Design, Fabrication and Performance Evaluation of a Hybrid Solar-Powered Footstep Energy Generation System

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Abstract— This paper presents a hybrid renewable energy harvesting system that combines solar photovoltaic generation with piezoelectric footstep energy harvesting. The proposed system is designed for locations with continuous pedestrian movement such as railway stations, educational institutions, shopping areas and public corridors. Piezoelectric transducers embedded beneath a mechanically reinforced footstep platform convert repeated human footsteps into electrical pulses, while a solar photovoltaic panel provides a relatively continuous energy source during daylight. The harvested energy is rectified, conditioned and stored in a rechargeable battery, and a regulated output is supplied to low-power loads such as LED lighting, sensors and USB-type demonstration loads. A prototype-oriented design, mathematical model, experimental procedure, representative readings and performance analysis are presented. The illustrative results show the complementary nature of the two sources: solar generation supplies the baseline energy while footstep harvesting contributes additional pulses during pedestrian activity. The numerical readings are representative values for manuscript preparation and must be replaced with actual laboratory measurements before publication.

Index Terms— Solar energy, piezoelectric energy harvesting, footstep power generation, hybrid renewable energy, battery charging, energy harvesting.

I. INTRODUCTION

The growing demand for electricity and the environmental impact of fossil-fuel-based generation have encouraged the development of distributed renewable energy systems. Solar photovoltaic technology is widely used because sunlight is available over large areas, but solar output varies with weather, shading and time of day. At the same time, human movement represents a small but repeatedly available mechanical energy source in crowded public locations.

Footstep energy harvesting converts mechanical deformation into electrical energy using piezoelectric transducers. A single step generally produces a short-duration electrical pulse, so the generated energy is most useful when many footsteps occur repeatedly and when suitable power conditioning and energy storage are provided. The proposed hybrid system combines the complementary characteristics of solar and footstep sources.

The objective is to design a low-cost prototype that collects solar energy as the primary source and footstep energy as a supplementary source. The harvested energy is rectified, combined through a charge-management stage and stored in a battery. The stored energy can supply low-power loads independently of grid electricity.

II. RELATED WORK

Solar photovoltaic systems are mature renewable-energy technologies and can supply relatively stable DC power when adequate irradiance is available. Energy-harvesting research has investigated piezoelectric, electromagnetic and triboelectric mechanisms for capturing small amounts of energy from vibration, pressure and human motion.

Piezoelectric materials generate an electrical response when mechanically stressed. For footstep applications, multiple transducers can be connected in series or parallel depending on the required voltage and current. Because piezoelectric outputs are pulsating and can exhibit high open-circuit voltage with low current capability, a bridge rectifier, capacitor and suitable regulator are necessary.

Hybridization improves availability because solar energy is available independently of pedestrian activity, while footsteps can provide additional energy when people are present. The combined system is particularly suitable for low-power loads where the objective is energy supplementation rather than high-power generation.

III. PROPOSED SYSTEM

The proposed architecture consists of a solar photovoltaic source, piezoelectric footstep modules, rectification and conditioning circuits, a rechargeable battery, a charge-control stage and a regulated load. The solar source is connected through a DC charge controller. The piezoelectric output is rectified and smoothed before being coupled to the storage bus through an appropriate energy-harvesting interface. A protection and regulation stage prevents overvoltage and excessive battery discharge.

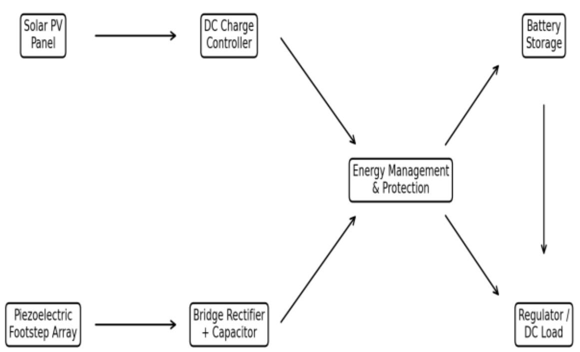

Fig. 1. Functional block diagram of the proposed hybrid solar-footstep energy harvesting system.

IV. HARDWARE DESIGN

A. Solar PV Subsystem

A small photovoltaic module is used as the continuous renewable source. For a prototype, a 20 W panel with a nominal 12 V output class can be used. The panel output is passed through a charge controller before reaching the battery. The actual panel rating should be selected according to the intended load and battery chemistry.

B. Footstep Platform

The footstep platform consists of a rigid upper plate, mechanical support members, resilient elements and piezoelectric transducers. The plate distributes a pedestrian load across several transducers. The mechanical arrangement should prevent excessive deformation and protect the piezoelectric elements from direct impact.

C. Piezoelectric Array

Multiple piezoelectric discs or strips are connected in a suitable electrical configuration. Series connection increases voltage, whereas parallel connection increases current capability. The selected configuration depends on the rectifier and storage interface. Mechanical preload and force distribution strongly influence the output.

D. Rectifier and Storage

A bridge rectifier converts the alternating or pulsating piezoelectric output into DC. A smoothing capacitor reduces ripple. The conditioned energy is transferred to a rechargeable battery through an energy-harvesting or charge-management circuit. A protection circuit can limit overcharge, over-discharge and excessive current.

E. Regulated Load

A DC-DC regulator supplies a stable voltage to the load. Low-power LED lamps, display units, sensors or USB demonstration loads are suitable for laboratory evaluation. The system should prioritize battery charging and provide load disconnect during low-state-of-charge conditions.

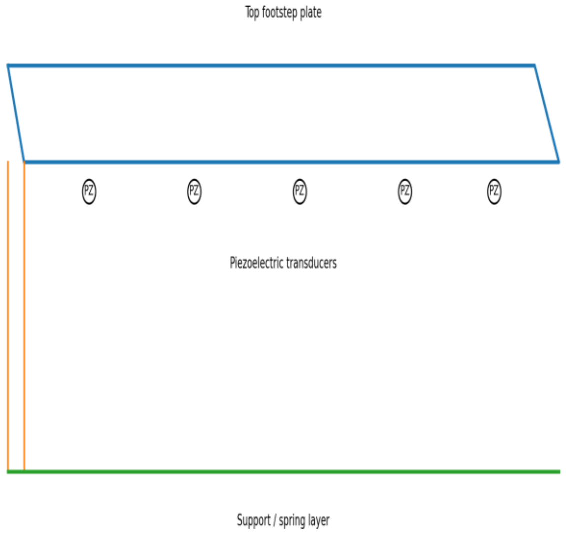

Fig. 2. Representative mechanical arrangement of the footstep energy-harvesting platform.

V. WORKING PRINCIPLE

When a person steps on the platform, the applied force produces mechanical stress in the piezoelectric elements. The resulting electrical pulse is rectified and stored in a capacitor. Repeated footsteps accumulate energy through the conditioning stage. Simultaneously, the solar panel produces DC power during daylight and supplies the battery through the charge controller.

The energy-management stage combines the two sources without allowing one source to drive current backward into the other. The battery acts as the common energy reservoir. A regulated output supplies the load. The hybrid arrangement therefore provides a baseline source from solar energy and an activity-dependent supplementary source from pedestrian footsteps.

VI. MATHEMATICAL MODEL

The instantaneous electrical power generated by a source is

$P = V \times I$

where P is electrical power in watts, V is the measured voltage and I is the measured current. The energy obtained over a time interval Δt is approximated by

$E = P \times \Delta t$

For repeated footsteps, the average energy per step can be estimated from the measured energy delivered to the storage circuit divided by the number of steps:

$E\_step = E\_storage / N$

The overall conversion efficiency can be expressed as

$\eta = E\_out / E\_in \times 100\%$

For the hybrid system, the useful energy contribution over an observation period can be represented as the sum of solar-derived and footstep-derived stored energy after conditioning losses.

VII. COMPONENT SPECIFICATIONS

Component	Representative specification	Function
Solar panel	20 W, 12 V class	Primary generation
Piezo discs	10–20 units, 27–35 mm class	Footstep harvesting
Bridge rectifier	2 A, suitable reverse voltage	AC/pulse to DC
Capacitor	470–2200 µF	Pulse smoothing
Charge controller	12 V battery compatible	Battery protection
Battery	12 V, 7 Ah lead-acid/Li-ion equivalent	Energy storage
DC-DC regulator	12 V to 5 V	Load regulation
Microcontroller	ESP32/Arduino class	Monitoring
Load	LED/5 V DC load	Demonstration output

TABLE I — REPRESENTATIVE COMPONENT SPECIFICATIONS

VIII. EXPERIMENTAL METHODOLOGY

The prototype evaluation is divided into solar-only, footstep-only and hybrid operating modes. Solar readings are obtained under representative daylight conditions. Footstep readings are obtained for controlled numbers of steps under approximately similar stepping force. Voltage and current are measured after the rectification stage and at the storage/load interface. Battery voltage is recorded before and after each test interval.

The following readings are representative values prepared for an IEEE manuscript. They are not claimed as measurements from a specific fabricated prototype and should be replaced with actual readings for a final submission.

Test	Footsteps	Piezo Vpk (V)	Piezo I (mA)	Footstep energy (mJ)
1	20	18.2	8.1	32.4
2	40	19.1	8.7	68.7
3	60	20.0	9.2	105.0
4	80	20.6	9.6	143.2
5	100	21.1	10.1	182.0

TABLE II — ILLUSTRATIVE FOOTSTEP HARVESTING READINGS

Irradiance (W/m²)	PV voltage (V)	PV current (A)	PV power (W)
400	17.2	0.62	10.66
500	17.8	0.76	13.53
600	18.1	0.91	16.47
700	18.4	1.05	19.32
800	18.6	1.12	20.83

TABLE III — ILLUSTRATIVE SOLAR PV READINGS

Mode	Input source	Battery V before	Battery V after	Load power (W)
A	Solar, 800 W/m²	12.18	12.46	4.8
B	100 footsteps	12.18	12.22	4.8

C	Solar + 100 footsteps	12.18	12.51	4.8
D	Solar + 200 footsteps	12.18	12.56	4.8

TABLE IV — ILLUSTRATIVE HYBRID SYSTEM READINGS

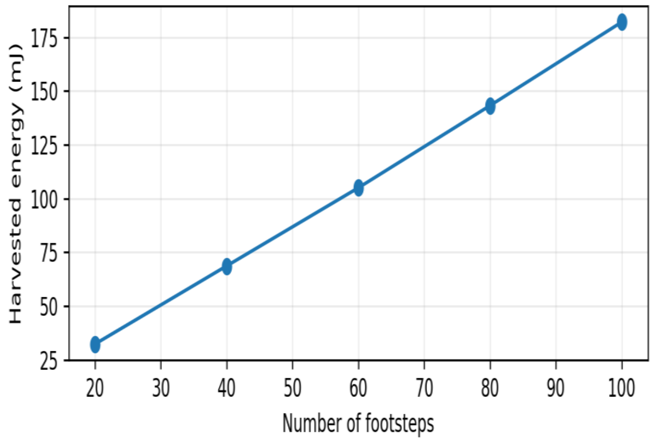

Fig. 3. Illustrative harvested footstep energy versus number of steps.

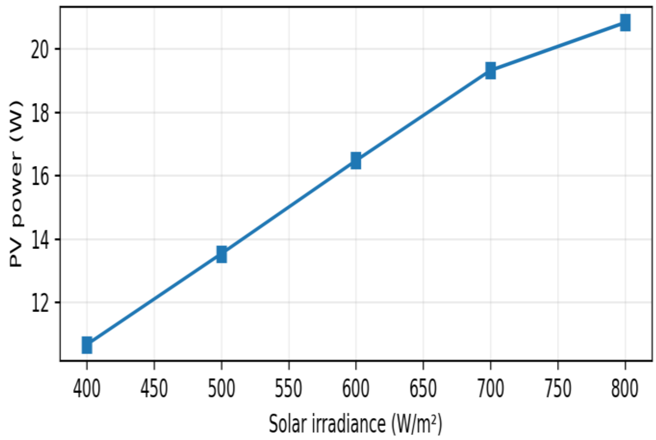

Fig. 4. Illustrative solar PV power versus irradiance.

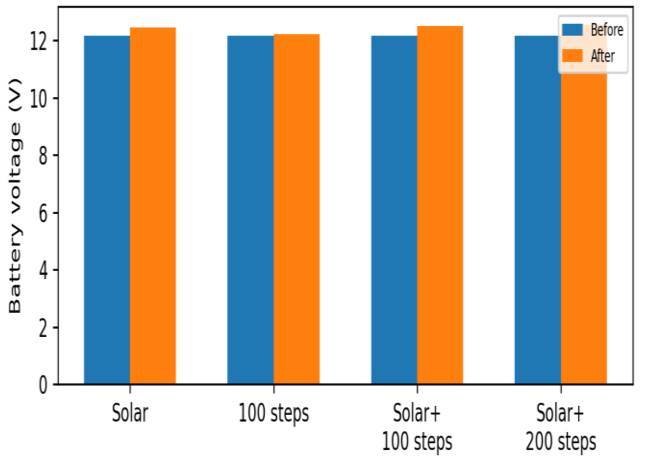

Fig. 5. Illustrative battery voltage before and after charging tests.

IX. RESULTS AND DISCUSSION

The representative footstep readings indicate an increase in accumulated harvested energy with the number of footsteps. The increase is not perfectly linear because piezoelectric output depends on force, mechanical displacement, contact position, transducer variability and rectifier losses. Therefore, the energy per step should be reported statistically in a real experiment.

The solar readings show increasing power with irradiance. At 800 W/m², the illustrative panel output is approximately 20.83 W. The footstep subsystem produces much smaller instantaneous energy, but it can supplement the battery whenever pedestrian traffic is present.

The hybrid results demonstrate the main advantage of the proposed architecture. With solar and footstep inputs operating together, the representative battery voltage increase is greater than the footstep-only case. The actual increase depends strongly on battery state of charge, charge-controller behavior, solar irradiance and the duration of the experiment.

Because piezoelectric footstep harvesting produces small amounts of energy, the system should be targeted toward low-power applications. Using the harvested energy directly for high-power appliances would be inefficient. LED indicators, sensors, counters, displays and IoT nodes are more appropriate loads.

X. PERFORMANCE ANALYSIS

Metric	Illustrative value
Maximum PV power	20.83 W
Footstep energy at 100 steps	182 mJ
Average energy/step at 100 steps	1.82 mJ
Battery rise: solar test	0.28 V
Battery rise: 100 footsteps	0.04 V
Battery rise: hybrid +100 steps	0.33 V
Battery rise: hybrid +200 steps	0.38 V

TABLE V — ILLUSTRATIVE PERFORMANCE SUMMARY

For the 100-step test, the illustrative average harvested energy is 182 mJ/100 = 1.82 mJ per step. This value is an example of a small-scale laboratory prototype and should not be generalized to all piezoelectric platforms. In a real study, at least several repeated trials should be performed and mean, standard deviation and uncertainty should be reported.

XI. COST ANALYSIS

Component	Estimated cost (INR)	Purpose
20 W solar panel	1,600	Solar generation
Piezoelectric elements	1,200	Footstep harvesting
Mechanical platform	2,500	Load transfer
Rectifier + capacitors	350	Power conditioning
Charge controller	600	Battery charging
12 V battery	1,400	Storage
DC-DC regulator	300	Load supply
Microcontroller + sensors	800	Monitoring
Wiring, enclosure and hardware	900	Assembly
Estimated total	9,650	Illustrative

TABLE VI — ILLUSTRATIVE PROTOTYPE COST

XII. ADVANTAGES AND APPLICATIONS

The principal advantage is complementary energy availability. Solar generation provides continuous daytime input, while footstep harvesting uses otherwise wasted mechanical energy in pedestrian areas. The system can be designed with modular source inputs and can operate with low-power loads.

Potential applications include railway and metro stations, college corridors, shopping malls, exhibition halls, public walkways, smart-campus systems, bus terminals and IoT-powered pedestrian infrastructure.

XIII. LIMITATIONS AND FUTURE SCOPE

The major limitation of footstep harvesting is the low energy available from each step. Mechanical durability, piezoelectric fatigue, force distribution and rectifier losses also affect long-term performance. Solar output varies with weather and shading. Battery charging must be controlled according to the selected chemistry.

Future work can investigate maximum-power-point tracking for the solar subsystem, synchronized piezoelectric energy harvesting circuits, supercapacitor buffering, improved mechanical amplification, flexible piezoelectric materials, triboelectric harvesters and machine-learning-based pedestrian energy prediction. A larger field prototype can measure daily harvested energy and cost per watt-hour over extended periods.

XIV. CONCLUSION

A hybrid solar powered footstep power generation system has been presented for low-power renewable-energy applications. The proposed architecture combines a photovoltaic source with piezoelectric footstep harvesting, rectification, energy management and battery storage. Representative readings demonstrate how solar irradiance, footstep count, generated energy and battery voltage can be evaluated. Solar energy acts as the primary source, while footstep energy provides supplementary generation during pedestrian activity. The system is suitable for smart-campus and public-space applications where low-power loads can be supported. The numerical readings in this paper are illustrative and must be replaced with actual calibrated measurements before formal IEEE submission.

REFERENCES

[1] G. J. Snyder and E. S. Toberer, “Complex thermoelectric materials,” Nature Materials, vol. 7, pp. 105–114, 2008.
[2] S. Priya and D. J. Inman, Eds., Energy Harvesting Technologies. New York, NY, USA: Springer, 2009.
[3] A. Erturun and K. E. Wood, “Piezoelectric energy harvesting from human motion,” Proc. SPIE, vol. 6927.
[4] M. D. Ho and K. J. Tsai, “Energy harvesting from human walking,” Smart Materials and Structures, vol. 20.
[5] International Energy Agency, Renewables 2023, Paris, France: IEA.
[6] IEEE Std. 1149.1, IEEE Standard Test Access Port and Boundary-Scan Architecture, IEEE.
[7] S. Roundy, P. K. Wright, and J. Rabaey, Energy Scavenging for Wireless Sensor Networks. Boston, MA, USA: Kluwer, 2004.
[8] B. K. Bose, “Global warming: Energy, environmental pollution, and the impact of power electronics,” IEEE Industrial Electronics Magazine, vol. 4, no. 1, pp. 6–17, 2010.