

ENERGY HARVESTING SYSTEM USING PIEZOELECTRIC SENSORS AND SOLAR PANEL : A REVIEW

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**HYBRID ENERGY HARVESTING SYSTEM USING PIEZOELECTRIC SENSORS AND
SOLAR PANEL: A REVIEW**

Abstract

This research focuses on the design and development of a hybrid energy harvesting system that combines solar photovoltaic (PV) panels with piezoelectric sensors to create an efficient and sustainable battery charging solution. Driven by the growing global demand for clean energy and the urgent need to reduce dependence on fossil fuels, hybrid renewable energy systems offer a promising path forward. Our system captures energy from both sunlight and mechanical vibrations—such as those produced by footsteps ensuring more consistent power generation regardless of environmental conditions. An Arduino-based control unit regulates power flow and maintains stable voltage levels for battery charging, while an integrated LCD display provides real-time feedback on system performance. The hybrid design effectively addresses the limitations of each individual energy source: solar dependency on weather and piezoelectric reliance on physical motion. The inclusion of a solar tracking mechanism and footstep-based energy harvesting further enhances overall efficiency. This system holds considerable promise for applications in portable electronics, smart cities, and off-grid rural areas, contributing to the advancement of practical and sustainable renewable energy solutions.

Keywords: Solar Energy, Piezoelectric Sensor, Hybrid Renewable System, Footstep Power Generation, Arduino, Battery Charging, Solar Tracking.

1. Introduction

The rapid increase in global energy consumption, driven by rising population and technological advancement, has intensified the demand for sustainable and eco-friendly power sources. Traditional fossil-fuel-based energy systems contribute significantly to environmental pollution and greenhouse gas emissions, ultimately accelerating climate change. As a result, renewable energy technologies have emerged as viable alternatives to support global energy security and reduce environmental impact [Shaopeng Guo et al. 2018]. Originally, the focus on the utilization of hybrid renewable energy (HRE) was mainly concentrated for power generation in remote areas. The feasibility of integrating wind-powered generator and photovoltaic (PV) array [Huicong Liu et al. 2021]. Solar photovoltaic systems convert sunlight into electrical energy, while piezoelectric materials generate electricity when subjected to mechanical stress or vibrations. When integrated, these two complementary sources can create a robust hybrid energy-harvesting system capable of delivering more stable power output compared to standalone systems. This research focuses on developing a hybrid Solar–Piezo Energy Harvesting System for efficient battery charging, supported by Arduino-based control circuitry.

The system combines solar tracking for maximum sunlight absorption and footstep-based piezoelectric modules to harness mechanical energy from human movement [A. P. Singh et al.2024]. Real-time monitoring using an LCD display provides users with essential information on voltage levels, charging status, and overall system performance. In this paper we report on experimental studies and system design for harnessing energy from two alternate energy sources, which are solar energy and piezoelectric energy. The proposed hybrid design not only enhances energy availability but also supports sustainability by reducing dependence on conventional power grids. This work aims to contribute to greener technologies while addressing the growing need for reliable and renewable battery charging solutions.

Finally, for the piezoelectric energy harvesting, we have made a series and parallel combination of piezoelectric sensors and this network is followed by a voltage doubler circuit, which is used to augment the voltage produced by the combination of sensors. Moving on to solar energy, we have used two solar panels and each can produce voltage up to five volts. The panels are placed both inside and outside the system, to ensure that we get power when case is open as well as when it is closed. Finally, for the piezoelectric energy harvesting, we have made a series and parallel combination of piezoelectric sensors and this network is followed by a voltage doubler circuit, which is used to augment the voltage produced by the combination of sensors

1.1 Objectives

The objective of an energy harvesting system using a piezoelectric sensor and solar panel is to create a hybrid power source that is more reliable and efficient than a single source alone. When pressure is applied to these sensors, an alternating voltage is produced across them. The voltage produced is proportional to the rate of change of applied pressure. Rose Mariya Davis et al. 2025 To store the harvested energy in a rechargeable battery or super capacitor for powering low-power devices.

2. Literature review

We have done extensive research on the areas pertaining to our project, ranging from piezoelectricity to the concept of energy harvesting. Recently, researcher had proposed variety of hybrid energy harvesting system which uses solar panel, Energy from Radio frequency wave, and piezoelectric sensor that convert mechanical energy to electrical energy. Asry, Anis et al.

[2019] demonstrated that power energy is generated by using piezoelectric transducer. In this study, lead zirconate titanate (PZT) piezoelectric transducer has been used to harvest the kinetic energy from the footstep. The output voltage of this piezoelectric transducer is dependent to the structure of the ceramic and magnitude of strain and stress that applies on its structure. This transducer has diameter of 5 cm crystalline structure. The common output voltage is around 0-12 V. However, at instant impact on this transducer, it can achieve until 30 V while the output current is about 5 mA.

There are two shapes of PZT piezoelectric transducer that been considering in this study which are the circular shape and the square shape. The circular shape of piezoelectric transducer is more suitable to accept the stress or strain. The circular shape piezoelectric transducer has been chosen because it is most suitable transducer for footstep rather than square piezoelectric transducer. The circular shape of piezoelectric give higher output voltage when testing on oscilloscope. This is due to the deflection on its structure when foot press is applied on it. The piezoelectric transducer is connected in series-parallel connection where the value of voltage as well as current output are both satisfactory. The output of the piezoelectric is in AC form. Before being stored in storage components such as battery or capacitor, it needs to be rectified into DC form then, supply it to the DC loads. In this study, the full wave bridge rectifier was used to rectify the output from the piezoelectric tile.

O. Hussein et al. 2025. demonstrated that energy generated by the ingress and egress of 150 personnel, utilizing the suggested footstep energy generation, is deemed significant for power supply with estimated harvested energy 0.12–0.42 kWh. The DC-to-DC appliance eliminates the complexities associated with battery charging and inverter conversion, resulting in 100 % efficiency in power transmission from its source. The proposed hybrid system comprises a solar tracking mechanism and energy harvested using piezoelectric footfalls. The tracking system is designed depending on the solar angle and direction gathered from geographical site characteristics. Existing studies on renewable energy harvesting highlight that solar energy alone is intermittent and depends on weather conditions, while piezoelectric systems generate small but continuous power from human footsteps. Prior research on hybrid systems shows that combining multiple sources improves reliability and overall power output. Solar tracking mechanisms have been reported to significantly increase photovoltaic efficiency compared to fixed panels. Meanwhile, piezoelectric floor tiles have mainly been explored for low-power applications such

as lighting and sensors in public spaces. However, the literature reveals limited work on integrating piezoelectric harvesting with a solar tracking system. This gap motivates the authors to develop a unified hybrid energy-harvesting model that enhances total energy generation. Researchers have demonstrated that series-parallel combinations of sensors significantly increase output voltage, making the technology suitable for crowded public areas. Prior literature highlights its sustainability, low maintenance, and potential for supporting renewable urban power solutions, forming the foundation for the present study [Withana, Anuji. (2023).].

Anmol D. Ganer et al. (2025) proposed system that uses rectifiers, capacitors, and an inverter to store and convert the generated power for practical use, such as lighting. A 12V battery and LCD display were added for storage and monitoring. Earlier systems used either piezoelectric or solar energy alone, but lacked a combined hybrid model that increases efficiency and ensures continuous power even when foot traffic is low. Yugam Doshi et al. 2024. demonstrated use of Arduino Uno to control and monitor energy flow and also supports real-time monitoring of charging status and system performance via IoT.

H. Yang et al.2025 experimentally validate the performance under different conditions, showing the device can operate in three modes: standalone vibration, standalone solar, and hybrid. The researcher demonstrated that the harvester is capable of powering a wireless sensor using the combined energy, making it useful for self-powered sensing applications layers and a solar cell to simultaneously. While Roberto Andrade et al. demonstrated developments in piezoelectric materials (such as PZT, PVDF) and how they can be optimized for energy harvesting in various environments. The authors also discusses a wide range of applications from wearable devices and smart infrastructure to fluid and structural vibration sources showing how piezoelectric harvesting can power low-power sensors. Zhou et al. presented comprehensive work on working mechanism three typical modes of piezoelectric vibration energy harvesting technology are introduced, along with the classification of different excitation types of collectors. The progress of research related to piezoelectric vibration energy harvesting technology was reviewed. Finally, challenging problems in the study of piezoelectric energy harvesting technology were summarized, and the future research and development trend of piezoelectric vibration energy harvesting technology is discussed in the light of the current research status of piezoelectric vibration energy harvesting technology which was very useful. Researcher also note that Piezoelectric vibration energy harvesting (PVEH) can outperform electromagnetic and

electrostatic harvesters in power density. The review covers advances in materials (inorganic, organic, nanocomposites) and device structures (e.g., cantilevers, multilayer), but they argue that prior reviews often neglect the impact of different working modes and real-world excitation conditions. They also discuss innovations such as nonlinear, wide-band, and multi-modal harvesting structures that improve performance under variable vibration environments.

Selim, K.K et al. 2024 highlighted that the growing demand for electrical energy calls for new, sustainable sources, and human footsteps represent a largely untapped kinetic energy source. Piezoelectric transduction is highlighted as a promising technology to convert this mechanical energy into electricity. Previous research is categorized into different structural designs for embedding piezoelectric elements in floor tiles (cantilever, curved, stacked types).

They also point out that while many studies target either mechanical or electrical design, few integrate both effectively and validate experimentally. The paper demonstrates that placing piezoelectric sensors under floor tiles can feasibly harvest significant power from footsteps (up to ~249.6 mW), using a simple rectifier circuit and low-cost components.

3. Proposed Methodology

The proposed hybrid energy harvesting system integrates piezoelectric sensors with solar photovoltaic panels to generate power for both urban and rural applications. The system comprises three main subsystems: a solar tracking mechanism to maximize photovoltaic efficiency, a footstep-based piezoelectric energy harvesting unit, and a central controller for power management and regulation.

3.1 System Design

The proposed hybrid energy harvesting system integrates solar and piezoelectric energy sources through a unified architecture. The hardware implementation comprises the following components: an Arduino Nano microcontroller, a 16×2 LCD display with an I2C module, piezoelectric plates, a solar panel, a 3.7 V lithium-ion battery, power bank modules, an IC 7805 voltage regulator, and associated connecting wires. A hybrid architecture is developed to combine the outputs from both energy sources into a single storage unit, ensuring efficient power management and regulation.

3.2 Footstep Energy Harvesting

The piezoelectric sensor configuration follows the method proposed by Hussein et al. (2025), as discussed in the literature survey. The system generates electrical energy from walking steps through an array of interconnected piezoelectric sensors. The complete sensor arrangement is illustrated in Figure 1.

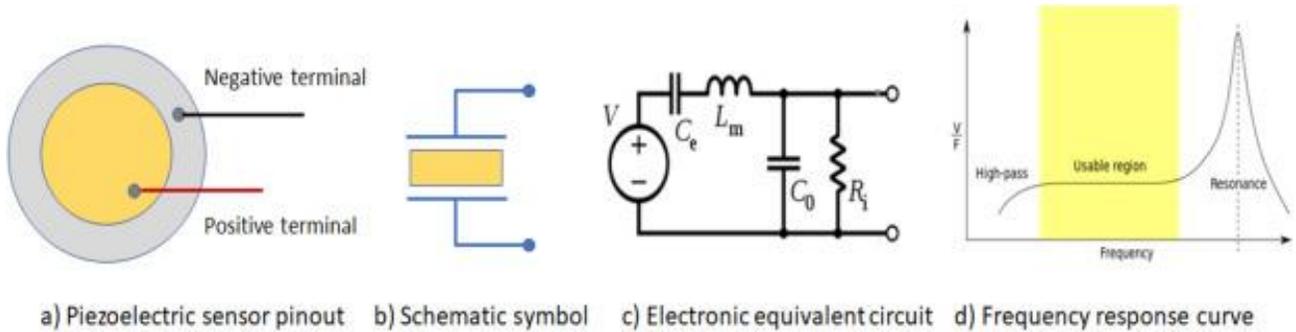


Figure. 1. Utilized piezoelectric Sensor.

The primary principle of piezoelectric sensors is power generation resulting from an applied force on its effective area, as depicted in the schematic picture in Figure.2

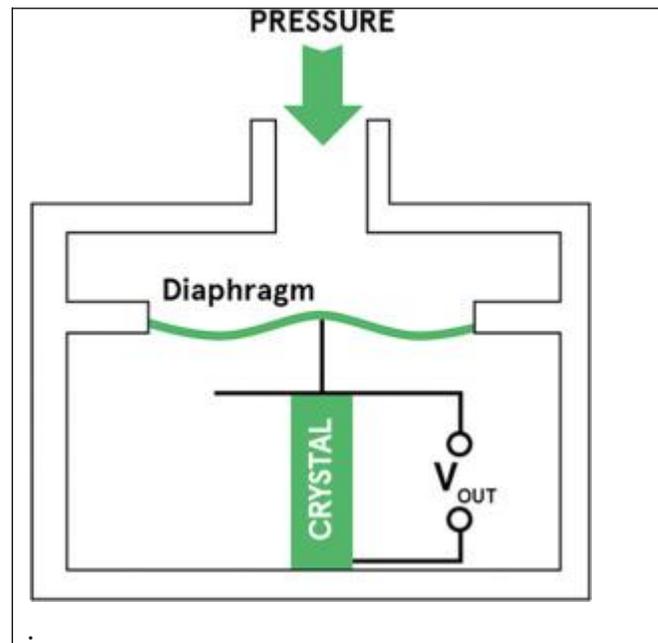


Figure. 2. Piezoelectric sensor diagram

The specification of the selected piezoelectric sensor is demonstrated as shown in Table 1

Table 1. Specification of piezoelectric sensor

S/N	Prosperities	Symbol	Values
A.	Physical Prosperities		
1.	Diameter (mm)		10
2.	Thickness (mm)		1
3.	Hardness		Hard
4.	Density(g/cm ³)	P	7.5
5.	Curie Temperature (°C)	Tc.	25
6.	Mechanical Quality Factor	Qm.p	70
B.	Dielectric properties		
1.	Dielectric constant at 1 KHZ	Kgt	2600
2.	Dissipation factor at 1 KHZ	tanδ	
3.	Resistivity	Ω-cm	10–12
C.	Electro-Mechanical Data		
1.	Planer coupling co-efficient	Kp	0.62
2.	Transverse coupling co-efficient	K31	0.37
3.	Longitudinal coupling co-efficient	K33	0.72
4.	Piezoelectric charge constant (C/NX10 ⁻¹²)	-d31	195
		d33	460
5.	Piezoelectric Voltage constant (10 ⁻³ V -meter / Newton)	-g31	13
		g33	27

The parameters are taken from research paper [Q. He, et al. 2024](#), [M Kim et al. 2012](#), [R. Liu et al. 2023](#)

After complete the selection process of the piezoelectric sensor, the design of footsteps has been assigned to be distributed on 12 footsteps with a dimension of 100×100 mm and 48 Piezoelectric sensors are distributed as illustrated in below Figure.3.

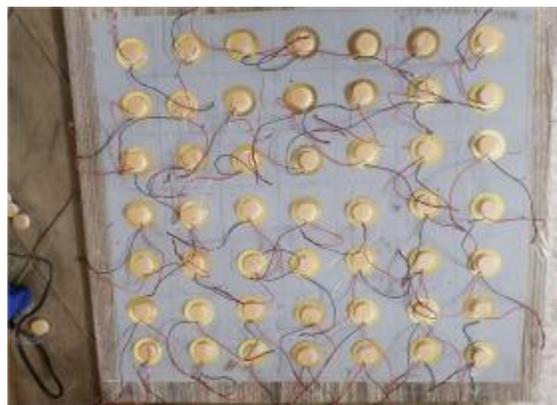


Figure.3. Piezoelectric sensors

The design of these footsteps is identified based on the following:

- The sensors are first tested individually.
- After testing, they are installed inside the footsteps.
- The sensors are calibrated, designed, and placed to cover the whole footstep area.
- Rigid spacers are fixed inside the working area of the piezoelectric sensors, as recommended by [O. Hussein et al. 2025](#).
- The sensors are distributed to cover the entire surface of each footstep.
- The system includes 12 footsteps.
- A total of 48 piezoelectric sensors are enough to cover this area.
- Inside each footstep, the sensors are connected in series to control and increase the voltage.
- The 12 footsteps are connected in parallel to increase the current while keeping the voltage stable.
- This connection allows the system to supply power directly to DC devices.
- No extra electrical circuits are needed.
- When 150 employees (weighing between 70–100 kg) walk through the entrance, the system can produce the required power.
- The system output is connected to a control unit.
- The control unit manages and regulates the power supplied to DC appliances.

3.3. Tracking solar system

This component is deemed the active element within the entire system, providing power to users; it comprises a solar unit with specifications detailed in Table 2.

Table 2. Utilized Solar characteristics.

Parameter	Value
STC Power Rating Pmp (W)	170
Open Circuit Voltage Voc (V)	44.2
Short Circuit Current Isc (A)	5.3
Voltage at Maximum Power Vmp (V)	35
Current at Maximum Power Imp (A)	4.86
Panel Efficiency	13.10 %
Fill Factor	72.60 %
Power Tolerance	5.00 % ~ 10.00 %
Maximum System Voltage Vmax (V)	1000
Maximum Series Fuse Rating (A)	15
Cells Dimensions	(32.5 × 62.0 × 1.8 inch)
Weight	17.0Kg

The parameters are taken from research paper by [M. J. Yaseen et al. 2022](#). The panel has been affixed to a mechanical structure and linked to a DC motor to facilitate the rotation of the structure, as depicted in Figure.4.



Figure.4. Tracked solar panel.

The mechanical structure is designed with flexibility to accommodate various solar panel sizes for future scalability. A shaft couples the structure to a DC motor, which enables the panel to track sunlight and optimize energy capture. The system is further integrated with an electronic circuit that governs the motor's movement and facilitates communication between subsystems. A schematic diagram of this electronic circuit is provided in Figure 5.

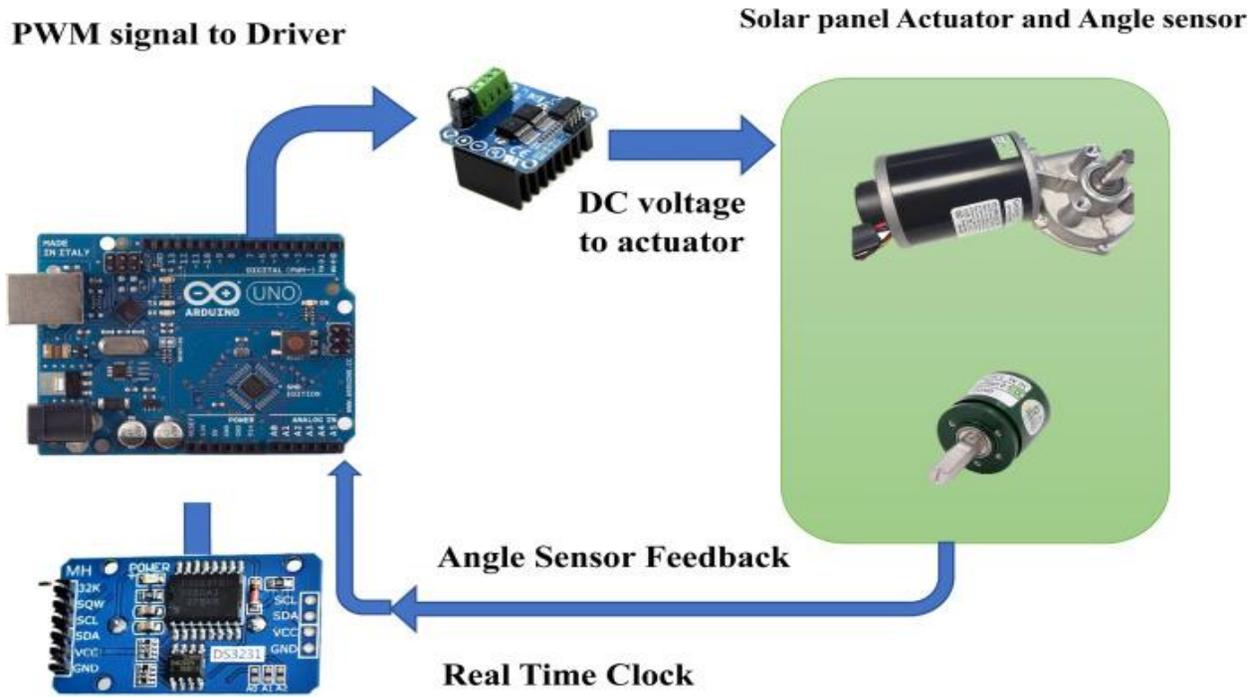


Figure.5. Solar panel controller schematic diagram.

Solar panel is designed to monitor the sun's angle independently of sunlight tracking. This system tracks the sun at specified periods of the day. The sun tracking method of the suggested system is built and programmed according to the procedure indicated in Figure. 6.

The system mechanism is illustrated from the below steps:

- The yearly morning solar angles are calculated using geographical site data in PV Sys 8 and previous studies for the Nagpur region.
- The calculated sun angle data is programmed into the controller.
- A reference position is set, and the tracker moves every 30 minutes with a 4-minute delay.
- The system follows pre-stored solar path data to handle seasonal changes and cloudy weather.
- After sunset, the tracker returns to its starting position for the next day.
- The system is designed to manage challenges such as location, climate conditions, complexity, and cost.

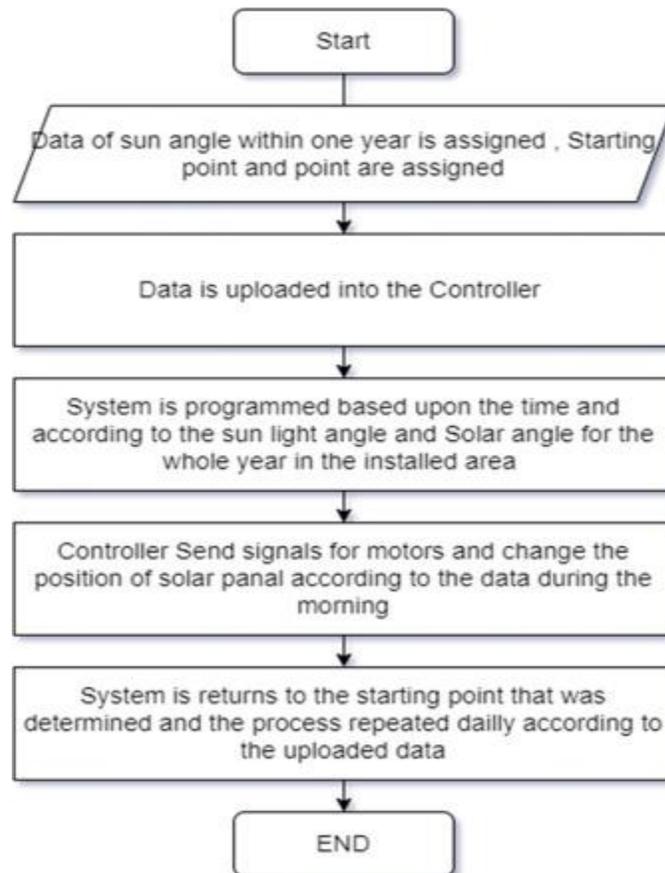


Figure.6. Solar panel tracking system algorithm.

3.4. Controller unit

This section is the third part of the system architecture and works as the main control unit. It controls all the stages of the system, manages the input voltage, and provides suitable output voltage to different appliances. The schematic diagram of the control unit is shown in Figure. 6. The figure below shows how all components of the system are connected, and each part has a specific function. Two electronic switches are used to control the output power, either from the solar panel or from the piezoelectric footstep generator. A battery is used to store the generated energy.

The control unit manages the power generation and distribution process based on the charging and power management strategy shown as reported by [M. Hasan et al. 2024](#) . This method helps reduce power loss, improves system efficiency, and keeps the design simple and reliable. The overall working method is shown in Figure. 7.

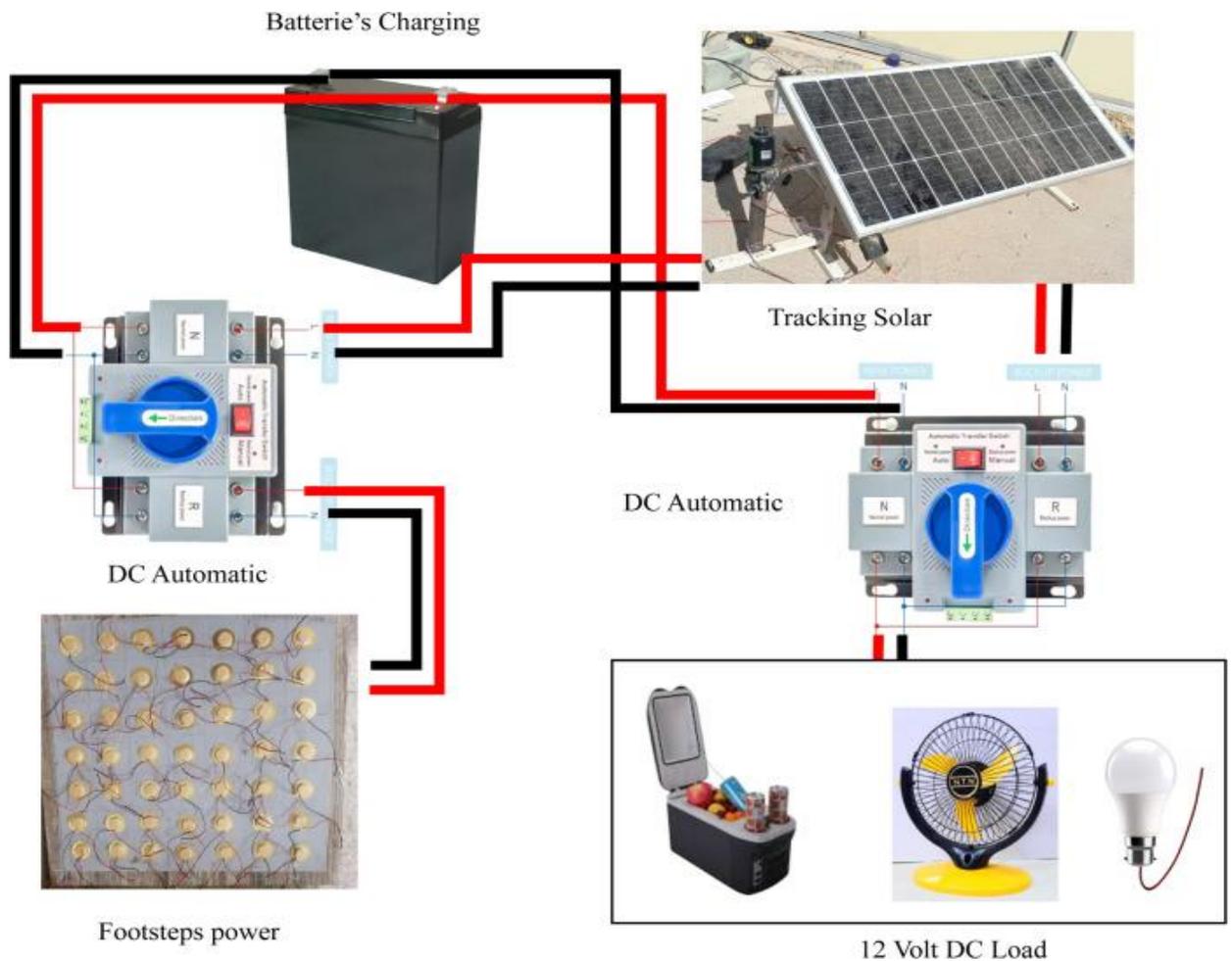


Figure.6. Schematic Diagram of the system controller.

Each section in the Figure.7. will be explained in the following:

- The tracking solar panel is set to collect data and adjust its position based on the season.
- The solar panel follows the sun from sunrise to sunset. It changes its angle according to the sun's position, which is different in each season.
- Electricity is generated from two sources:
 - Tracking solar panel
 - Piezoelectric footstep system
- The batteries are charged using power from both the solar panel and the piezoelectric system.
- An automatic smart switch is used to control charging. It decides whether the battery will charge from the solar panel or from the piezoelectric system.
- DC appliances can run using:
 - Direct power from the solar panel
 - Power stored in the batteries
- The power collected from both sources goes to a booster circuit. The booster circuit increases the DC voltage to 12V, even if the input power changes.
- This ensures that:
 - DC appliances can run properly
 - Batteries can be charged safely

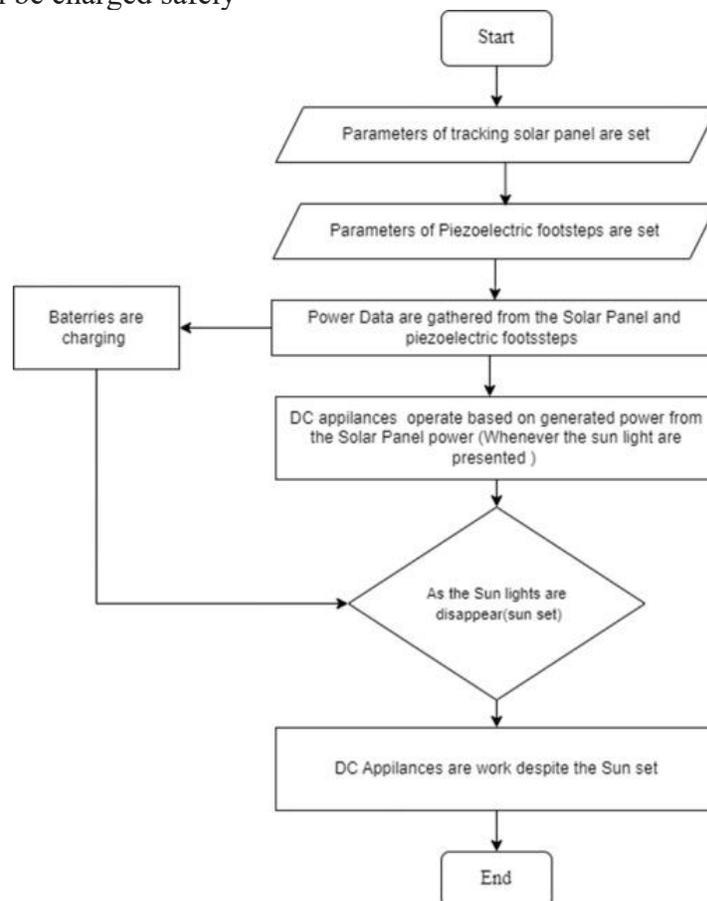


Figure.7. System overall methodology.

4. Evaluation Metrics

To assess the performance of a hybrid energy-harvesting system integrating piezoelectric footstep energy and a solar tracking mechanism, the following evaluation metrics are typically adopted:

Result: Piezoelectric Sensor Readings

Footsteps/min	Voltage (V)	Current (mA)	Power (mW)
5	2.1	3	6.3
10	3.5	5	17.5
20	5.2	8	41.6
30	6.8	12	81.6
50	8.5	18	153

Result: Solar Panel Readings

Condition	Voltage (V)	Current (mA)	Power (W)
Morning	4.2	180	0.75
Noon	6.1	480	2.93
Evening	3.8	120	0.45
Cloudy	2.5	90	0.22

Result: Hybrid System Output Readings

Condition	Total Voltage (V)	Total Current (mA)	Total Power (W)
Day + 20 steps	6.3	500	3.15
Day + 50 steps	6.8	520	3.53
Cloudy + 30 steps	5.0	150	0.75
Night + 40 steps	7.0	15	0.105

1. Power Output and Power Density:

The total electrical power generated by the piezoelectric modules and the solar subsystem is measured under various operating conditions. Power density (mW/cm^2 or mW/m^2) is used to normalize performance with respect to area, enabling fair comparison between different designs.

2. Energy Conversion Efficiency:

Conversion efficiency is evaluated separately for the solar and piezoelectric units. For the solar

subsystem, efficiency reflects the ability of the tracking mechanism to maintain optimal panel orientation. For piezoelectric elements, mechanical-to-electrical conversion efficiency is quantified based on force input and electrical output.

3. Daily Energy Harvest and Temporal Performance:

Energy harvested over a 24-hour cycle is measured to capture variations due to sunlight availability and footfall density. This metric highlights the complementary behavior of the two sources and indicates system reliability across different time intervals can be observed from result of hybrid power generation.

5. Challenges

Hybrid energy harvesting systems encounter several technical and practical challenges that limit their scalability and performance:

1. **Low Output from Piezoelectric Footsteps** Although piezoelectric materials can convert mechanical stress into electrical energy, the energy generated per footstep is relatively small. This creates difficulty when powering medium-to-high-load devices without supplemental sources.
2. **Mechanical Fatigue and Material Degradation** Piezoelectric tiles placed in high-traffic zones experience continuous stress cycles, leading to fatigue, fracture, or loss of polarization over time. Ensuring long-term durability remains a major challenge.
3. **Solar Tracking Limitations and Environmental Variability** Solar trackers improve efficiency but introduce moving parts susceptible to wear, misalignment, or increased maintenance costs. Cloud cover, rainfall, and environmental dust can further reduce system performance.
4. **Power Electronics Complexity** Integrating two heterogeneous sources requires robust power-conditioning circuits to handle variable voltages and currents. Losses in rectifiers, converters, and protection circuits significantly impact overall system efficiency.
5. **Installation and Maintenance Issues** Embedding piezoelectric tiles under floors requires structural modifications, while solar trackers require alignment checks and periodic cleaning. These factors increase maintenance overhead.

6. Future Directions

1. Several research opportunities remain open for improving hybrid energy harvesting systems. These directions can significantly contribute to enhancing efficiency, durability, and real-world adoption.
2. Development of Advanced Piezoelectric Materials.
3. Future work can focus on high-performance materials such as PVDF composites, nano-structured ceramics, and flexible piezo-polymers that offer higher conversion efficiency, improved durability, and easier integration into flooring systems.
4. Hybridization can be extended by incorporating triboelectric, electromagnetic, or thermoelectric harvesters. Multi-source systems can further stabilize the output and reduce reliance on foot traffic or sunlight alone.
5. Intelligent Power Management and Optimization Algorithms. Integration with Additional Energy Sources.
6. Machine learning or adaptive control algorithms can be developed to predict solar irradiance and footfall activity, allowing dynamic allocation of harvested energy between loads and storage to maximize system performance.
7. Enhanced Power Electronics and MPPT Techniques.
8. Future designs should focus on high-efficiency buck-boost converters, integrated MPPT algorithms, and low-loss rectification solutions to minimize conversion losses and improve energy utilization.
9. Improving Durability Through Structural Redesign Innovative mechanical designs such as shock-absorbing layers, modular piezo tiles, and optimized load distribution can improve lifespan and reduce maintenance requirements.

7. Conclusion

The present study demonstrates a hybrid energy harvesting system that integrates piezoelectric and solar photovoltaic modules to generate clean and renewable power. The dual-source design effectively meets small- to medium-scale energy demands in public and semi-urban environments.

Experimental analysis confirms that piezoelectric tiles efficiently convert mechanical pressure from footsteps into electrical energy, especially in high pedestrian-traffic locations such as malls,

stations, airports, hospitals, and campuses. While the energy from a single step is small, continuous foot movement provides a considerable cumulative output.

The solar photovoltaic module ensures stable daytime power, maintaining operation during periods of low footfall. This hybrid configuration leverages both intermittent kinetic and consistent solar energy, thereby enhancing voltage stability, improving efficiency, and ensuring reliable output.

Optimized storage and power regulation circuits deliver clean, usable electricity suitable for low-power applications such as LED lighting, IoT-based devices, sensors, and mini charging systems. The performance is further improved through appropriate material selection, efficient piezoelectric tile design, and strategic solar panel positioning.

This study concludes that hybrid piezoelectric–solar harvesting is technically feasible, economically viable, and environmentally sustainable. It offers a scalable solution that supports smart city initiatives and reduces dependence on fossil-based energy sources.

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Biography

Dr. Muzaffar. Khan senior faculty with 26 years of teaching experience to under graduate and post graduate student. He has obtained PhD in biomedical Engineering from National Institute of Technology Raipur. His area of expertise is in AI and its application medical diagnostic field. He has worked a eminent reviewer for internal journal such as Elsevier journal.

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