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Advanced Footstep Power Generation System: A Piezoelectric Footstep Tile with Battery Storage and ESP32-Based Monitoring

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ABSTRACT

The growing demand for clean, decentralised electricity has drawn attention to unconventional sources such as the mechanical energy released when people walk. This paper presents an Advanced Hybrid Footstep Power Generation System that combines piezoelectric elements with a synchronous motor-generator. Piezoelectric elements convert direct pressure into electrical pulses, while a mechanical linkage converts the downward movement of the footstep plate into rotary motion to drive the generator. The generated outputs are conditioned through suitable circuits and can be stored in a battery pack for powering a low-power load. An ESP32, LCD and relay provide monitoring and load control. The paper describes the proposed design, working principles, methodology, applications and limitations.

Keywords: hybrid footstep power generation, piezoelectric effect, synchronous motor-generator, energy harvesting, ESP32, battery storage, renewable energy.

1. Introduction

Electricity demand continues to rise while conventional fuels deplete and cause environmental damage. Renewable sources such as solar and wind are widely adopted, but they depend on weather and daylight. Human movement is an additional, largely wasted source of energy: every footstep applies a force to the ground that is normally lost as heat and sound. In densely populated countries such as India, places like railway stations, bus terminals, temples, malls and college campuses see continuous foot traffic, which makes them natural sites for harvesting this energy.

A recent review describes how kinetic energy from human locomotion has emerged as a promising clean source for low-power smart electronic devices, and surveys piezoelectric, rack-and-pinion, triboelectric, Pavegen-type and fluid-based harvesters [1]. The energy of a single step is small, so practical systems target low-power loads such as LED lighting, sensors, mobile charging and IoT nodes rather than the grid.

This work presents an Advanced Hybrid Footstep Power Generation System that combines piezoelectric harvesting and a synchronous motor-generator with battery storage, a relay-switched load and microcontroller-based monitoring. to build a compact platform that converts footstep force into electrical energy;

- to store the harvested energy and use it to light an LED load;
- to display system status using an ESP32 and LCD; and
- to estimate the energy yield and identify limits, applications and improvements.

2. Literature Review

2.1 Piezoelectric footstep harvesters

Piezoelectric materials generate an electric charge when mechanically stressed. A 2025 study designed, modelled and tested a piezoelectric footstep platform in which transducers are arranged beneath a rigid plate; it observed measurable AC voltage peaks during loading and regulated DC power after rectification, concluding that the approach is feasible for lighting, sensor powering and low-energy IoT use [3]. The same work reviews PZT and PVDF materials and notes that hybrid solar-piezoelectric systems can raise generation by roughly 30–60% depending on usage [3].

2.2 Rack-and-pinion harvesters

In rack-and-pinion designs the vertical travel of a tread plate is converted into rotary motion that drives an electromagnetic generator. Zaidi et al. reported an average power of 3 W over 0.5 s at a peak load of 60 kg, with 1.8 J of electrical energy per step; about 75% of the available potential energy was transmitted by the paver and half of that was converted into electricity, with storage in a battery bank [2]. A theoretical and experimental investigation of footstep tiles reports an achieved energy efficiency of 17.2% and summarises earlier work, including a design reported to generate 34 W per footstep for a 75 kg person [4]. A 2026 case study describes a mechanical generator using spring pressure and a rack with two pinions [5], and an Indian preprint describes a rack-and-pinion with chain drive, DC generator and battery for crowded places such as railway stations and temples [6].

2.3 Research gap

Reported systems often stop at the harvesting tile. The review in [1] concludes that piezoelectric flooring, rack-and-pinion harvesters, triboelectric nanogenerators and wave-spring generators all hold promise, and that improving materials and falling power needs of portable devices will help. A complete, low-cost unit that also stores energy, switches its load and reports its state fills a practical gap and forms the basis of this work.

3. Working Principles

3.1 Piezoelectric effect

When a piezoelectric element is compressed, it produces an electrical pulse across its electrodes. Because this output is brief and may be alternating, it must be rectified and buffered before it can contribute to charging the battery. This forms the first energy-generation path in the hybrid system.

3.2 Storage, switching and monitoring

The conditioned DC outputs from the harvesting stages are directed through suitable power-conditioning and charging circuitry to the rechargeable battery pack. A relay module connects the stored energy to the load under control of the ESP32 microcontroller, which also drives a character LCD to display system readings. The two generation paths should be electrically conditioned before they are combined; their outputs should not be connected directly together.

3.3 Mechanical alternative

In the hybrid design, the vertical movement of the tread plate drives a mechanical linkage such as a rack-and-pinion or crank mechanism. This linkage rotates a synchronous motor used as a generator, producing electrical output when its shaft is driven. The generator output requires appropriate rectification and voltage regulation before battery charging. The actual output depends on linkage design, rotational speed and generator characteristics, and must be measured experimentally.

4. Proposed System Design

4.1 Overview

The platform consists of two boards separated by spacer strips. The upper board is the tread plate and is held on bolts with springs and washers at its corners, so that it moves down under load and returns when the load is removed. Piezoelectric harvesting elements are positioned beneath the plate. A mechanical linkage connected to the plate transfers part of its movement to a synchronous motor-generator. The piezoelectric and generator outputs pass through their respective conditioning circuits before feeding the battery-charging stage.

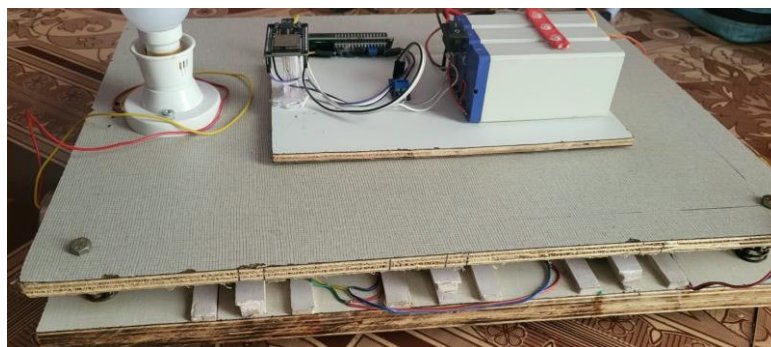


Fig. 1. Side view of two-layer, spring-supported platform with the control board and lamp mounted on top

The hybrid energy flow is: footstep force → tread plate → (1) piezoelectric elements → rectifier, and (2) mechanical linkage → synchronous motor-generator → rectifier/regulator → charging circuit → battery pack → relay → LED load. The ESP32 and LCD monitor the system. Separate conditioning is required for the two sources before their outputs are combined for storage.

4.2 Main components

Component	Function
Two-layer platform	Receives footstep load
Corner springs and bolts	Allow travel and restore the plate
Harvesting elements	Convert pressure to electricity
Rectifier and charge circuit	AC to DC, battery charging
Battery pack (3 cells)	Stores harvested energy
Rocker switch	Isolates the supply
Relay module	Switches the load
ESP32 board	Control and monitoring
16x2 LCD	Displays readings
LED module and bulb	Demonstration loads
DC input lead	External charging option
Synchronous motor-generator	Converts linkage-driven rotary motion into electrical output
Mechanical linkage	Transfers tread-plate movement to the generator shaft
Generator rectifier/regulator	Conditions generator output before battery charging

Table 1. Principal components of the prototype

5. Prototype Implementation

The prototype electronics are mounted on a separate board, as shown in Fig. 2. The battery pack, LED module, rocker switch, relay, ESP32 and LCD form the storage, load-control and monitoring unit. For the hybrid implementation, piezoelectric elements are fitted beneath the tread plate and a mechanical linkage is connected to a synchronous motor-generator. The generator and piezoelectric outputs must be measured and conditioned separately before charging the battery.

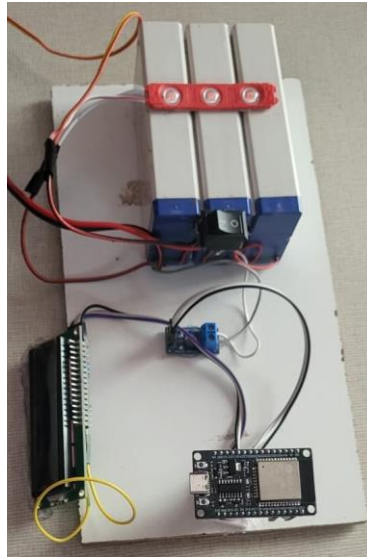


Fig. 2. Control and storage board: battery pack, LED module, switch, relay, ESP32 and LCD

During operation, each footstep presses the tread plate. The piezoelectric elements produce electrical pulses, while the plate movement drives the mechanical linkage and rotates the synchronous motor-generator. Each source is conditioned separately, then routed to the battery-charging stage. The ESP32 displays system status on the LCD and controls the relay that connects the stored energy to the LED load.

6. Methodology

- Define the design load range of 40–80 kg, matching the range tested in [2].
- Fabricate the two-layer platform, install piezoelectric elements, and connect a suitable mechanical linkage to the synchronous motor-generator.
- Assemble the piezoelectric rectifier, motor-generator output rectifier/regulator, battery-charging circuit, relay, ESP32 and LCD.
- Apply varying loads and step rates; record piezoelectric output, generator output, charging current and stored energy separately and in hybrid operation.
- Check the LED load operation from the stored energy.
- Compare measurements with the estimate in Section 7 and refine the design.

7. Theoretical Analysis

The mechanical work done on the platform by one step is $W = m \cdot g \cdot d$, where m is body mass, $g = 9.81 \text{ m/s}^2$ and d is the downward travel of the tread plate. The electrical energy per step is $E = W \cdot \eta$, where η is the overall conversion efficiency.

For an assumed 70 kg user and 5 mm travel, $W = 70 \times 9.81 \times 0.005 \approx 3.43 \text{ J}$. The travel of the prototype should be measured and substituted for this assumed value. Because the efficiency of the harvesting elements is not yet measured, Table 2 shows the effect of assumed efficiencies of 1%, 5% and 10%. For comparison, the rack-and-pinion tile in [2] delivered 1.8 J per step, equal to 5 Wh for 10,000 steps.

η (assumed)	Energy per step (J)	10,000 steps (J)	10,000 steps (Wh)
1%	0.034	343	0.095
5%	0.172	1717	0.477
10%	0.343	3434	0.954

Table 2. Sensitivity of harvested energy to efficiency ($W = 3.43 \text{ J per step}$, $1 \text{ Wh} = 3600 \text{ J}$)

The values are small, which explains why footstep harvesting suits low-power distributed loads and why busy locations are essential.

8. Results and Discussion

Table 3 gives the energy expected at the three test loads, calculated with the model of Section 7 (5 mm travel, assumed 5% efficiency). These are calculated estimates, not measurements; measured values from the prototype should be compared against them.

Load (kg)	Work per step (J)	Energy per step (J)	10,000 steps (Wh)
40	1.96	0.098	0.272
60	2.94	0.147	0.409
80	3.92	0.196	0.545

Table 3. Estimated energy versus load (calculated, $W = m g d$, $d = 5 \text{ mm}$, $\eta = 5\%$)

The literature indicates what to expect: output rises with load [2], a piezoelectric layer yields clean but small pulses [3], and losses reduce the usable fraction of the input work [4].

9. Applications, Advantages and Limitations

9.1 Applications

- Lighting of staircases, platforms, subways and campus pathways.
- Charging points in railway stations, bus stands and temples.
- Powering low-energy sensors and IoT nodes, and counting footfall.

9.2 Advantages

- Uses an otherwise wasted, renewable source with no emissions.
- Works day and night, indoors and outdoors.
- Simple, low-cost construction that can be built locally.

9.3 Limitations

- Low energy per step, so high foot traffic is required [1].
- Wear of springs and harvesting elements under repeated loading.
- Weatherproofing is needed for outdoor installation.

10. Conclusion and Future Scope

Footstep power generation can convert pedestrian movement into small amounts of electrical energy. The proposed hybrid system combines piezoelectric elements, which generate electrical pulses under pressure, with a synchronous motor-generator driven by the mechanical movement of the tread plate. Conditioned outputs from both generation paths can be stored in a battery and used for a low-power LED load, while the ESP32 and LCD provide monitoring. The practical benefit of the hybrid approach must be established by measuring each source under repeated loading; output depends on tread travel, mechanical losses, generator speed and electrical conversion efficiency.

Future work includes fabricating and testing the mechanical linkage, measuring piezoelectric and synchronous motor-generator outputs independently, optimizing rectification and charging circuits, and comparing total stored energy against a piezoelectric-only baseline. Further improvements may include stronger mechanical components, better power electronics, weatherproofing and IoT logging of generated energy and footfall.

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