Power Supply of Ultra-low-power IoT sensors through Energy Harvesting

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***Abstract*— This work addresses the problem of supplying ultra-low-power electronic systems and Internet of Things devices using multiple energy harvesting sources. The study investigates the integration of solar, thermoelectric, piezoelectric, and radio frequency sources to ensure continuous operation under variable environmental conditions. Circuit architectures were designed, simulated, and experimentally validated, including rectification and conversion stages for each energy source. A solar cell bypass circuit using a MOSFET was implemented to prevent system interruption under low-illumination conditions, maintaining a stable 500 mV output. A piezoelectric harvesting circuit produced a 0.5 V DC output with parallel elements, ensuring stability when the solar cell was inactive. A multiple-input Boost converter achieved output voltages above 1.2 V when at least one source was active, demonstrating efficient series integration. The 2.4 GHz RF energy-harvesting system demonstrated the ability to serve as an effective alternative power source for IoT sensor networks.. The step-up converter LTC3525-3.3 boosted input voltages from 0.85 V to 3.3 V. The results confirm the feasibility of combining heterogeneous energy harvesting systems to supply autonomous low-power circuits, though losses due to impedance mismatch and environmental dependency remain critical challenges. Future developments should focus on adaptive power management and optimization of hybrid harvesting structures for improved reliability and higher efficiency.**

***Index Terms*— Energy Harvesting; Internet of Things, Ultra-Low Power Systems, DC-DC Converters, RF Energy Harvesting, Hybrid Power Management.**

I. INTRODUCTION

The present work addresses the application of Energy Harvesting (EH) techniques for collecting power to supply ultra-low-power sensors capable of wirelessly communicating with each other. The Internet of Things (IoT) has gained a crucial role in connecting society worldwide. IoT devices are interconnected to enable the exchange of information and data, forming a global network with potential applications in areas such as smart agriculture, healthcare, vehicles, satellites, scientific development, and the military, among others [1].

Batteries generally occupy a considerable portion of the volume and weight of a typical portable IoT system. EH techniques are widely employed to reduce maintenance costs and to replace conventional batteries. However, environmental variations can cause disturbances in the input power, potentially leading to system failure. Therefore, ensuring smooth energy transfer remains a significant challenge for the power management system.

The human body is one of the most extensively studied energy sources for powering wearable electronic devices, using piezoelectric, triboelectric, and other electromagnetic mechanisms integrated into clothing or directly on the skin [2].

The main objective of this work is to employ more than one EH source as a DC input for various DC-DC converter topologies, namely classical Boost, Buck, and Buck-Boost converters. The final electronic system is powered by at least two EH generators (solar, piezoelectric, among others) in parallel or series configuration, targeting ultra-low-power (ULP) remote applications to increase autonomy in IoT sensors and data monitoring applications embedded in future soldier equipment.

To make the system autonomous, a 1.2 V battery is added to supply the integrated circuits and ensure system start-up. This work focuses on implementing solutions that address the drawback of applying the solar cell in series topology.

II. STATE OF THE ART

To understand the operating principle of the sensors and how they are powered, it is essential to comprehend the general concepts behind the Internet of Things (IoT) and how energy harvesting (EH) techniques are applied. This section reviews the fundamental aspects of IoT, ultra-low-power circuits, energy-harvesting principles, and the converter topologies used for power management in such systems.

A. Internet of Things

IoT systems are typically organized in layered architectures composed of three main layers: the device (perception) layer, responsible for sensing, actuation, and data acquisition; the network layer, which handles connectivity and communication through lightweight IP stacks (e.g., IPv6/6LoWPAN); and the application layer, which processes and delivers services to end users [3].

IoT applications rely on a common IP-based communication protocol stack, enabling interoperability among multiple devices. They can be used in smart grids, renewable energy systems, healthcare monitoring, and transportation.

In military applications, IoT supports risk analysis, drone-deployed sensor swarms, threat monitoring, asset tracking, and real-time localization systems [4]. There is a natural evolution of IoT into the Internet of Battlefield Things (IoBT), which integrates sensors, actuators, and autonomous systems for defense operations, combining communication and energy transfer to improve autonomy in harsh environments [5], [6].

B. Ultra-low-power Circuits

In the sub-threshold regime, current flow is exponentially dependent on gate voltage, leading to minimal dynamic and leakage power consumption. However, this mode of operation imposes trade-offs between speed, stability, and noise immunity [7] [8].

Designing ULP circuits is crucial for IoT systems powered by small batteries or energy harvesters. Advanced CMOS and FinFET transistor technologies further reduce leakage currents and improve efficiency, allowing for reliable long-term operation in constrained environments [5].

C. Energy Harvesting

Energy Harvesting (EH) is the process of collecting energy from the environment and converting it into electrical energy for powering electronic devices. A typical self-powered system includes an energy transducer, a rectifier stage, a voltage regulator, optional energy storage, and the electronic load block [9].

The available EH sources include solar, vibration-based, acoustic noise, temperature gradients, and electromagnetic radiation (light or RF). When selecting an EH device, power reserves must ensure reliable sensor operation even under low-harvest conditions.

Few studies explore series configurations, such as solar cells connected in series with other EH sources, which could potentially increase input voltage without additional converters. This represents a significant gap addressed in this work.

D. Radio Frequency Energy Harvesting

Radio Frequency Energy Harvesting (RFEH) converts electromagnetic energy into DC power for ULP nodes or for extending battery life. An RFEH front-end typically consists of an antenna, an impedance-matching network, and a rectifier, followed by energy storage and a Power Management Unit (PMU) [10] [11].

1) RFEH in Urban Military Operations

Future military operations will take place in highly connected and contested environments. Urban areas exhibit higher ambient RF field strengths due to the coexistence of Wi-Fi, cellular, and broadcast systems, making RF energy particularly suitable for powering wearable or unattended sensors [12]. Measurements indicate that available RF power in urban areas usually ranges between –20 dBm and –40 dBm at the antenna port [10]. System efficiency depends heavily on impedance matching, minimization of front-end losses, and the design of compact matching networks [11] [13].

E. Classical Inductive DC-DC Converters

DC–DC converters transform unregulated input voltages into stable DC outputs. The most common topologies are the Step-Down (Buck), Step-Up (Boost), and Step-Down/Up (Buck–Boost) converters [14].

These circuits regulate output voltage by controlling the switch duty cycle through Pulse Width Modulation (PWM). Multiport converters are categorized as Multiple-Input Single-Output (MISO), Single-Input Single-Output (SISO), and Single-Input Multiple-Output (SIMO) [15].

This work focuses on MISO architectures that allow combining multiple EH sources at lower cost and complexity.

F. Power Converters for IoT

IoT devices require flexible DC–DC converters capable of handling variable power from EH sources. Among IoT subsystems, transmitters consume the most energy, so optimizing conversion efficiency is critical [1].

Boost converters, implemented as charge-pump (Dickson) or inductive step-up circuits (Figure 1), are commonly used for generating higher output voltages from low-level EH inputs [1].

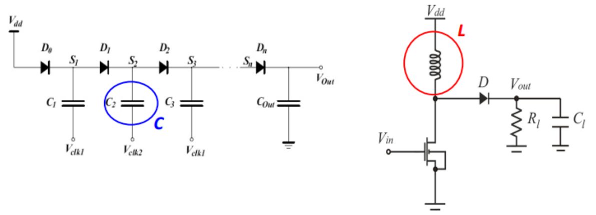

Figure 1. Converter Topologies: charge pump and inductive step-up (respectively)

III. SOLUTIONS FOR SOLAR CELL SHORT-CIRCUIT CONDITIONS

All the Multiple-Input Single-Output (MISO) DC–DC converters presented in Section II use input configurations where the EH sources are connected in parallel. In this work, a MISO DC–DC converter incorporating two or more EH sources connected in series is studied, with one of the sources being a solar cell and the other a thermoelectric (TE) generator or another EH type.

However, this topology introduces a critical issue: when the solar cell stops generating current (for example, under low illumination), it behaves as a high-impedance element, interrupting the circuit and preventing power delivery from the other sources. To overcome this limitation, several circuit-level solutions were developed to ensure continuous current flow in series-connected EH systems.

A. Support Circuit for Solar Cell Short-Circuit Protection

The interruption of the power path occurs when the solar cell current (I_1) becomes null, limiting the generator current (V_{PELT}) due to the reverse bias of the diode and the high parallel resistance of the solar cell, typically in the order of MΩ.

To avoid this, the proposed solution introduces a support circuit capable of bypassing the solar cell whenever it ceases to generate voltage.

1) Solar Cell Bypass Using a MOSFET

The first proposed architecture employs a MOSFET controlled according to the operating condition of the solar cell (Figure 2). Simulation results show that the load voltage (V_{LOAD}) remains stable whenever at least one of the EH sources—solar or thermoelectric—is active (Figure 3). When both sources are inactive, the output voltage drops to zero, confirming that the circuit effectively prevents power interruption in normal operation.

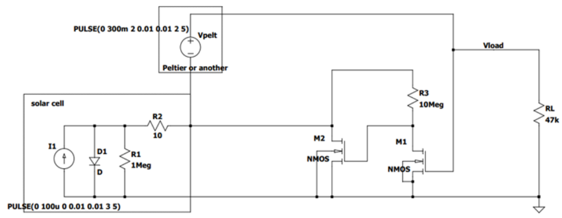

Figure 2. Electrical schematic of the circuit for solar cell bypass

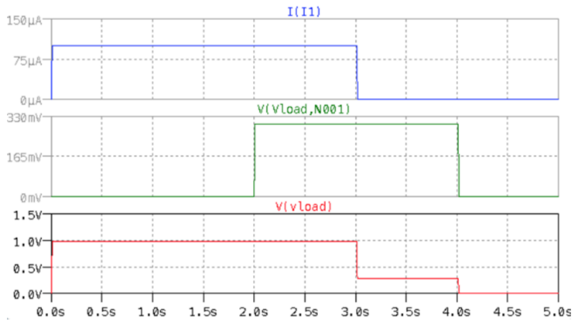

Figure 3. Graph of the temporal evolution of the current in the solar cell, the voltage in V_{PELT} and the voltage across the load

This configuration demonstrates that the solar cell support circuit allows current continuity even when illumination is lost, preventing the system from entering a short-circuit state and ensuring that the load remains powered.

2) Solar Cell Bypass Using a Switch

An alternative implementation uses the TPS22860 Ultra-Low Leakage Load Switch, controlled through its ON and V_{BIAS} pins.

The switch operates according to the thresholds, where $V_{ON} < 0.3\times V_{BIAS}$ corresponds to the OFF state and $V_{ON} > 0.9\times V_{BIAS}$ corresponds to the ON state. When activated, the switch connects the stable EH voltage directly to the output (Vo), bypassing the inactive solar cell.

In the OFF state, the output is isolated from the input, and the internal leakage current remains below 70 nA, eliminating the need for additional isolation components. If experimental validation reveals residual current leakage, a Schottky diode can be placed at the switch output to prevent reverse conduction.

3) Solar Cell Bypass Using Piezoelectric Elements

In the third approach, piezoelectric elements act as a stable voltage source that powers the switch circuit. These elements produce an alternating voltage when subjected to mechanical stress, requiring a rectifier to generate a usable DC signal. Two rectifier configurations were studied: a half-wave rectifier and a full-bridge rectifier with filtering circuit.

While the half-wave rectifier uses only half of the available energy, the full-bridge configuration is more complex. The implemented circuit (half-wave rectifier) with parallel-connected piezoelectric elements achieved a stable output voltage of 500 mV, sufficient to supply the control circuit even when the solar cell was inactive. This setup ensures uninterrupted power flow in the hybrid series-connected EH topology.

B. Preliminary Study of a MISO Boost Converter

To validate the non-cancellation concept, the solar bypass circuit was connected to an inductive Boost converter, replacing the resistive load with an energy-conversion stage (Figure 4). The Boost converter included a 300 µH inductor, a Schottky diode ($V_f = 0.1$ V), a 4.7 nF output capacitor, and an n-channel MOSFET driven by a 1 MHz PWM signal with a duty cycle of 0.7. Simulation results (Figure 5) demonstrated that the output voltage (V_{OUT}) exceeded 1.2 V whenever at least one source was active, confirming the ability of the circuit to maintain energy conversion independently of individual source conditions.

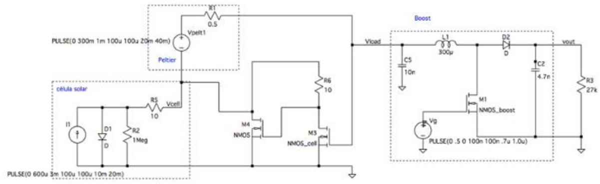

Figure 4. Solar Cell Bypass Circuit with an Inductive Boost Converter

The converter operated properly under both single-source and dual-source modes, achieving efficient voltage amplification from the combined EH inputs.

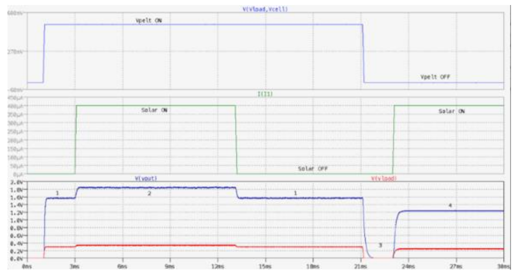

Figure 5. Temporal Evolution of the Boost converter input voltage and the Boost converter input voltage

C. System Architecture for RFEH

In addition to solar and thermoelectric sources, a Radio Frequency Energy Harvesting (RFEH) circuit was designed for operation at 2.4 GHz, one of the most common frequencies used in civilian and military communication systems. This band includes Wi-Fi, Bluetooth, and tactical communication links, providing abundant ambient electromagnetic energy.

The proposed RFEH circuit (Figure 6) was designed to process an input RF signal of 1 V amplitude. Simulations yielded a stable DC output voltage of 0.910 V, confirming that the harvested RF energy could supplement the hybrid EH power system.

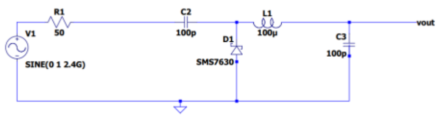

Figure 6. Proposed Circuit for RFEH

By exploiting the electromagnetic energy already present in the environment, this approach enables the development of autonomous IoT sensors and wearable systems with reduced dependence on batteries.

Figure 7 presents the proposed hybrid energy-harvesting circuit, designed to evaluate the combined use of a stable EH source, a low-power photovoltaic cell and a RFEH circuit.

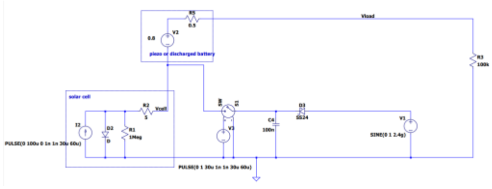

Figure 7. Hybrid EH Circuit

The system consists of two independent micro-energy sources: a PV cell modeled as a current source under pulsed illumination conditions, simulating intermittent exposure to light, a second low-voltage source that represents a discharged rechargeable battery, and a RFEH circuit.

Energy from both sources is routed through a switching stage (SW1) and stored in a 100 nF capacitor. The load is modeled as a 100 kΩ resistor, representative of ultra-low-power IoT sensor electronics. In a practical implementation, this switching function could be realized by a sensor-triggered circuit, for example based on a Light-Dependent Resistor (LDR). Under light conditions, the LDR would reduce its resistance and activate the switch, enabling the harvesting path; under darkness, the circuit would remain in a low-leakage standby mode.

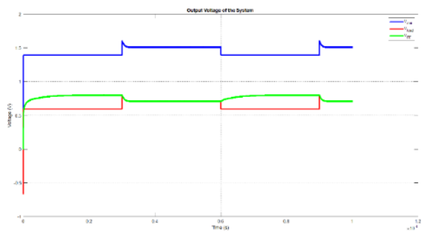

Figure 8. Simulations Results of the Hybrid EH Circuit

Figure 8 shows the simulated voltages at the Solar Cell and at the load over time. Voltage at the load (V_{LOAD}) remain strictly positive throughout the simulation, even during periods when the solar cell is unilluminated.

D. *Experimental Implementation of the Step-Up DC-DC Converter*

To increase the voltage from energy harvesters that produce lower output levels, the step-up DC-DC converter LTC3525-3.3 is used. This converter provides a fixed output voltage of 3.3 V and can start operating with input voltages as low as 0.85 V and up to a maximum of 4.4 V. One of its main features is that the output is electrically isolated when the device is turned off. It also includes a control mode in which the SHDN pin activates the circuit when the voltage exceeds 1 V and disables it when it falls below 0.4 V. To validate the previously studied strategy, the control model was applied to the LTC3525-3.3 Boost Converter (Figure 9).

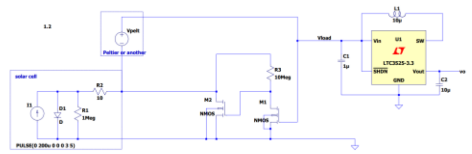

Figure 9. Solar Cell Bypass Circuit Connected to a Step-Up Converter LTC3525-3.3

The circuit successfully started operating supplied by the EH sources, and once the input voltage reached the threshold the converter was activated and increased the voltage to a stable 3.3 V (Figure 10).

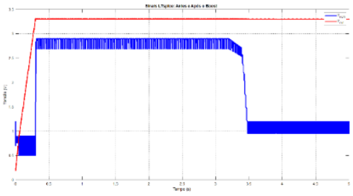

Figure 10. Simulation Results showing the harvested voltage (blue) and the regulated output voltage (red)

IV. Experimental Validation

The experimental phase of this work aims to validate the theoretical concepts and circuit architectures previously developed for integrating multiple EH sources into IoT applications.

A. *Experimental Application of the Solar Cell Bypass Circuit using a MOSFET*

The experimental setup (Figure 11) was assembled considering a battery voltage of 1.2 V and solar cell voltages under different illumination conditions. The output behaviour of the circuit (Figure 12) confirms that it effectively prevents a short-circuit condition when the solar cell ceases to generate voltage. The orange trace represents the solar cell voltage, and the blue trace represents the voltage across the load.

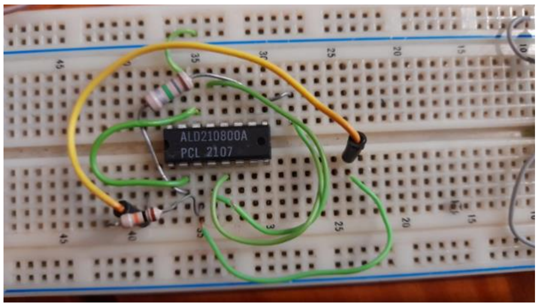

Figure 11. Experimental Setup of the Solar Cell Bypass using MOSFET

It can be observed that the solar cell is active between 0–8 s and 16–24 s, and inactive between 8–16 s, simulating low-light conditions. Despite this interruption, the circuit maintains a stable output voltage, demonstrating the correct operation of the bypass mechanism. A second test was performed with a load resistance of 10 kΩ (Figure 12).

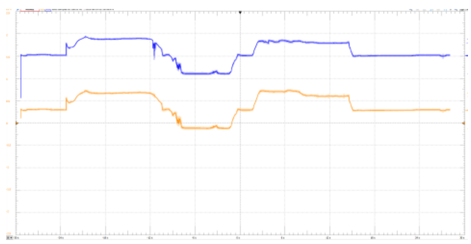

Figure 12. Solar Cell Bypass using MOSFET implementation (R_L = 10 kΩ)

The results confirm the robustness of the bypass configuration for series-connected EH sources: even when the solar cell is inactive, the circuit continues to deliver power to the load, ensuring continuous system operation under varying illumination.

B. Experimental Application of the RFEH Circuit

The next stage involved the experimental implementation of the RFEH circuit. Antenna characterization was a fundamental step in optimizing system performance at the operating frequency of 2.4 GHz.

Using an Anritsu MG3740A Analog Signal Generator operating at 2.45 GHz, with 14 dBm transmit power and an additional 15 dBm amplifier, the received power was 1 dBm at a 5 cm distance. Considering a 50 Ω antenna impedance, this corresponds to a signal amplitude of approximately 0.7 V.

The PCB circuits were fabricated using a Roland SRM-20 CNC milling machine at the facilities of the Military Academy (Figure 13).

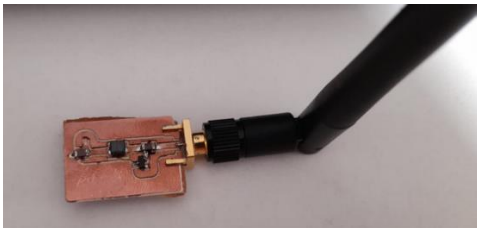

Figure 13. RFEH PCB

However, the results obtained experimentally did not fully reproduce the simulated values under the same conditions, likely due to losses in the prototype assembly and mismatch between components at high frequencies.

C. Experimental Application of the DC-DC Converter

The step-up DC-DC converter previously analyzed is experimentally implemented. The goal is to validate, under real operating conditions, the behavior of the control strategy and power-management architecture developed during the simulation phase (Figure 14).

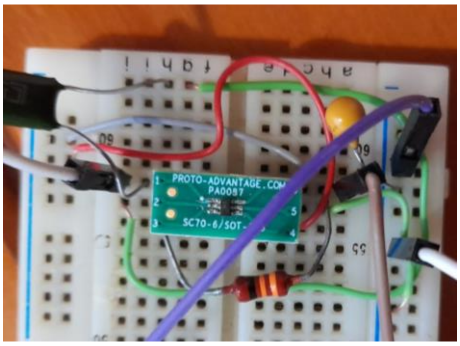

Figure 14. Experimental implementation of Step-Up DC-DC Converter Circuit

The converter effectively raised the low voltages provided by the EH sources to levels sufficient for powering low-consumption electronic systems, validating its suitability for integration in autonomous IoT devices.

The successful operation of this converter in conjunction with the solar, piezoelectric, and RF modules confirms the feasibility of the hybrid EH power architecture proposed in this work.

V. Results and Discussion

The experimental results confirm the validity of the proposed architectures for powering ULP electronic systems through the integration of multiple EH sources.

Each subsystem—solar, piezoelectric, and RF—was analysed individually and in combination to verify their ability to ensure continuous power supply and system stability under varying operating conditions.

A. Solar Cell Bypass Performance

The MOSFET-based solar cell bypass circuit effectively prevented power interruption when the solar cell became inactive due to low illumination. Experimental results demonstrated that the circuit maintained a stable 500 mV output, regardless of the solar cell's operating state.

This confirms that the bypass architecture provides a reliable alternative current path, ensuring uninterrupted power flow in hybrid series-connected EH systems.

The switching circuit solution using the TPS22860 Ultra-Low Leakage Load Switch proved equally efficient in simulations, with negligible leakage current (<70 nA). This implementation offers an efficient alternative for low-current applications and can be powered directly by the piezoelectric harvesting circuit, further enhancing system autonomy.

The piezoelectric harvesting module, composed of parallel-connected elements, successfully produced a stable DC voltage of 0.5 V. This output level is sufficient to supply low-power control circuits and switching devices, validating its role as a secondary EH source to maintain system functionality.

B. Solar Cell Bypass Performance

The MISO Boost converter provided experimental evidence of stable output operation when powered by multiple EH sources connected in series. Simulations showed output voltages exceeding 1.2 V whenever at least one source was active. This behaviour confirms the proper operation of the hybrid converter under alternating or complementary source activity, highlighting its capability to compensate for environmental fluctuations.

C. RFEH Analysis

The RFEH subsystem, operating at 2.4 GHz, demonstrated that the antennas used were correctly matched and capable of efficient energy capture within the Wi-Fi and ISM bands. However, the experimental prototype did not achieve the same output levels as simulated, mainly due to impedance mismatch and parasitic losses introduced by PCB traces and connectors. These discrepancies indicate that further optimization of matching networks and component layout is required for efficient energy transfer at high frequencies.

D. Step-Up Converter Efficiency

The step-up DC–DC converter based on the LTC3525-3.3 successfully boosted low input voltages from the EH sources to a regulated output of 3.3 V.

This high efficiency demonstrates the suitability of the converter for integration into hybrid EH architectures, enabling the powering of IoT nodes and wireless sensors with minimal energy loss.

E. Discussion

Overall, the experimental validation confirmed the feasibility of combining heterogeneous EH sources to power ULP electronic systems and IoT sensors, providing a scalable and sustainable alternative to traditional battery-based solutions.

VI. Conclusions

This work presented the design, implementation, and experimental validation of a hybrid power-supply system for ultra-low-power (ULP) Internet of Things (IoT) sensors, based on the integration of multiple energy-harvesting (EH) sources. The study explored the use of solar, piezoelectric, thermoelectric, and radio-frequency (RF) generators to ensure continuous operation under different environmental conditions.

MOSFET-based bypass circuit was successfully developed to mitigate the short-circuit issue that occurs when a solar cell is connected in series with other EH sources and becomes inactive under low illumination. The circuit maintained stable power delivery to the load, validating the feasibility of series connection between heterogeneous sources. The piezoelectric harvesting circuit provided a stable 0.5 V DC output, effectively supporting the system when the solar cell was inactive.

The multiple-input boost converter achieved output voltages above 1.2 V when at least one source was active, demonstrating efficient hybrid integration. Additionally, RF energy-harvesting tests at 2.4 GHz confirmed the capability to capture ambient electromagnetic energy, although performance was limited by impedance mismatches and PCB losses.

Finally, the step-up DC–DC converter (LTC3525-3.3) boosted input voltages from 0.85 V to 3.3 V, proving its effectiveness for low-voltage energy sources.

The results confirm the technical feasibility of combining multiple EH technologies to power autonomous ULP systems, reducing dependency on traditional batteries. Despite minor limitations associated with environmental variability and impedance mismatch, the proposed system demonstrates a robust and sustainable power-supply approach for next-generation IoT and wearable electronics.

Future work should focus on: adaptive power management for dynamic source selection and optimization of hybrid structures to increase overall performance efficiency and reliability.

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