

Ultra-Low Power Solar DC System Using Supercapacitor and Low-Power Environment Monitoring

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Abstract—This work presents an ultra-low power solar-driven DC power system developed for continuous environment monitoring applications. The proposed design combines a photovoltaic power source with a supercapacitor-based storage unit to provide a maintenance-free alternative to conventional battery-operated systems. A Single-Ended Primary Inductor Converter (SEPIC) is employed to regulate the output voltage and maintain stable power delivery despite variations in solar input conditions. System parameters such as voltage and current are monitored using a microcontroller to ensure reliable operation of low-power sensing loads. The integration of supercapacitor energy storage with efficient DC–DC conversion enhances system durability, reduces component degradation, and supports long-term deployment in remote monitoring environment solutions.

Keywords—Sensor networks, Energy-aware systems, Energy harvesting.

I. INTRODUCTION

Environmental monitoring systems are increasingly deployed in applications such as smart agriculture, industrial safety, pollution tracking, and remote climate observation [3]. These systems are often installed in locations where access to grid power is unavailable or unreliable, making autonomous power solutions essential. Traditional battery-powered monitoring units require periodic replacement or recharging, which increases maintenance effort and limits long-term deployment, particularly in remote and unattended environments.

Solar energy offers a practical and sustainable power source for low-power electronic systems. However, photovoltaic output is inherently variable due to changes in sunlight intensity, weather conditions, and diurnal cycles. These variations result in fluctuating voltage levels that negatively affect the performance of sensing and control electronics if not properly regulated [4].

Energy storage plays a crucial role in mitigating the intermittency of solar power. While rechargeable batteries are commonly used, they suffer from limited charge–discharge cycles, ageing effects, and reduced efficiency over time [5]. Supercapacitors provide an alternative energy storage solution with rapid charging capability, high power density, and extended operational lifetime. These characteristics make supercapacitors particularly suitable for ultra-low power systems that require frequent charge–discharge cycles and minimal maintenance [6].

To maintain stable power delivery under varying input conditions, an appropriate DC–DC conversion stage is required. The Single-Ended Primary Inductor Converter (SEPIC) topology is well suited for solar-powered applications because it supports both step-up and step-down voltage regulation without polarity inversion [7]. This flexibility allows the system to provide a consistent output voltage even when the solar input voltage fluctuates above or below the desired level.

In this work, an ultra-low power solar DC system integrating a SEPIC converter and supercapacitor-based energy storage is proposed for environmental monitoring applications. The system includes a microcontroller-based monitoring unit to observe electrical parameters and support the reliable operation of low-power sensing loads. The proposed approach aims to reduce maintenance

requirements, improve power stability, and enable long-term deployment in remote monitoring scenarios.

The rest of the paper is organised as follows: Section II: Literature Review; Section III: Problem Statement; Section IV: Methodology; Section V: Expected Results; Section VI: Conclusion; Section VII: Future Scope.

II. LITERATURE REVIEW

A. Energy Harvesting Sensor Nodes

Energy harvesting enables electronic systems to operate by utilising energy available from their surrounding environment rather than relying solely on conventional power sources. In the context of sensor nodes, this approach allows naturally occurring energy to be converted into electrical power to support sensing, processing, and communication tasks, thereby extending operational duration and reducing maintenance requirements [3]. Depending on the power consumption characteristics of a sensor node, harvested energy may partially supplement or fully satisfy its energy demand [4].

Among the available energy harvesting methods, solar energy conversion using photovoltaic devices is the most commonly adopted due to its wide availability and relatively high power density [5]. Although solar irradiance cannot be controlled, it exhibits pattern-based daily and seasonal patterns, making it suitable for long-term power planning [6]. In addition to solar energy, other harvesting techniques extract energy from mechanical motion, wind flow, or vibrations [7].

B. Energy Harvesting Architectures

Broadly, energy harvesting systems can be categorised based on how harvested energy is delivered to the load. Two widely used architectural approaches are direct utilisation of harvested energy and storage-assisted energy utilisation [20].

Direct Energy Utilisation Architecture: Direct utilisation architectures are commonly applied in systems that harvest short bursts of mechanical energy, such as button presses, walking motion, or pedalling actions [22].

Storage-Assisted Energy Utilisation Architecture: In storage-assisted architectures, harvested energy is first accumulated in an energy storage element before being supplied to the sensor node [22]. This approach enables energy collected during periods of availability to be used later when the power source is absent or insufficient.

C. Sources of Harvestable Energy

The selection of an appropriate power source is a critical factor in the design of an energy harvesting system, as it

directly influences the quantity, continuity, and rate at which electrical energy is generated [20]. Examples include solar radiation, wind flow, and radiofrequency (RF) signals, all of which can be harvested without direct user involvement [22]. Among these, solar energy is widely adopted due to its relatively high power density and pattern-based daily patterns.

D. Energy Conversion Mechanisms

In solar-based energy harvesting systems, electrical energy is obtained using photovoltaic modules that convert incident light into usable electrical power. The electrical output of a photovoltaic module depends on factors such as panel surface area, conversion efficiency, and the intensity of incident sunlight [13]. Mechanical energy harvesting systems rely on the conversion of physical motion into electrical energy using piezoelectric transducer materials, which generate an electrical potential when subjected to mechanical stress [21]–[23].

E. Storage Technologies

Energy storage is a critical component in energy harvesting systems, as it directly affects system reliability, efficiency, and long-term operability. In practical energy harvesting applications, rechargeable storage devices are commonly employed to accumulate harvested energy and supply power during periods of low or no energy generation. Common rechargeable battery technologies include Sealed Lead Acid (SLA), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), and Lithium-based batteries. Despite their advantages, supercapacitors possess lower energy density and higher self-discharge rates compared to rechargeable batteries. In hybrid storage configurations, supercapacitors are often used alongside batteries to smooth power fluctuations and reduce stress on the battery, thereby extending overall system life.

III. PROBLEM STATEMENT

This section describes various problems encountered in the design of various power sources, including: Solar power [12]; Active user [20], [21].

A. Solar Energy Harvesting Systems

Due to its widespread availability and suitability for outdoor deployments, solar energy has been extensively explored as a power source for sensor node platforms. Multiple solar-powered sensor node implementations have been reported in the literature, including Prometheus [21], HydroWatch [22], Heliomote [20], Ambimax [18], Everlast [34], and Sunflower [15].

1) Nodes - Battery-Based Storage

HydroWatch [16] is an example of a solar-powered sensor node that employs a single-stage battery-based energy storage system. The platform is built on the TelosB mote [13] and utilises Nickel Metal Hydride (NiMH) batteries as the primary storage element. Experimental observations reported in [16] indicate that eliminating inefficient regulation stages significantly improves overall system efficiency.

HydroWatch [16] employs NiMH batteries primarily influenced by the relative simplicity of NiMH charging requirements. Unlike lithium-ion batteries, which demand precise current regulation and protection circuitry, NiMH batteries can be charged using simpler control logic, reducing hardware complexity and design overhead.

2) Nodes with Supercapacitor-Based Storage

Everlast [34] is a representative example of a wireless sensor node that relies exclusively on supercapacitors for energy storage, eliminating the use of batteries entirely. The energy harvesting subsystem of Everlast consists of a photovoltaic source, an intermediate charge-transfer stage, a supercapacitor, and a regulation circuit. Using a regulated charging technique, Everlast reports extended operational lifetimes under periodic duty-cycled operation.

Prometheus [25] exemplifies a hybrid energy storage approach that combines supercapacitors and rechargeable batteries within a single system. In this architecture, supercapacitors serve as the primary storage element to absorb rapid fluctuations in harvested energy, while a lithium polymer battery functions as secondary storage to provide long-term energy buffering.

B. Piezoelectric Harvesting Nodes

Piezoelectric-based harvesting: Piezoelectric transducer materials are widely used to convert mechanical deformation into electrical energy. Polymer-based piezoelectric films such as PVDF generate electrical charge when bent or stretched. A shoe-powered RF tag system demonstrates the use of piezoelectric energy harvesting for self-powered wireless identification [22]–[24]. Another example is a battery-less wireless push-button controller powered by piezoelectric energy [21].

IV. METHODOLOGY

This paper follows a structured survey methodology to identify the design implications of energy harvesting for low-power environmental monitoring nodes.

- Scope definition: the review focuses on sensor nodes powered by solar, piezoelectric, wind, and RF energy

sources, with specific attention to storage topology, power conditioning, and operational continuity.

- Literature screening and grouping: representative studies are grouped according to harvesting source, storage element, converter architecture, and intended sensing application so that similar systems can be compared consistently.
- Comparative analysis: each group is examined in terms of source availability, harvested power level, storage behaviour, conversion efficiency, and practical suitability for long-term wireless sensing.
- Design implication mapping: the survey findings are translated into requirements for the proposed photovoltaic-supercapacitor-SEPIC platform, especially low leakage storage, efficient DC regulation, and energy-aware load management.

The methodology begins with subsystem selection. The photovoltaic source is chosen as the primary energy input for outdoor availability, the supercapacitor is selected as the storage element for high cycle life and rapid charge acceptance, and the SEPIC converter is adopted as the regulating stage because the input voltage can cross the desired output level during operation [2], [6].

The operating method is analysed in two modes. During sufficient sunlight, harvested energy charges the supercapacitor while the SEPIC stage powers the load from the available input path. During reduced irradiance or brief shading, the stored energy in the supercapacitor continues supplying the converter so that the monitoring node can keep operating without an immediate voltage collapse.

Evaluation of the design is based on project-relevant metrics: charging response under solar input variation, regulated output stability, energy buffering during low-input intervals, low-power load support, and the expected reduction in maintenance compared with battery-dominant approaches.

V. RESULTS

Sensor: Traditional wireless sensor networks are typically designed under the assumption of limited and non-replenishable energy. As a result, system optimisation often involves trade-offs among node lifetime, sensing reliability, coverage, and deployment cost.

A. Energy-Neutral Operation

Energy-neutral operation refers to maintaining a balance where the energy consumed by a sensor node does not exceed the energy harvested over time. At the node level, this means adapting the operation such that the node

continues functioning without depleting its energy storage. In systems without energy storage, continuous operation is possible only when harvested power consistently meets or exceeds consumption. In contrast, systems with energy storage tolerate temporary mismatches between harvested and consumed energy, provided sufficient energy is available in storage.

B. Performance Adaptation

To fully benefit from energy harvesting, sensor nodes must adapt their performance parameters dynamically. A key requirement for such adaptation is the ability to estimate future energy supply. Simple prediction models based on historical energy patterns help nodes anticipate recharge opportunities and plan energy usage accordingly. Node-Level Adaptation Strategies: Energy-aware nodes tune multiple parameters to improve performance. Duty Cycling: nodes with higher available energy remain active for longer durations, improving sensing reliability and reducing communication delay. Transmit Power Control: adjusting radio transmit power allows nodes to trade communication range for energy savings.

C. Network-Level Implications of Energy Harvesting

- **Data Collection:** Data collection is a fundamental operation in most wireless sensor network applications. In energy-harvesting networks, aggregation strategies can be made energy-aware by selecting aggregation points based on harvesting potential and residual energy [11][13].
- **Node Placement and Coverage:** Energy harvesting also influences sensor node deployment strategies. With harvesting-aware nodes capable of extended or perpetual operation, fewer nodes may be sufficient to provide long-term sensing coverage.
- **Medium Access Control (MAC) and Communication Protocols:** The presence of energy harvesting has significant implications for MAC layer protocol design. Energy harvesting allows protocol parameters to be adapted dynamically based on a node's energy state.
- **Cross-Layer Design Considerations:** Energy harvesting introduces strong coupling between node-level power management and network-level protocol behavior. Effective exploitation of energy harvesting requires coordinated cross-layer design.

TABLE I. RESULTS SUMMARY

Result	Basis in Proposed System	Implication for Deployment
Energy-neutral operation	Solar harvesting and supercapacitor buffering keep average energy use within harvested energy over time.	Supports long-duration autonomous monitoring.
Stable regulated supply	The SEPIC stage conditions variable photovoltaic output into a usable DC supply for the node.	Reduces brownouts and improves sensing continuity.
Lower maintenance demand	Supercapacitors tolerate repeated charge and discharge cycling better than batteries.	Reduces replacement frequency in remote locations.
Adaptive node performance	The controller can scale duty cycle, sensing rate, and communication activity with available energy.	Improves reliability under changing sunlight conditions.
Better network sustainability	Harvesting-aware nodes remain available longer and recover faster after low-energy periods.	Improves long-term coverage and data availability.
Efficient energy storage utilisation	The supercapacitor stores excess harvested solar energy during	Enables continuous monitoring even during

	peak sunlight and supplies power during low irradiance.	temporary shading.
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VI. CONCLUSION

Energy harvesting enables a new generation of wireless sensing systems by reducing dependence on finite power sources and enabling long-term autonomous operation. In this paper, an Ultra-Low Power Solar DC System Using Supercapacitor and SEPIC Converter for Environmental Monitoring has been explored within the broader context of energy harvesting sensor networks.

The study reviewed existing energy harvesting sensor node implementations and applications to illustrate how design choices in storage and power management influence system efficiency and reliability. Particular attention was given to the use of supercapacitors as energy storage elements, which offer fast charging, high cycle life, and maintenance-free operation. The integration of a SEPIC DC–DC converter enables stable voltage regulation under fluctuating solar input conditions.

Overall, the proposed approach demonstrates that combining solar energy harvesting with supercapacitor-based storage and efficient DC–DC conversion provides a robust and scalable solution for long-term environmental monitoring applications.

VII. FUTURE SCOPE

- **Integration of Maximum Power Point Tracking (MPPT):** Future implementations can incorporate MPPT algorithms to optimise the power extraction from photovoltaic panels under varying sunlight conditions.
- **Hybrid Energy Storage Systems:** Combining supercapacitors with rechargeable batteries could improve long-term energy storage capacity, providing both high power density and higher energy density.
- **Advanced Power Management Algorithms:** Future designs can integrate intelligent energy management techniques using machine learning or predictive models to analyse historical solar patterns.
- **Integration with IoT and Cloud Platforms:** The monitoring system can be extended by integrating wireless communication technologies such as LoRa, NB-IoT, or Wi-Fi to transmit collected environmental data to cloud platforms.

- **Miniaturisation and Hardware Optimisation:** Further work can focus on reducing the size and power consumption of system components through custom PCB design and ultra-low-power microcontrollers.

TABLE II. CHARGE–DISCHARGE CHARACTERISTICS HIGHLIGHTING SUPERCAPACITOR PERFORMANCE

Total Voltage (V)	Capacitor Voltage (V)	Charge (%)	Charging Behaviour	Discharging Behaviour	System Implication
0	0	0	High inrush current	No discharge	System OFF
1	0.5	~20	Rapid charging	Fast voltage drop	Cannot drive load
2	1.0	~40	Moderate charging	Fast discharge	Limited operation
4	1.5	~60	Charging slows	Stable discharge	Startup possible
6	1.8	~80	Near saturation	Good discharge	Reliable operation
8	2.1	~95	Very slow charging	Strong output	Near peak
10 (Max)	2.7	100	Charging stops	Maximum energy	Fully charged
>10.8	>2.7	—	Overcharge	Risk of damage	Unsafe condition

Ethics declaration: Not applicable.

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