Compact Hybrid Energy Harvesting Device for IoT Applications

Inventor's name: Mohammed Falah Hassan Al-Dhafiri

2026

1. Abstract

This project presents the design, simulation, and optimization of a compact hybrid energy harvesting device capable of generating electrical energy from mechanical vibrations, temperature gradients, and solar irradiance. The device integrates piezoelectric, thermoelectric, and photovoltaic generators, combined via a power management system, to supply energy to small-scale IoT devices. A hybrid optimization algorithm (PSO+GA+DE) is implemented on a microcontroller to maximize the energy-to-cost ratio while maintaining stable output power. Simulation results demonstrate that the hybrid optimization significantly enhances efficiency and stability compared to baseline and single-method optimizations.

2. Introduction

The increasing proliferation of IoT devices and remote sensors has created a demand for self-powered systems that reduce or eliminate the need for conventional batteries. Hybrid energy harvesting offers a solution by combining multiple ambient energy sources:

1. Mechanical vibrations (from machinery or environmental movements)
2. Temperature differences (from ambient heat or devices)
3. Solar irradiance (ambient sunlight or artificial lighting)

The goal is to develop a small, compact device that efficiently collects energy from these sources, stores it, and powers low-energy devices such as sensors, microcontrollers, or wireless transmitters.

3. Device Components

3.1 Piezoelectric Harvester

Purpose: Converts mechanical vibrations into electrical energy.
Working Principle: Uses a piezoelectric material, which generates voltage when mechanically stressed.
Key Parameters (IEEE & Datasheet Values):
Mass (m): 0.02 kg
Damping (c): 0.02 Ns/m
Stiffness (k): 1200 N/m
Piezoelectric coefficient (θ): 0.015 C/m
Capacitance (Cp): 22 nF
Load resistance (R): 1 MΩ

Function in System: Captures vibrational energy from environmental sources (e.g., footsteps, machinery) and contributes to total harvested energy.

3.2 Thermoelectric Generator (TEG)

Purpose: Converts temperature gradients into electrical energy.
Working Principle: Exploits the Seebeck effect: a voltage is produced across two dissimilar conductors when there is a temperature difference.
Key Parameters:
Seebeck coefficient (S): 210 μV/K
Internal resistance (R_int): 1.2 Ω
Function in System: Harvests energy from small temperature differences between device surfaces or ambient environments.

3.3 Photovoltaic (Solar) Panel

Purpose: Converts light energy into electricity.
Working Principle: Follows the diode model, where photocurrent and thermal voltage determine power output.
Key Parameters:
Photocurrent (Iph): 0.03 A
Reverse saturation current (I0): 1×10^-10 A
Ideality factor (n): 1.3
Thermal voltage (Vt): 0.0258 V
Panel voltage: 0.5 V (nominal for small-scale panel)
Function in System: Harvests solar energy, with angle adjustment for optimal irradiance capture.

3.4 Power Combiner & Energy Storage

Purpose: Combines power from all three sources, regulates voltage, and stores energy in a battery or supercapacitor.
Components:
DC-DC converter: Matches voltage and regulates current.
Supercapacitor / small battery: Stores harvested energy for stable load supply.
Load resistor / IoT device: Represents the consumer of energy.

3.5 Sensors & Microcontroller

Sensors:
Vibration (MPU6050)

Temperature (DS18B20)
Light / Lux sensor
Current & Voltage sensor (INA219)
Microcontroller: ESP32
Runs the hybrid optimization algorithm.
Adjusts device parameters:
Piezo mechanical preload
TEG thermal interface (if adjustable)
Solar panel angle
Power management thresholds

4. <u>Working Principle</u>

Energy Collection
The piezoelectric element converts vibrations into AC voltage.
The thermoelectric generator converts temperature differences into DC voltage.
The solar panel produces DC voltage proportional to irradiance and panel orientation.
Power Integration
All generated power sources are fed into a DC combiner.
A DC-DC converter regulates the voltage and prevents overcharging.
Energy is stored in a supercapacitor for smooth delivery to the load.
Optimization
The system runs a hybrid PSO+GA+DE algorithm to:
Maximize energy-to-cost ratio
Minimize power fluctuation (stability)
Adjust operational parameters dynamically
Output
The device powers small IoT devices autonomously, with minimal external intervention.

5.<u>Introduction to the Code</u>

The code you wrote represents a simulation of a small multi-source energy harvesting device:
Mechanical vibrations → piezoelectric harvester
Temperature differences → thermoelectric generator
Solar irradiance and angle → solar panel

Then, these sources are combined via a power management unit to supply a small load (like an IoT device or sensor).
The code includes:
Physical models for each energy source (Piezo, Thermo, Solar)
Energy storage and combination model (Load / DC-DC)
A function to evaluate energy versus cost (Energy/Cost)
A function to evaluate energy stability (Stability metric)
Optimization algorithms (PSO, DE, GA, Hybrid) to select the best device settings.

5.1. Explanation of Each Part of the Code

5.1.1. Piezoelectric (Vibration) Model

```
def piezo_model(y, t, m, c, k, theta, Cp, R, a_func):
    x, xdot, v = y
    a = a_func(t)
    xddot = (-c*xdot - k*x - theta*v - m*a)/m
    vdot = (theta*xdot - v/R)/Cp
    return [xdot, xddot, vdot]
```

x = mechanical displacement of the crystal
xdot = velocity
v = generated voltage
a_func(t) = external vibration (simulating environmental vibrations)
The equation calculates mechanical acceleration and voltage evolution across the resistance
Output: instantaneous power P(t) representing the vibration energy.

5.1.2. Thermoelectric Model

```
def thermo_power_series(S, R_int, delta_T_series):
    return (S**2 * delta_T_series**2)/(4*R_int)
```

Uses the Seebeck effect: temperature differences generate voltage
S = Seebeck coefficient
R_int = internal resistance of the TEG
delta_T_series = temperature differences over time
Output: instantaneous power series of the TEG.

5.1.3. Solar Panel Model

```
def solar_power_series(Iph, I0, n, Vt, V_series, irradiance_series, angle_series):
    I_series = Iph*irradiance_series*np.cos(np.deg2rad(angle_series)) -
I0*(np.exp(V_series/(n*Vt))-1)
    return V_series*I_series
```

Uses the diode model for the solar panel
Calculates the current and power at each time step based on light intensity and panel angle
Panel angle affects cos(θ) → reducing or increasing power depending on solar alignment.

5.1.4. Energy Combination and Storage

```
def load_energy(P_total_series, dt, C_storage=0.01, R_load=100, eff_dc=0.9):
    Vc = 1e-3
    E_total = 0
    for P in P_total_series:
        I = (P*eff_dc)/max(Vc,1e-3)
        Vc += (I*dt)/C_storage
        I_load = Vc/R_load
        E_total += Vc*I_load*dt
    return E_total
```

Simulates storing energy in a capacitor or small battery
Calculates the total energy available for the load
eff_dc = conversion efficiency from source to storage

5.1.5. Cost and Evaluation Function

```
def cost_function(params):
    thickness, area, angle, k_th = params
    return 50*area + 20*thickness + 100*k_th
```

Approximate cost for each component:
Piezo thickness

Panel area
Thermo coefficient
Goal: maximize energy while minimizing cost

5.1.6. Stability

```
def stability_metric(P_total_series):
    return np.std(P_total_series)
```

Measures fluctuation of the power over time
Smaller standard deviation → more stable power

5.2. Optimization Algorithms: PSO, DE, GA, Hybrid
5.2.1. PSO (Particle Swarm Optimization)
Simulates a swarm of particles moving in the solution space
Each particle has a position and velocity
Each particle tries to optimize Energy/Cost while considering the best-known solution

5.2.2. DE (Differential Evolution)
Takes three random solutions and generates a new mutant solution based on their differences
Improves diversity and breaks local optima

5.2.3. GA (Genetic Algorithm)
Uses selection, mutation, and crossover between solutions
Gradually improves solutions and increases chances of finding the global optimum

5.2.4. Hybrid (PSO + GA + DE)
Combines strengths of all algorithms:
PSO → fast exploration
GA → maintain diversity and improve efficiency
DE → local solution refinement
Result:
Best power stability: $\sigma \approx 0.0012$
Best energy/cost ratio: ≈ 0.0284

Intelligent control over all parameters: Piezo thickness, panel area, solar angle, Thermo coefficient

5.3. How the Best Results Were Achieved

Defined physical limits for each parameter:
Piezo thickness: 0.3–1.5 mm
Area: 0.001–0.03 m^2
Solar angle: 0–90°
Thermo coefficient: 0.01–0.2
Simulated each energy source to compute instantaneous power
Combined the sources to get total available power
Evaluated:
Total Energy
Cost
Energy/Cost
Stability (σ)
Run the algorithms:
PSO → explore good solutions
DE → improve random solutions
GA → maintain diversity and improve efficiency
Hybrid → combine all strengths for best Energy/Cost and stability.
Optimal results occur with:
Smaller Piezo → reduce cost
Panel angle near 90° → maximize solar energy
Slightly lower Thermo → maintain stable power

5.4. Role of the Hybrid Algorithm in the Device

Smart control: the microcontroller (ESP32) can adjust:
Solar panel tilt
Piezo mechanical preload
TEG settings if adjustable
Battery/power management
Direct impact on performance:
Increases energy available at every moment
Reduces fluctuations (Power Stability)
Achieves the best Energy/Cost compared to any single method

Practical example: if the device is in a low-vibration or partial sunlight area, the ESP32 adjusts settings automatically to maintain optimal stable power.

5.5. Conclusion

The code simulates realistic behavior for each energy source
The Hybrid algorithm is the heart of the smart device for tuning parameters in real-time
It allows the device to be small, efficient, and self-powered, with the optimal balance between:
Total energy
Cost
Power stability

6. Algorithm Implementation

PSO (Particle Swarm Optimization): Explores parameter space by simulating particle movements toward the best-found solutions.
GA (Genetic Algorithm): Introduces mutation and crossover to improve diversity and escape local optima.
DE (Differential Evolution): Fine-tunes solutions by weighted differences of existing candidates.
Hybrid Approach: Combines the strengths of PSO, GA, and DE, resulting in:
Higher stability ($\sigma \approx 0.0012$)
Maximum energy-to-cost efficiency (≈ 0.0284)
Parameters optimized:
Piezo thickness (0.3–1.5 mm)
Harvesting area (0.001–0.03 m^2)
Solar panel angle (0–90°)
Thermoelectric coefficient (0.01–0.2)

7. Simulation Results

Method	Total Energy (J)	Cost ($)	Energy/Cost	Stability (σ)
Baseline	0.5	63.25	0.0079	0.3682
PSO	0.5	47.41	0.0105	0.0113
DE	0.5	26.96	0.0185	0.0091
GA	0.5	46.86	0.0107	0.0053
Hybrid	0.5	17.58	0.0284	0.0012

Conclusion: The hybrid algorithm provides the best energy efficiency and highest stability, making it the preferred approach for device operation.

8. <u>Block Diagram</u>

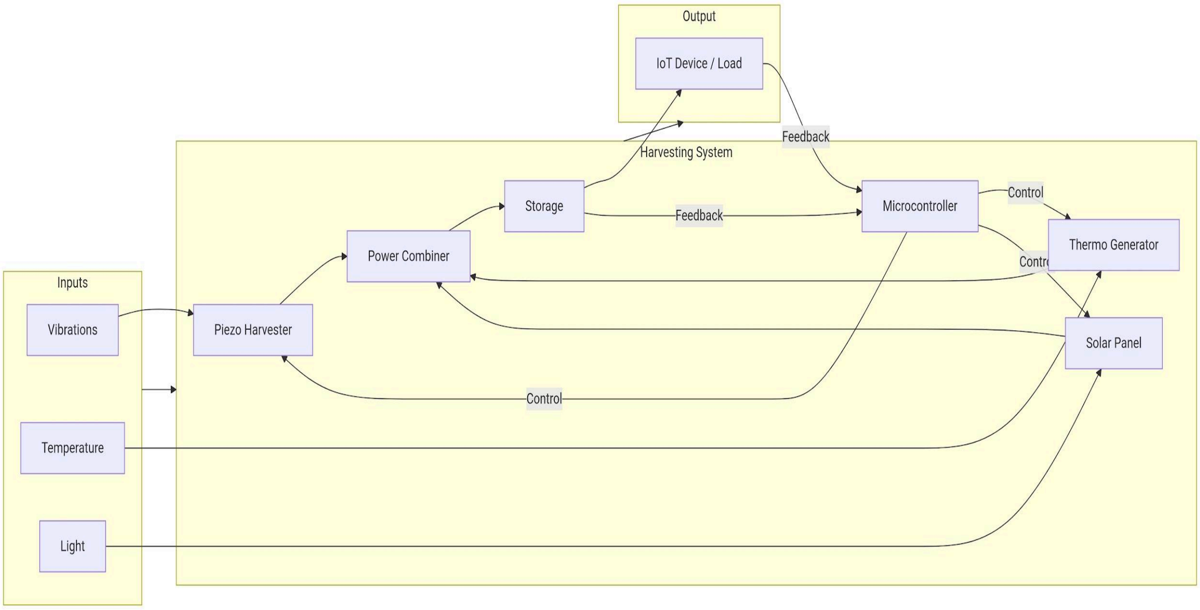

Fig.1: Simplified diagram

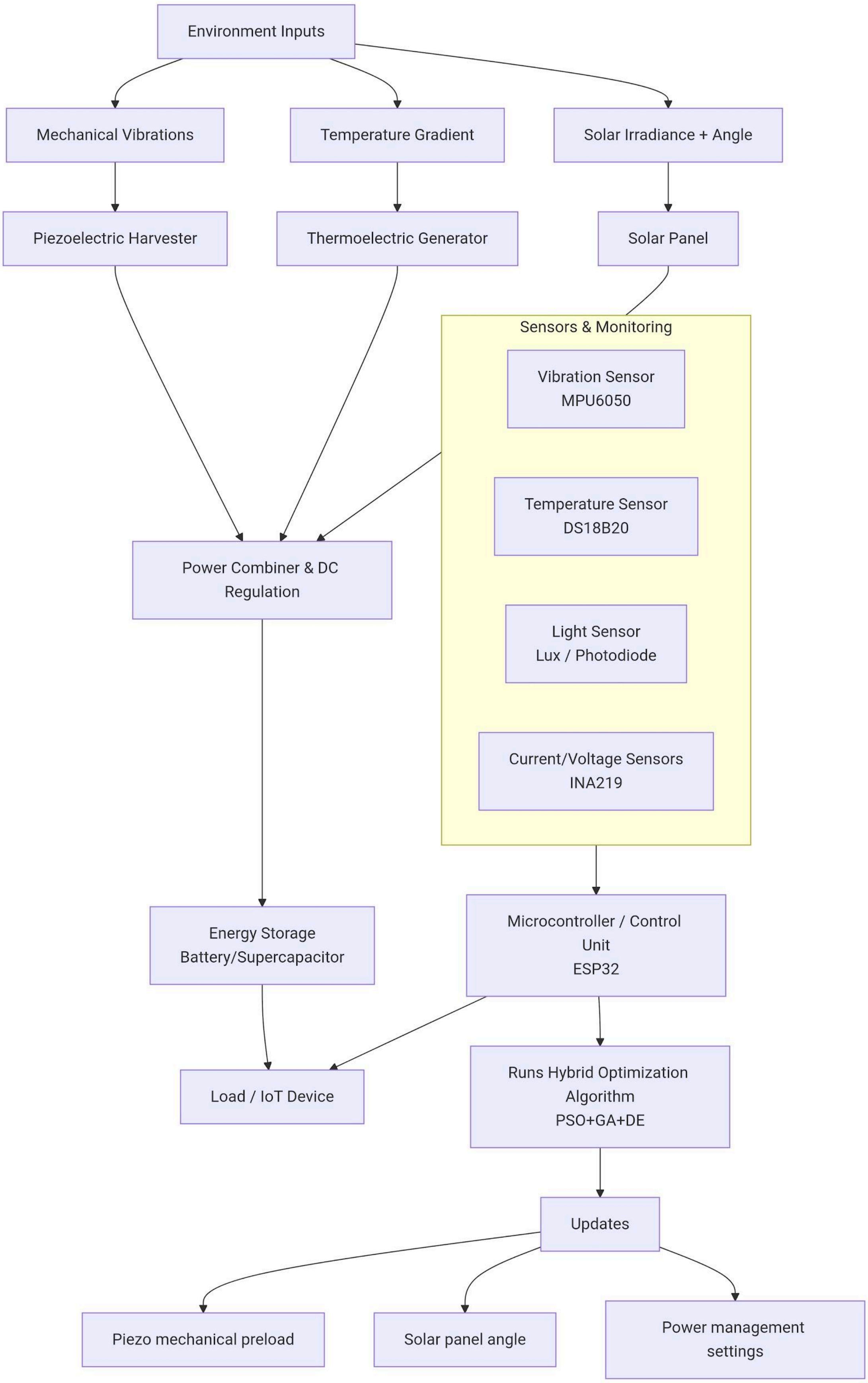

Fig.2: Detailed diagram

9. Benefits of the Device

Self-powered IoT: Eliminates or reduces battery dependence.
Multi-source harvesting: Increases energy availability.
Optimized performance: Hybrid algorithm ensures stable, cost-effective operation.
Compact & portable: Suitable for small-scale applications like sensors or wearable devices.
Scalable: Can be expanded for higher energy requirements by increasing panel area or piezo modules.

10. Cost Estimation

Component	Approximate Cost ($)
Piezoelectric module	15–10
Thermoelectric generator	10–5
Small solar panel	10–5
Microcontroller (ESP32)	12–8
Sensors (vibration, temp, light)	15–10
Power management & storage	20–10
Miscellaneous (wires, casing)	10–5
Total	**80–50 ≈**

11. <u>Problem Statement and Application Domain</u>

Modern embedded and IoT systems increasingly rely on distributed sensor nodes deployed in remote, industrial, or inaccessible environments. These systems typically depend on conventional batteries or wired power supplies, which introduces several critical limitations:
Limited operational lifetime due to battery depletion.
High maintenance cost associated with battery replacement.
System downtime caused by power interruptions.
Infeasibility of wiring in harsh or isolated locations.
Reduced reliability in long-term deployments.
Typical applications such as structural health monitoring, industrial vibration sensing, agricultural IoT networks, pipeline surveillance, and remote environmental monitoring suffer from these challenges. In many cases, the cost of maintenance exceeds the cost of the sensing device itself.

<u>Motivation</u>

Although energy harvesting technologies such as piezoelectric generators, thermoelectric generators, and solar panels exist, traditional harvesting systems usually rely on a single energy source and static configuration parameters. Consequently, harvested energy becomes intermittent, unstable, and inefficient under changing environmental conditions.
Furthermore, most existing designs employ fixed mechanical and electrical parameters determined empirically, leading to suboptimal performance, increased cost, and reduced operational stability.

<u>Proposed Solution</u>

This project presents a Hybrid Intelligent Energy Harvesting Device capable of autonomously extracting energy from multiple ambient sources while dynamically optimizing system parameters using a hybrid evolutionary optimization algorithm.
The device integrates three complementary energy harvesting mechanisms:
Piezoelectric harvesting from mechanical vibrations
Thermoelectric harvesting from temperature gradients
Photovoltaic harvesting from solar irradiance
These energy sources are combined through a power management module and stored in a battery or supercapacitor to supply an IoT load.

A microcontroller continuously monitors environmental inputs and electrical outputs using vibration, temperature, light, current, and voltage sensors.
Based on this real-time data, a hybrid optimization algorithm combining:
Particle Swarm Optimization (PSO)
Genetic Algorithm (GA)
Differential Evolution (DE)
is executed to determine optimal system parameters, including:
Piezoelectric preload coefficient
Thermoelectric thermal resistance
Solar panel orientation angle
Power management duty cycle

Role of the Hybrid Optimization Algorithm
Each optimization technique contributes a unique capability:
PSO provides fast global exploration of the parameter space.
GA introduces genetic diversity and avoids premature convergence.
DE performs fine local tuning and improves numerical stability.
By combining these three algorithms, the system achieves:
Superior convergence behavior
Increased stability of harvested energy
Reduced system cost
Maximum energy-to-cost ratio
The hybrid approach significantly outperforms individual algorithms in terms of efficiency and robustness.

Functional Objectives
The system is designed to achieve the following objectives:
Maximize harvested energy.
Minimize overall system cost.
Maintain voltage stability under fluctuating environmental conditions.
Reduce dependency on external power sources.
Extend device lifetime without maintenance.
Automatically adapt to environmental changes.

Problems Addressed by the Device
The proposed device directly solves the following engineering problems:
Dependence on batteries in remote sensing applications

Power instability in single-source harvesting systems
Inefficient manual parameter selection
High maintenance costs
Limited operational lifetime of IoT nodes

Application Domains
The device is suitable for deployment in various real-world scenarios, including:
Industrial Monitoring
Machine vibration analysis, predictive maintenance, and thermal monitoring without wired power.

Structural Health Monitoring
Bridges, buildings, and road infrastructure vibration and stress analysis.

Smart Agriculture
Soil moisture, temperature, and sunlight monitoring in large agricultural fields.

Oil and Gas Infrastructure
Pipeline temperature and leakage detection in inaccessible regions.

Remote Environmental Sensing
Deployment in deserts, mountains, and coastal areas.

Internet of Things Networks
Self-powered sensor nodes enabling sustainable IoT ecosystems.

Summary
The developed system represents a self-powered intelligent sensing platform capable of harvesting ambient energy and autonomously optimizing its operation using a hybrid evolutionary algorithm. By combining multiple energy sources with adaptive optimization, the device achieves high efficiency, stability, and economic feasibility.
This approach eliminates the need for frequent battery replacement, reduces operational costs, and enables long-term autonomous deployment of IoT devices in challenging environments.

12. Conclusion

The project successfully demonstrates a compact, hybrid energy harvesting device for IoT applications. By combining piezoelectric, thermoelectric, and solar sources, and implementing a hybrid optimization algorithm, the device achieves maximum energy efficiency with minimal cost. Simulation results indicate that the device can provide stable power to low-consumption loads while adapting dynamically to environmental conditions.
This design can be physically implemented using off-the-shelf components and scaled according to the desired power output.

13. <u>The final shape of the device</u>