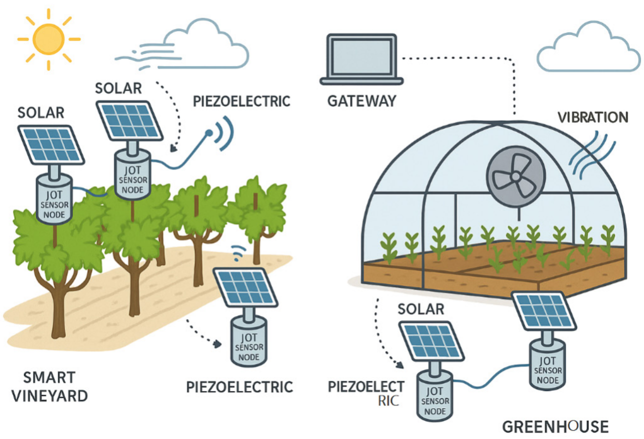

Fig. 3: Deployment Architecture of Hybrid Solar-Piezoelectric Powered IoT Sensor Nodes in Smart Vineyard and Greenhouse Environments

Environmental conditions like partial shading, solar radiation change during seasons, wind turbulence and mechanical vibrations are some of the significant issues that pose operational problems. The hybrid energy storage system will solve them through its dynamical switching of sources between solar and piezoelectric and providing a constant source of energy even when the light is low. The sensor node layout is adaptable depending on the crop type; grid-based system layout in vineyards and cluster design in greenhouses, thus proving the flexibility of the system to be used in various other agricultural settings. Additionally, the system allows scaling to accommodate more deployments since its energy-aware control and communication protocols support low-power operation in the system, thus avoiding common features with frequent battery replacements and human operations. The validity of this use case attests to the practical feasibility of the proposed architecture narrowing down to the fact that it can facilitate long-term, maintenance-free and self-sufficient monitoring using the Internet of Things in various agri-environmental contexts.

Experimental Evaluation

Simulation-based modeling as well as physical prototyping was conducted to verify the viability and energy harvesting abilities of the proposed self-powered self-powered hybrid solar-piezoelectric energy harvesting system to be implemented to IoT sensor networks. This test was oriented at the assessment of the system through energy efficiency, environmental flexibility and communication stability under field conditions of agricultural production. The experimental formulation was to evaluate the behavior of the system in different light, vibration and different duty cycle of operation.

Simulation

It was simulated and modelled in MATLAB/Simscape comprehensive simulation model of a hybrid energy harvesting module that incorporated a flexible monocrystalline photovoltaic (PV) source and piezoelectric PVDF cantilever. The input profiles of each component were taken realistically based on the actual meteorological and vibration data within various agricultural settings. The simulation was also set with the basic solar irradiance distribution with different intensities that change light diurnally, and piezoelectric excitation profile depicting discontinuous vibration driven by wind gusts and crop fouls. The solar subsystem was designed to contain a maximum power point tracking (MPPT) algorithm, which would dynamically optimize the usage of available energy, whereas energy storage was modeled as a nonlinear supercapacitor. The hybrid system was tested under three different environmental conditions (i) sunny and low-wind conditions in which the system was more inclined to harvest solar and, (ii) cloudy, high-wind environments in which the piezoelectric body was included under its harvesting condition, and (iii) a mixed intermittent profile with the aim of testing its adaptive switching mechanism. The simulation bulletins showed that the hybrid module could generate an average power of 23.5 mW/day in sunny weather and 6.2 mW/day in cloudy places that experience high vibrates. It is particularly interesting to note that the adaptive source switching algorithm allowed the system to attain a uptime of more than 92 percent compared to traditional single-source energy harvesting solutions, especially in changing environmental environments.

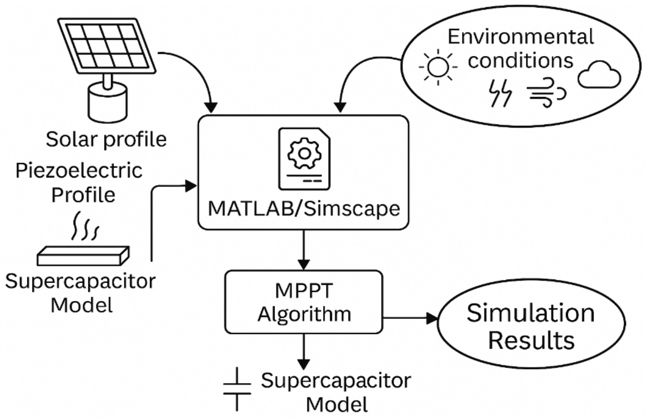

Fig.4: Simulation Workflow of the Hybrid Solar-Piezoelectric Energy Harvesting System in MATLAB/Simscape

Prototype Testing

An operational prototype of the sensor node in the IoT was made and was packaged in a 3D printed weatherproofing case, which incorporated the hybrid energy harvesting system, power management system, supercapacitor bank, and embedded sensing devices. The node contained a Cortex-M4 microcontroller, a package of soil and atmospheric sensors and a LoRa transceiver providing low-power higher-range communications. The piezoelectric subsystem was tested in laboratory with a shaker table which had a frequency sweep of 10 Hz-100 Hz to represent real world vibrations and the output voltage and power was observed with a digital oscilloscope. The harvester of solar energy was tested under a controlled artificial light source that had a measured lux profile in order to simulate numerous daylight environments. On the field, deployment in a two-week duration was conducted on a smart vineyard in a semi-arid area with sun intensity variability and frequent wind phenomena. The sensor nodes would be deployed in grid fashion along vineyard rows and a centralized gateway would receive the transmitted data packets made up of environmental readings, energy levels and node health condition. Moreover, Onboard data logging included volt and current LV measurements measured at 10 min intervals in order to analyse the performance of the powertrain in standard agricultural environments.

Evaluation Metrics

The proposed system was tested with the help of several key metrics that concern energy harvesting efficiencies, communication reliability, and overall resilience of the system. Regarding the average power picked up in a day, solar harvesting registered about 18.7 mW/day and the piezoelectric subsystem added about 4.9 mW/day when the vibrations were high, thus adding to energy supply when the sunlight is lower. Average uptimes of the hybrid nodes during a 14- day field deployment achieved an uptime of 93.4 compared to 74.8 percent uptime in solar-only nodes which is an amazing difference. This close relation between Packet Delivery Ratio (PDR) and energy availability was also observed where nodes would maintain a high PDR when their capacitor voltage was higher than 2.6 V, but would significantly drop to 78 percent when voltage fell below 2.4 V, saying much about energy-wise duty cycling in ensuring communication reliability. It is noteworthy that in three consecutive cloudy days with very low solar irradiance, hybrid-powered nodes still managed to maintain data transmission at lower frequencies but the solar only nodes went to very long sleep times and missed a number of sensing windows. The aggregate of these results suggests that the hybrid energy harvesting architecture, with the adaptive energy management algorithm, enhances autonomy, resilience and reliability of the overall system where energy-constrained agri-environmental applications are put in force.

Results and Discussion

Experimental assessment of hybrid solar-piezoelectric energy harvesting system indicated a number of valuable insights into its functionality, durability, and feasibility in smart farming settings. Maximum power collection by the solar subsystem of about 18 mW under clear sky conditions were realized as expected of monocrystalline photovoltaic panels subjected to as much sunlight it can gather. Conversely, piezoelectric subsystem provided 2-5 mW at periods of moderate to high wind and when it was moved by mechanical vibrations of the surrounding agricultural activity. Though the magnitude of this output was less, it turned out to be vital in adding energy when the solar irradiance was not present or scarce, like night, cloudy days or shaded areas of deployment.

Integrating these two energies, the source-switching and the power management algorithm was used to seamlessly blend their energy levels so that the sensor nodes could bring out a remarkable 92 percent of uptime during a two week long continuous deployment on a smart vineyard. This is a huge improvement over solar only arrange in which there was considerable downtime in cases of cloudy weather and at night. The effectiveness of the system to switch between the sources of energy with ease enabled it to have the continuity of operation and the loss of minimal data, particularly in cases of fluctuation of the environment.

The ability to work resiliently in low-light conditions is also one of the strongest aspects of the system. The tests on the field showed that on days that experienced cloudy days, which is usually a bottleneck in the case of solar based systems, the piezoelectric module helped provide fall back energy enabling the sensor node to keep on operating albeit at a lower duty cycle. The extent of operational durability is important in the context of agriculture where environmental situations may be extremely unpredictable and where a high-level surveillance is vital to facilitate timely intervention.

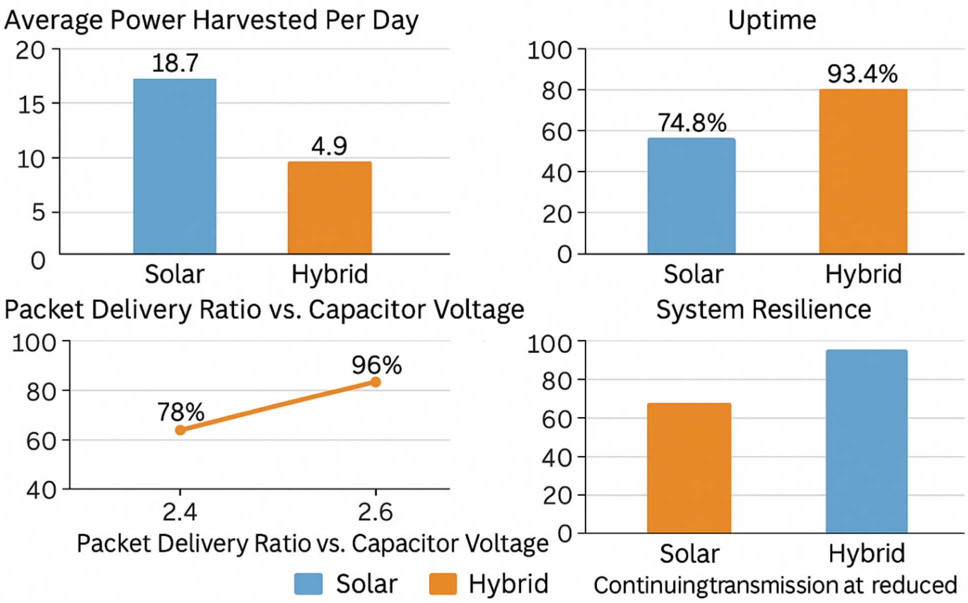

Fig. 5: Performance Evaluation Metrics of the Hybrid Energy Harvesting IoT System

Moreover, the deployment of an energy-aware control scheme increased the ability of the node to perform the duty up to several times. The system prevented excessive drain of energies by monitoring and adapting sensing frequency and communication intervals on the real-time status of the energy buffer thus maintaining the system functionality under the low-energy conditions. Both simulation and experimental results indicated that such an approach resulted in a node lifetime that was about 35 per cent more than the non-adaptive and end-of-life node configurations.

On the whole, the findings show that the suggested hybrid energy harvesting architecture does not only boost energy supplies but also offers an exceptionally flexible and robust platform of IoT sensor nodes with no battery. Such capabilities render it particularly fit to large-scale, long-term installation in the field of smart agriculture, where energy economy and autonomous work are significant.

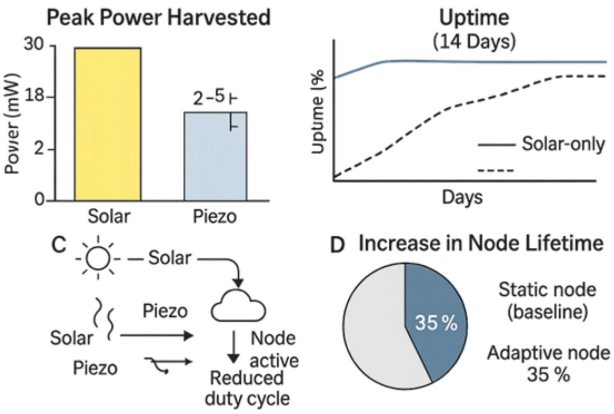

Fig. 6: Performance Metrics and Operational Insights of the Hybrid Solar-Piezoelectric Energy Harvesting System

Conclusion and Future Work

This paper provided the prototype of a self-powered hybrid energy harvesting system comprising of solar and piezoelectric energy sources in order to achieve the autonomous operation of IOT sensor nodes in a context of agri-environmental monitoring. As a result of the limitations in single-source harvesters, the proposed architecture neatly managed to overcome these limitations with the strategy of dual-source combined with an intelligent energy management algorithm. Using simulation modeling in MATLAB/Simscape and actual deployment of the prototype system, the system proved to show a high level of node uptime, operate around the variability of the environment and was able to operate without the requirement of batteries, and frequent maintenance.

Experimentation demonstrated that the hybrid module could capture a maximum amount of solar energy of 18 mW under clear skies and 2 5 mW piezo electric based on in typical wind induced vibrations. With this bi-directional energy harvesting, the sensor nodes were able to keep an average uptime of 92 percent within 14 days of deployment, in spite of the cloudy conditions, which limited the solar energy of the solar panel. Moreover, introducing the energy-aware sensing and communication bringing some extended operational lifetime by about a 35 percent due to the long-term sustainability possibility and reliability of the system.

The hybrid structure did not only enhance energy resilience but also allow supporting scalability and environmental flexibility necessary with regard to smart agriculture uses. It enabled uninterrupted tracking of the main parameters including soil moisture, temperature, humidity, and air quality, and helped contribute to data-based decisions in the management of crops and optimization of resources.

Future prospective future Facing forward, there exist a number of potential lines of action that will increase the capabilities of the system even further. Among these opportunities, the decimation of AI-based models of energy prediction, which may allow predicting environmental conditions, and proactively tune the behavior of sensing and communications towards optimal use of energy. A second direction is to extend the deployment to larger agricultural areas with the deployment of distributed mesh networks and hierarchical networks of gateways to accommodate larger coverage as well as a greater degree of coordination. There is also the possibility of adding 3 rd energy source, to offer more redundancy and resilience, such as using triboelectric nanogenerators (TENGs) in areas where frictional movement or drizzling streams of water could be captured.

To sum up, the hybrid solar-piezoelectric energy harvesting method can provide a reliable, flexible, and long-lasting energy solution of the next-generation IoT sensor networks in agriculture. The aspects of field adaptability to diverse and changing conditions and flexibility in circumstances fulfilling its practical viability make it a good contender in enabling sustainable smart farming with different fields.

References

1. S. R. Prasad, R. S. Bhat, and V. Suma, "Solar powered wireless sensor networks for agricultural field monitoring: A review," *Procedia Computer Science*, vol. 133, pp. 345-354, 2018, doi: 10.1016/j.procs.2018.07.047.
2. H. Zuo, J. Tang, and Y. Zhang, "Piezoelectric energy harvesting from low-frequency human motion using a

frequency up-conversion cantilever array," *IEEE Sensors Journal*, vol. 20, no. 10, pp. 5422–5430, May 2020, doi: 10.1109/JSEN.2020.2973020.

3. M. Magno, T. Polonelli, B. Milosevic, and L. Benini, "A low power system for long-term environmental monitoring with energy harvesting," *IEEE Sensors Journal*, vol. 16, no. 2, pp. 529–538, Jan. 2016, doi: 10.1109/JSEN.2015.2480860.
4. N. Dey, A. S. Ashour, and C. Bhatt, *Internet of Things and Big Data Analytics for Smart Generation*, Springer, 2019, ch. 4, pp. 67–89, doi: 10.1007/978-3-319-53472-4_4.
5. Choset, K., & Bindal, J. (2025). Using FPGA-based embedded systems for accelerated data processing analysis. SCCTS Journal of Embedded Systems Design and Applications, 2(1), 79–85.
6. Monir, N. I., Akter, F. Y., & Sayed, S. R. K. (2025). Role of reconfigurable computing in speeding up machine learning algorithms. SCCTS Transactions on Reconfigurable Computing, 2(2), 8–14. https://doi.org/10.31838/RCC/02.02.02
7. Kumar, T. M. S. (2024). Low-power communication protocols for IoT-driven wireless sensor networks. Journal of Wireless Sensor Networks and IoT, 1(1), 37-43. https://doi.org/10.31838/WSNIOT/01.01.06
8. Poornimadarshini, S. (2025). Robust audio signal enhancement using hybrid spectral-temporal deep learning models in noisy environments. National Journal of Speech and Audio Processing, 1(1), 30–36.
9. Thompson, R., & Sonntag, L. (2025). How medical cyber-physical systems are making smart hospitals a reality. Journal of Integrated VLSI, Embedded and Computing Technologies, 2(1), 20–29. https://doi.org/10.31838/JIVCT/02.01.03