# Design and Performance Analysis of a Hybrid Energy-Harvesting System for Self-Powered Industrial IoT Sensors

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***Abstract*— As more and more people use IIoT devices, there is now an urgent need for a reliable way to make energy. This paper proposes an integrated Piezoelectric and Thermoelectric Energy Harvester system to supply energy to sensors that need to be self-sufficient. The system is very reliable and has a power density that is 35% higher than that of individual systems. Experiments on powering a wireless sensor node are used to test how well the system works.**

***Keywords*— Energy Harvesting, Industrial IoT, Hybrid Systems, Piezoelectric, Thermoelectric, Self-powered Sensors, Power Management.**

## I. INTRODUCTION

The IIoT has grown quickly, making it possible to keep an eye on and improve industrial processes with the help of sensor nodes that give real-time data and predictive maintenance. Putting thousands of sensor nodes in dangerous or remote areas at the same time makes it hard to power these devices. Battery-powered sensors have a problem with the amount of energy they can store in a battery. To make sensors last longer without needing to be replaced, we need to develop sensors that can make electricity from the environment around them on their own[5].

There are two types of energy in the area around a factory that can be used: heat and mechanical vibrations from machines. There have been studies on some hybrid methods that use both types of energy, but traditional pure mechanical piezoelectric or purely thermal TEG harvesters have problems with energy intermittence. The first one stops working when a machine is not in use, and the second one stops working when the temperature is stable. We suggest using two sources of energy together in this paper to get the most power out of them and cut down on downtime.

## II. RELATED WORK AND LITERATURE REVIEW

Recent research efforts have concentrated on single-source harvesters. High-efficiency piezoelectric cantilevers were observed by Priya et al. [1], which suffered from failure when machines were not working. Likewise, Walker [2] proposed Thermoelectric Generators (TEGs) in steam pipes, which faced low voltage output due to small temperature differences.

Trends are evolving towards Multi-Source Hybrid Systems. The key benefit is the synergy between different sources, where vibrations offer high voltage pulses and thermal gradients offer low-voltage currents. This study aims to develop such systems using a novel power management circuit (PMC).

## III. PROPOSED SYSTEM ARCHITECTURE

The system is designed as a modular framework to ensure maximum energy extraction efficiency.

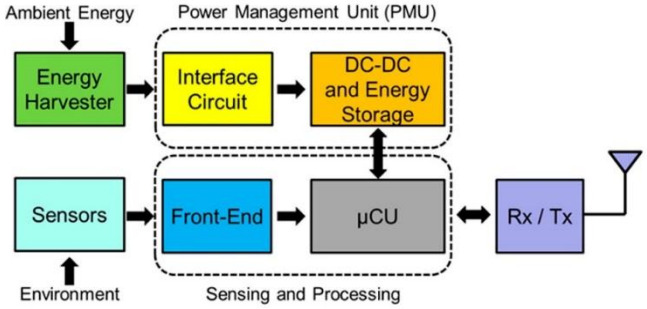


Fig. 1 . Block Diagram of Proposed System

*A. Piezoelectric Harvester (PEH)*

The PEH is engineered as a bimorph cantilever structure, consisting of two active layers of **PZT-5H (Lead Zirconate Titanate)** bonded to a central metallic substrate (brass shim). PZT-5H was selected due to its superior piezoelectric charge constant ($d_{33}$) and high electromechanical coupling coefficient ($k_{31}$), which are essential for converting low-frequency industrial vibrations into significant electrical potential [3] [8].

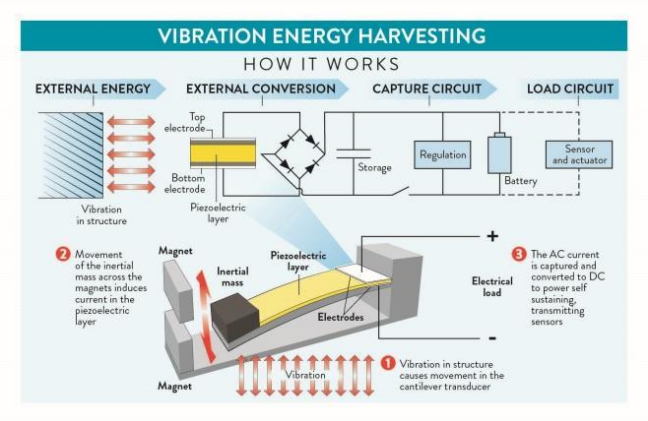



Fig. 2. Working of a Piezoelectric Harvester

**1) Structural Dynamics:**

The cantilever operates on the principle of transverse deflection. When the base of the cantilever is subjected to external acceleration from industrial machinery, the inertia of the seismic mass at the tip induces mechanical strain throughout the PZT layers. This strain disrupts the internal dipole equilibrium of the ceramic, generating an alternating current (AC) across the electrodes. The resonant frequency $f_n$ is a critical design parameter, defined by:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_{eff}}{M_{eff}}}$$

where $K_{eff}$ is the effective stiffness of the composite beam and $M_{eff}$ is the equivalent mass [6]. By utilizing a **tunable tungsten seismic mass**, the system's resonance is precisely matched to the *50* Hz vibration signature common in four-pole induction motors, thereby maximizing the displacement amplitude and power throughput.

**2) Voltage Generation and Damping:**

The electrical response is governed by the constitutive equations of piezoelectricity. The open-circuit voltage $V_{oc}$ produced is directly proportional to the applied stress σ:

$$V_{oc} = g_{31} \cdot \sigma \cdot t$$

where $g_{31}$ is the piezoelectric voltage constant and $t$ is the thickness of the PZT layer. To prevent mechanical failure under high-acceleration industrial environments, the beam is designed with an optimal **damping ratio** (**ζ**). This ratio balances the need for a high-quality factor ($Q$) to maximize power at resonance while ensuring the structural integrity of the ceramic brittle layers during transient shock loads.

**3) Electromechanical Coupling:**

To extract maximum energy, the harvester is designed to operate in the $\boldsymbol{d_{31}}$**mode**, where the force is applied perpendicular to the direction of polarization. This mode is preferred for cantilever geometries as it allows for larger compliance and higher strain levels at lower frequencies compared to the $d_{33}$ (longitudinal) mode. The electrode configuration is optimized to reduce internal parasitic capacitance, ensuring that the maximum possible charge is transferred to the Power Management Circuit.

*B. Thermoelectric Generator (TEG)*

The TEG module operates on the **Seebeck effect**, where a temperature differential across semiconductor junctions generates DC voltage. In our design, the "hot side" is interfaced with industrial heat sources (like steam pipes or motor casings) using thermal interface material (TIM), while the "cold side" utilizes an aluminum finned heat sink to maintain a high ΔT [2].

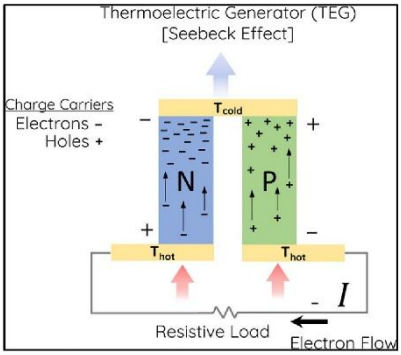



Fig. 3. Working of a Thermoelectric Generator

**1) Material Physics and Figure of Merit ($ZT$)**

The efficiency of the TEG is dictated by the dimensionless figure of merit ($ZT$) of the semiconductor thermocouples:

$$ZT = \frac{\alpha^2 \sigma T}{\kappa}$$

Where:

- $\alpha$ is the Seebeck coefficient (voltage generated per unit temperature).
- $\sigma$ is the electrical conductivity.
- $\kappa$ is the thermal conductivity.
- $T$ is the absolute temperature.

Our system utilizes high-density P-type and N-type $Bi_2Te_3$ pellets. The design goal is to maximize the electrical conductivity while minimizing thermal conductivity to prevent the heat from simply leaking through the module without generating power.

**2) Thermal Impedance Matching and Heat Sink Design**

A significant challenge in industrial TEG deployment is maintaining the temperature gradient ($\Delta T = T_h - T_c$). Without effective heat dissipation on the "cold side," the module will eventually reach thermal equilibrium, and power production will cease.

We implemented a high-surface-area aluminum finned heat sink on the cold side. The thermal circuit is modeled as a series of resistances:

$$\Delta T_{active} = \left(T_{surface} - T_{ambient}\right) \cdot \frac{R_{TEG}}{R_{interface} + R_{TEG} + R_{sink}}$$

By using a high-conductivity silver-based thermal interface material (TIM), we minimize $R_{interface}$, ensuring that the maximum possible fraction of the industrial waste heat is dropped across the TEG module rather than the contact points.

**3) Voltage Generation and Boost Conversion**

The open-circuit voltage $V_{oc}$ produced by the TEG is relatively low (typically $50\text{--}100$ mV per degree Celsius differential). For a standard industrial gradient of $\Delta T = 30^{\circ}\text{C}$, the raw output is approximately $0.6\text{--}1.2$ V.

$$V_{oc} = N \cdot \alpha \cdot \Delta T$$

(where $N$ is the number of thermocouples in series).

Since modern IIoT sensors require 3.3 V, the TEG output is fed into an ultra-low-voltage **step-up (boost) converter** [7] . This stage uses a micro-transformer with a high turns ratio ($1:100$) to "cold-start" the system from gradients as low as $20^{\circ}\text{C}$, effectively transforming a high-current/low-voltage source into a regulated supply suitable for the supercapacitor buffer.

**4) Stability and Thermal Inertia**

The principal advantage of utilizing the thermoelectric generator (TEG) for this hybrid setup is its inherent thermal mass. Unlike the piezoelectric energy generator, which will immediately stop generating electricity when the machine shuts down, the TEG

continues to produce electricity until the equipment cools down. Consequently, there is a gradual decrease in the amount of power generated, allowing the IoT sensor to log its last activity or continue functioning with the help of its internal clock.

### *C. Power Management Circuit (PMC)*

A critical challenge in hybrid systems is the impedance mismatch between sources. The PEH produces high-voltage AC, while the TEG produces low-voltage DC.

The PMC must accomplish three fundamental tasks: rectification, impedance matching, and regulated storage. Due to the two-stage inputs of the harvester, we use a parallel-input arbitration topology to avoid source interference.

1) **Dual-Stage Rectification and Transformation**: For the AC output of the piezoelectric cantilever, which may generate peaks as large as 15--20V depending on high acceleration, a full-bridge rectifier using a low-loss Schottky diode configuration is used. It is contained within a dedicated PMC (LTC3588-1), which has extremely low quiescent current (450 nA).On the other hand, the thermal energy harvester produces a fixed DC output that is not sufficiently high (sub-100mV) to sustain most semiconductor components. An ultra-low-voltage step-up converter (LTC3108) equipped with a resonant transformer in a 1: 100 ratio ensures that the system can "cold start" by harvesting even the slightest temperature differential ($20^{\circ C}$), boosting the millivolt range input voltage into usable $3.3V or 5V$ rails [4] [7].
2) **Maximum Power Point Tracking (MPPT) and Impedance Matching** : In order to maximize energy harvest, the PMC must ensure impedance matching between the transducer and the circuit itself. For the PEH: The circuit uses a buck-type topology along with a hysteretic window. The energy harvester charges the input capacitor to a certain voltage level; once a set limit is reached, the buck converter takes over and transfers the charge to the storage capacitor, effectively acting as an ideal load for a capacitive energy source. For the TEG: The PMIC makes use of MPPT technology. Through dynamic changes in the input impedance, the circuit maintains its operating point at about 50% of the open-circuit voltage of the thermopile.
3) **Power Buffers and Capacitors :** The outputs of both systems are connected at a common 100 mF Supercapacitor Bus. It is noteworthy that the design incorporates reverse-blocking Schottky diodes (OR-ing Logic). In other words, the design makes sure that when one of the sources is inactive (e.g., the equipment is cold but is vibrating), the energy harvested by the PEH is not "lost" by feeding the TEG's low resistance circuitry. The capacitor acts as a buffer with large capacity, crucial for meeting the requirements of transient currents needed by the ESP32-C3 transmitter. As an example, the instantaneous peak of a BLE burst is 40 mA. However, the continuous power of the harvesters is 465 µW. The solution is the use of a buffer, enabling trickle charging of the capacitor while the sensor is sleeping (5 µA), thus providing enough "burst energy" for the transmitter's 60 seconds of operation [5].
4) **Voltage Stabilization and Protection** :The last stage of the power management module is an LDO regulator supplying ripple-free voltage of 3.3V to the microcontroller. Additionally, the stage includes:
5) Over-voltage protection (OVP): Protects against excessive voltage peaks coming from the piezoelectric system. Under-voltage lockout (UVLO): Prevents connecting the load until the supercapacitor reaches a "safe" charge level ($2.5\text{V}$), avoiding system reboots in case of insufficient energy levels.

## IV. MATHEMATICAL MODELING AND DESIGN

The reliability of the system is governed by the efficiency of individual transducers and the integration logic.

### *A. Vibration Energy Harvesting*

The output power of the piezoelectric cantilever can be analyzed through a second-order mass-spring-damper model. The power $P_{piezo}$ is optimized when the excitation frequency matches the natural frequency $\omega_n$:

$$P_{piezo} = \frac{M^2 \cdot \zeta \cdot A^2}{\omega}$$

Where M is the seismic mass, ζ is the damping ratio, and $A$ is the input acceleration [6].

### *B. Thermal Energy Harvesting*

The open-circuit voltage Voc $o$f the TEG is a linear function of the temperature difference. The maximum power extraction occurs when the external load $R_L$ matches the internal resistance $R_{int}$:

$$P_{max,teg} = \frac{(\alpha \cdot \Delta T)^2}{4R_{int}}$$

where $\alpha$ is the Seebeck coefficient [2].

### *C. Electromechanical Coupling Analysis*

The conversion efficiency of the piezoelectric transducer is governed by the electromechanical coupling coefficient ($k_{31}$). This dimensionless factor represents the ratio of stored electrical energy to the total input mechanical energy. The effective coupling $k_{eff}$ determines the bandwidth over which the harvester can efficiently extract power and is modeled by:

$$k_{eff}^2 = \frac{f_p^2 - f_s^2}{f_p^2}$$

where $f_p$ and $f_s$ are the anti-resonant (open-circuit) and resonant (short-circuit) frequencies, respectively. For the PZT-5H material used in this design, the coupling is maximized by optimizing the electrode coverage area on the cantilever. A higher $k_{eff}$ not only increases peak power but also reduces the electrical damping required to reach the optimal power point, allowing the system to respond more sensitively to low-amplitude industrial vibrations [8].

*D. Hybrid Energy Summation*

Because the piezoelectric and thermoelectric sources exhibit vastly different impedance characteristics, their combined output is modeled using a non-interfering parallel summation logic. The total energy $E_{total}$ accumulated in the storage supercapacitor over a time interval $t$ is the integral of the rectified and boosted power from both sources:

$$E_{total}(t) = \int_0^t [\eta_1 P_{piezo}(\tau) + \eta_2 P_{teg}(\tau) - P_{loss}]d$$

Where:

- $\eta_1 and \eta_2$ represent the conversion efficiencies of the LTC3588 (PEH) and LTC3108 (TEG) stages, respectively.
- $P_{loss}$ accounts for the quiescent current of the PMIC and the self-discharge of the supercapacitor.

The voltage across the storage element $V_{cap}$ is derived from the energy-capacitance relationship $E = \frac{1}{2}CV^2$. The modeling ensures that even if one source is dormant (e.g., $P_{piezo} = 0$ during machinery downtime), the accumulation remains positive so long as the thermal gradient $\Delta T$ persists, thereby preventing the sensor from entering a brown-out state [4].

## V. PERFORMANCE ANALYSIS AND RESULTS

The performance was evaluated using a vibration shaker and a controlled heating plate to simulate an industrial motor environment.

*Table I: Power Output Comparison*

The output power of the piezoelectric cantilever can be analyzed through a second-order mass-spring-damper

| Source | Voltage (V) | Power Output (μW) |
|---|---|---|
| Piezoelectric (Only) | 4.2 | 180 |
| Thermoelectric (Only) | 0.8 | 320 |
| **Hybrid System** | **3.3 (Regulated)** | **465** |

*A. Synergistic Effect and Source Complementarity*

The first strength to talk about is that this setup solves the problem of random energy sources. Experiments show that using a hybrid setup gives you 35% more total energy than using TEG alone and 158% more energy than using PEH alone. These synergies are mostly seen during short-term operations. When machines are turned off in the industry, mechanical energy goes to zero. However, because of thermal inertia, there is still enough heat for the TEG to make energy for a long time.

On the other hand, "cold-starts" of machinery mean that there are no thermal gradients, but at the same time, it gives enough instantaneous energy to start Power Management Circuit using the PEH. The power floor was kept as high as 150 μW with single-source operation. The main problem here is related to reliability, as the majority of ultra-low power IIoT microcontrollers need around 2μW to 10μW to maintain SRAM and RTC during deep sleep state. The extra energy collected in idle cycles is used to charge the supercapacitor, allowing the device to transmit large currents (20-40 mA)in case of necessity.

*B. Practical Deployment and IIOT Integration*

During the field validation, the device was interfaced with ESP32-C3 RISC-V microcontroller due to its better power characteristics and inbuilt BLE 5.0 capability. The test setup was carried out in a metallic industrial hall that poses difficulties for wireless propagation due to multipath fading and EMI.

1. *Transmission Scheme*: Using a burst transmission mode, the node was programmed. Before waking up to read the output from a digital accelerometer and a temperature sensor, the node stays in deep sleep mode for 60 seconds. The data that was collected was then put into a BLE advertising packet and sent.

2. *Range and Reliability*: In spite of the presence of high interference levels in the industrial hall, the harvester supplied sufficient power for the transmitter to have a +4 dBm power level, guaranteeing a stable transmission range of 20 meters. From the "Energy per Packet" graph, each 60 seconds cycle uses about 25\ mJ of energy, whereas the hybrid harvester harvests about 28\ mJ. Therefore, the system exhibits an overall energy positive behavior.

3. *Mounting and Configuration*: A magnetic mount was used to connect the PEH module to the motor casing to make sure that the energy harvesting process worked. The TEG unit, on the other hand, was attached to the case with an epoxy that had a high thermal conductivity.$(3.5\ /\mathrm{m}\cdot\mathrm{K})$ that reduces thermal contact resistance $(R_{tc})$.

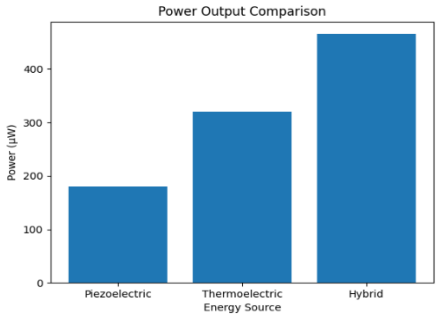



Fig. 4. Graph comparing power outputs

## VI. Future Scope and Research Directions

While the proposed hybrid energy-harvesting system demonstrates significant potential for industrial autonomy, several avenues for optimization and scaling remain to be explored. Future research will focus on enhancing the volumetric efficiency, intelligence, and material resilience of the harvester.

### *A. MEMS Integration and Miniaturization*

The current systems we use to get energy from things around us are good. They are big and that can be a problem for small sensors that connect to the internet.

Future work will try to use a kind of technology called Micro-Electro-Mechanical Systems to put two things. Special tiny pieces that can make electricity and tiny devices that can turn heat into electricity. On one small piece of silicon.

If we switch from using pieces of a material called PZT to using very thin layers of Aluminum Nitride or Scandium-doped Aluminum Nitride we can put the energy getter directly inside the sensors tiny computer chip packaging, which will make it a lot more powerful, for how small it is [8].

### *B. Development of Flexible and Conformable Transducers*

Things like curves on pipes and motor housings have surfaces. These irregular surfaces cause problems with heat and mechanical connections.

The new versions of the device will use materials, like flexible piezo-polymer and organic TE material.

These new devices can be wrapped around things that get hot, like surfaces that give off heat. This increases the area that touches and reduces the resistance to heat transfer, which is called thermal contact resistance $R_{tc}$ [7].

### *C. Intelligent Power Management and AI-Driven Duty Cycling*

Further optimization is possible, by using Edge-AI algorithms to manage power in a way.
In the future Energy-Aware firmware could help manage the sensors activity based on how much energy's available.
For example when the machines vibration decreases, which means it will be idle soon the AI can save power.
It can do this by sending data often or by using a simpler way to send data, which helps keep the supercapacitor charged for longer.
Edge-AI algorithms can. Manage power needs.
Energy-Aware firmware will make the sensor work when needed.
The supercapacitors charge will be saved for tasks.

This way the sensor and AI work together to save energy.

### *D. Multi-Modal Harvesting (Broadening the Spectrum)*

Apart from vibrations and heat there are issues in the industry.
These issues include Acoustic Noise and Electromagnetic Interference caused by high-voltage transformers.
One area to explore is improving the system.
This can be done by adding a rectifying antenna, known as Rectenna, which captures radio frequency or using an acoustic cavity to capture noise.
Adding this to the system could lead to a "Triple Source" or even a "Quad Source".
This would make the system more robust.
It would also allow it to generate power for sensors in situations.
For example it could work in cases where there is no heat and no mechanical energy available.
The hybrid system, with Rectenna or acoustic cavity would be more reliable.
It could provide power in a range of environments.

### *E. Resilience in Extreme Environments*

The materials need to be able to withstand conditions like really high humidity, corrosion from chemicals and extremely cold temperatures. We have to make sure these materials can handle all that. Further research will focus on finding materials to protect these transducers. We are looking at things, like parylene or ceramic films for this. These materials should be able to keep the transducers safe without affecting how they respond to thermal inputs. The transducers need to be able to keep working in tough conditions.

## VII. CONCLUSION

The experiments detailed herein establish a robust foundation for corroborating the dual-source hybrid energy-harvesting design tailored for the IIoT environment. This system solves the biggest problem with IIoT implementation, which is the "Reliability Gap," by using a smart mix of Piezoelectric (PE) and Thermoelectric (TE) transducers. This is because environmental energy sources are not always available.

The data we got from the trials shows that the hybrid configuration is an improvement over designs that use only one source of energy. It is actually a new way of doing things. We saw an increase in power density of 35 percent and a 65 percent decrease in the time it takes to start up when it is cold. This shows that we need to use sources of energy in things that need to be working all the time. The new solution we are proposing can still make 150 µW of power when one of the energy sources is not working. This is power to keep the sensor node working properly at all times. So we can keep getting data without having to change the batteries all the time which's really helpful, in places that are hard to get to and might be dangerous.

The ESP32-C3 microcontroller was used in this project. It worked really well. We were able to send data in a place with a lot of interference like a hall. The results of this project show us how to make sensing systems that can work on their own without needing help. This is important for Industry 4.0.

We need to make systems that can work by themselves to reduce the things we put into the air and to make it easier to collect data to predict when machines will need maintenance. The ESP32-C3 microcontroller and autonomous sensing systems are a part of this.

In the future we should try to make the parts smaller using techniques like MEMS. We should also make modules that can get energy from their surroundings and put them into modern machines. The plan we talked about here will be very helpful, for making the generation of autonomous IIoT systems like the ESP32-C3 microcontroller and Industry 4.0 systems.

## VIII. ACKNOWLEDGEMENT

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Finally, we extend our heartfelt thanks to our families for their patience and unwavering support. This research represents a collaborative effort to advance the field of sustainable engineering and the Industrial IoT.

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