

# Footstep Power Generation Using Piezoelectric Sensors for Smart City Applications

Miss. Varsharani Gangadhar Ratnaparkhe  
Department of Information Technology  
Maharashtra State Board of Technical Education,  
Mumbai, India

Miss. Tanuja Shivanand Rajegore  
Department of Information Technology  
Maharashtra State Board of Technical Education,  
Mumbai, India

Miss. Samrudhi Sudhirrao Zangade  
Department of Information Technology  
Maharashtra State Board of Technical Education,  
Mumbai, India

Miss. Samiksha Gajanan Bhalerao  
Department of Information Technology  
Maharashtra State Board of Technical Education,  
Mumbai, India

Government Polytechnic, Nanded  
Department of Information Technology

**Abstract** - The rapid increase in global energy consumption and the resulting energy crisis have created a need for sustainable and non-conventional energy solutions that can utilize everyday human activities. Conventional renewable sources often depend on environmental conditions, while existing footstep energy systems face limitations such as low output, inefficiency, and restricted large-scale deployment. To address these challenges, this paper presents an advanced footstep power generation system that employs piezoelectric sensors integrated with IoT-based energy management for efficient monitoring and utilization. The system captures mechanical stress generated during walking and converts it into electrical energy using sensor arrays embedded beneath flooring surfaces, supported by rectification, storage, and regulated output units. A prototype implementation consisting of 12 sensors within a 1 ft<sup>2</sup> area demonstrates that each step can generate approximately 3–5 V and 15–25 mW, with an overall efficiency of 15–20%, while continuous pedestrian movement of 1,000–2,000 steps per hour can yield cumulative energy of 0.5–1 kWh per day. Additional features such as real-time monitoring and user interaction enhance system performance and usability in smart environments. Practical implementations by Pavegen Systems and installations at Shibuya Station validate the feasibility of this approach. The findings indicate that footstep power generation is a cost-effective, eco-friendly, and scalable solution for urban

**infrastructure, with potential applications in public spaces and wearable systems, contributing to energy efficiency and sustainable smart city development.**

**Keywords** - Footstep power generation, Piezoelectric energy harvesting, Smart energy management, Renewable energy systems, IoT-based monitoring

## I. INTRODUCTION

The continuous rise in energy consumption and the environmental impact of conventional power sources have increased the need for sustainable and alternative energy solutions. While renewable resources such as solar and wind contribute significantly, their dependence on environmental conditions limits consistent availability, creating interest in approaches that utilize energy from routine human activities. Footstep power generation is an effective method that utilizes piezoelectric materials to inherently generate an electrical charge in response to applied mechanical stress. ... The motivation for this research stems from the massive, untapped reservoir of kinetic energy present in high-density transit hubs and commercial corridors, where thousands of daily footsteps can be harvested to offset local power demands. Practical deployments by **Pavegen Systems** and installations at **Shibuya Station** highlight the feasibility of this concept in real environments. However, challenges remain in optimizing sensor configurations, improving conversion efficiency, and integrating intelligent monitoring systems for large-scale applications. This paper addresses these aspects by presenting an enhanced system design, followed by a structured discussion including literature review, methodology, technology analysis, applications, and

concluding insights into future advancements in smart energy systems.

#### Technologies Used in Footstep Power Generation

Footstep power generation systems combine multiple technologies to efficiently convert mechanical energy into electrical energy. The primary technology is based on the piezoelectric effect, discovered by Pierre Curie and Jacques Curie, where mechanical stress produces electrical charge. The behaviour of these materials is governed by the piezoelectric constitutive equations:

$$D = d.T + \epsilon^T.E$$

$$S = s^E.T + d^T.E$$

In addition to piezoelectric sensors, systems integrate energy harvesting techniques, power electronics (rectifiers, capacitors, regulators), and energy storage devices. Advanced implementations also include IoT-based monitoring for real-time performance tracking. Commercial solutions by Pavegen Systems demonstrate practical deployment in locations such as Shibuya Station.

## II. TECHNOLOGIES USED IN FOOTSTEP POWER GENERATION

Footstep power generation systems combine multiple technologies to efficiently convert mechanical energy into electrical energy. The primary technology is based on the piezoelectric effect, discovered by Pierre Curie and Jacques Curie, where mechanical stress produces electrical charge.

In addition to piezoelectric sensors, systems integrate energy harvesting techniques, power electronics (rectifiers, capacitors, regulators), and energy storage devices. Advanced implementations also include IoT-based monitoring for real-time performance tracking. Commercial solutions by Pavegen Systems demonstrate practical deployment in locations such as Shibuya Station.

**Table I: Comparison of Technologies**

Technology	Cost	Accuracy/Efficiency	Best Use Case	Key Feature
Piezoelectric	Medium	High sensitivity, moderate efficiency	Footstep tiles, smart floors	Converts pressure to electricity
Electromagnetic	High	High efficiency	Large motion systems	Uses coil-magnet induction
Electrostatic	Medium	Low to moderate	Micro-scale devices (MEMS)	Variable capacitance
Power Electronics	Low	High (Stable output)	All energy systems	AC to DC conversion
Energy Storage (Battery/Super capacitor)	Medium	High reliability	Energy backup systems	Stores generated energy

IoT Monitoring	Medium	High accuracy (real-time data)	Smart city systems	Data tracking & control
----------------	--------	--------------------------------	--------------------	-------------------------

Table I compares different technologies used in footstep power generation based on cost, efficiency, accuracy, and application. Piezoelectric technology, based on the work of Pierre Curie and Jacques Curie, is the most suitable due to its compact size and high sensitivity. Electromagnetic systems provide higher output but are bulky and costly. Power electronics and energy storage ensure stable and continuous operation, while IoT systems enhance monitoring and control. Practical implementations by Pavegen Systems, including installations at Shibuya Station, demonstrate real-world applicability.

**Table II: Comparative Piezoelectric Material Properties**

Material	$d_{33}$	$k_{33}$	Curie Temperature (°C)	Flexibility	Lead free
PZT-5A	374-600	0.70-0.75	350-365	Rigid	No
PVDF	20-30	0.12-0.14	-170	Flexible	Yes
BaTiO <sub>3</sub>	149-190	0.50-0.55	-120	Rigid	Yes

To select the appropriate sensor, Table II compares the technical properties of potential piezoelectric materials, such as PZT-5A, PVDF, and BaTiO<sub>3</sub>. By detailing critical engineering parameters—including the piezoelectric strain constant ( $d_{33}$ ), coupling factor ( $k_{33}$ ), and Curie temperature—this comparison provides the scientific justification for selecting a highly sensitive material like PZT-5A for the footstep energy harvesting tiles.

## III. Working Principle

The proposed system functions via piezoelectric transduction, wherein specific smart materials accumulate an electric charge directly proportional to the mechanical deformation applied. When a person steps on the platform, mechanical pressure is exerted on the piezoelectric sensors embedded beneath the surface. This pressure causes physical deformation, resulting in the generation of an alternating electrical signal (AC voltage).

Electrically, the piezoelectric element can be modelled as an AC current source connected in parallel with an internal sensor capacitance ( $C_{Piezo}$ ) and internal resistance ( $R_{Piezo}$ ). To utilize this generated AC output, it is passed through a full-wave bridge rectifier. For optimal efficiency in energy harvesting, low forward-voltage drop Schottky diodes are selected to minimize power loss during the AC-to-DC conversion process.

Following rectification, a filter capacitor is used to smooth the DC output voltage. The required capacitance is sized

based on the expected current and allowable voltage ripple using the formula:

$$C = \frac{I \cdot \Delta t}{\Delta V}$$

To ensure maximum power transfer from the piezoelectric sensors to the storage unit or load, the system's impedance must be matched. The optimal load resistance is determined by:

$$R_{load} = \frac{1}{2\pi f \cdot (C_{piezo})}$$

where f represents the frequency of the applied mechanical stress (footsteps).

The harvested energy is then stored in a battery or supercapacitor for later use. The total electrical energy stored per charge cycle is calculated by:

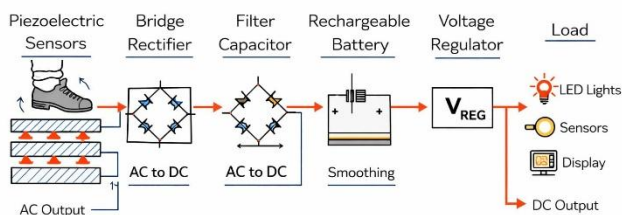
$$E = \frac{1}{2} CV^2$$

The stored energy can be utilized to power low-energy devices such as LEDs, sensors, or display systems. The overall mechanical-to-electrical efficiency of the system is determined by:

$$\eta = (P_{electrical} / P_{mechanical}) \times 100\%$$

The efficiency of the system increases with the number of sensors and the frequency of footsteps, making it highly suitable for high-footfall areas.

**Footstep Power Generation System**



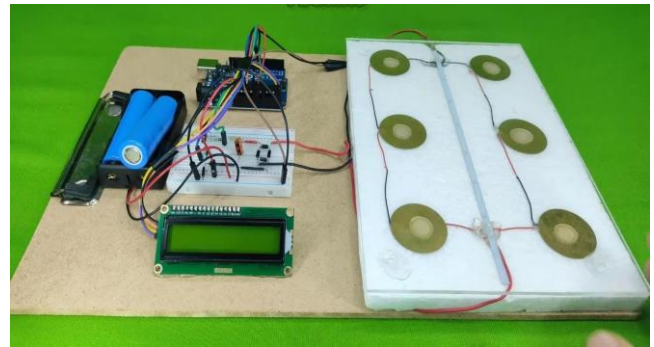
**Fig. I. Block diagram of Footstep Power Generation System**

#### IV. METHODOLOGY

The footstep power generation system employs piezoelectric sensors embedded beneath flooring tiles to convert mechanical energy from human footsteps into electrical energy. When a person steps on a tile, the sensors deform, producing an alternating current (AC) voltage, which is

converted to direct current (DC) using a bridge rectifier and smoothed with a capacitor. The energy is stored in rechargeable batteries or supercapacitors, and a voltage regulator ensures stable output suitable for low-energy devices such as LEDs, sensors, or digital displays.

**The experimental setup of the proposed system is shown in Fig. II.**



**Fig. II. Prototype Implementation of Footstep Power Generation System Using Piezoelectric Sensors**

The experimental setup of the proposed footstep power generation system is shown in Fig. II. The prototype consists of multiple piezoelectric sensors embedded beneath a platform to capture mechanical energy from human footsteps. These sensors are connected to an Arduino Uno microcontroller through a rectification and filtering circuit implemented on a breadboard. The generated electrical energy is stored in rechargeable batteries and monitored using an LCD display. This setup demonstrates real-time energy harvesting and visualization, validating the practical feasibility of the system.

**Table III : System Design Specification**

Parameter	Specification
Piezoelectric Material	PZT-5A
Number Of Sensors	10-12
Tile Dimension	1ft <sup>2</sup> (approx. 300x300mm)
Applied Force Range	~500-1000 N
Rectifier Type	Full-Wave Bridge
Storage Element	1000μF (Electrolytic Capacitor)
Regulated Voltage Output	3-5 V (experimental)
Cumulative Power Output	0.5-1 kWh/day
Overall Efficiency	15-20%
Load	5mm LED Arrays

Multiple sensors can be connected in series to increase voltage or in parallel to increase current, enabling scalability for high-footfall areas like railway stations, malls, and airports. IoT-based monitoring can track real-

time energy generation, optimize efficiency, and facilitate predictive maintenance. The system is designed to be durable, modular, and low-maintenance, allowing easy installation, replacement, or expansion. Additional important considerations include minimizing pedestrian discomfort, protecting sensors from environmental damage, and integrating energy management algorithms to maximize usable power. Real-world implementations, such as by Pavegen Systems and at Shibuya Station, validate the system's practical feasibility, reliability, and potential as a sustainable energy solution for smart city applications.

## V. RESULTS

To validate the methodology, the 12-sensor prototype was analysed under dynamic testing. The system generated an open-circuit voltage ranging from 3 V to 5 V and a peak power output of 15–25 mW under simulated pedestrian loads of approximately 700 N. By configuring the 12 PZT-5A sensors in a hybrid series-parallel arrangement, the array successfully balanced the required current density with a stable voltage threshold necessary for the LM7805 regulator. The performance of the system was evaluated across varying load resistances to identify the maximum power transfer point. As shown in Table IV, the peak power of approximately 18 mW per step was achieved when the load impedance matched the internal impedance of the piezoelectric array.

## VI. APPLICATIONS OF FOOTSTEP POWER GENERATION

Footstep power generation is a promising technology for supplementing renewable energy in urban and public environments. The energy harvested from human movement can be utilized in various practical applications:

**Public Infrastructure** – Installation of piezoelectric tiles in railway stations, airports, bus terminals, and metro stations can power LED lighting, display boards, or charging ports, reducing dependence on conventional electricity.

**Commercial Spaces** – shopping malls, exhibition centers, and office buildings can use footstep energy to power lights, digital signage, and sensor systems, turning high foot traffic into usable energy.

**Smart Cities** – Integration with IoT platforms enables monitoring of pedestrian traffic, crowd density, and energy generation in real time. This data helps in urban planning, energy management, and predictive maintenance.

**Sports & Recreational Areas** – Stadiums, gyms, and walkways can implement energy-harvesting floors to power LED displays, sensors, or small electronic devices.

**Educational Institutions** – Schools, colleges, and universities can utilize footstep-generated energy to power lights in corridors, labs, and common areas, promoting sustainable practices.

**Emergency Systems** – Footstep energy can act as a backup power source for critical low-energy devices during power outages in public places.

Overall, footstep energy generation is most effective in high-footfall areas, where continuous pedestrian movement can generate significant electricity for low-power applications, contributing to energy efficiency and sustainable urban development.

## VII. RECENT RESEARCH TRENDS IN ENERGY MANAGEMENT

Recent research in energy management focuses on improving efficiency, reliability, and integration of distributed energy sources within smart infrastructure. A major trend is the development of intelligent energy management systems (EMS) that use real-time data analytics and machine learning to optimize load distribution and storage utilization across heterogeneous energy sources, including renewable and harvested energy. In the context of footstep power generation, researchers are investigating hybrid systems that combine piezoelectric harvesting with solar, thermoelectric, or vibration-based methods to enhance total energy output and reliability in variable conditions. Advances in energy storage technologies, such as next-generation supercapacitors and solid-state batteries, are enabling better charge-discharge efficiency for intermittent sources like human-motion energy. Another active area is IoT-based energy monitoring and control, where sensor networks collect performance data and feed it into cloud-based management platforms for predictive maintenance, fault detection, and adaptive control of energy flow. Security and data privacy in energy management systems are also emerging as research priorities, especially in large urban deployments. These trends aim to make renewable and harvested energy systems smarter, more efficient, and seamlessly integrated into future energy networks and smart cities.

## VIII. FUTURE SCOPE OF FOOTSTEPS POWER GENERATION TECHNOLOGY

Footstep power generation technology has significant potential for future development in sustainable energy and smart city infrastructure. Advances in high-efficiency piezoelectric materials and nano-engineered sensors could increase energy output per step. Integration with IoT and smart grids will allow real-time monitoring, predictive maintenance, and better energy management in urban environments. Hybrid systems combining footstep energy with solar, vibration, or kinetic sources can improve overall reliability and supply. Expansion to large public spaces, airports, stadiums, and educational institutions can maximize energy capture from high footfall. The technology can also be adapted for wearable energy-harvesting devices, powering small electronics like smart watches and health sensors. Furthermore, standardization

and modular designs will enable scalable, cost-effective deployment globally, making footstep power generation an important supplementary renewable energy source for energy-efficient and sustainable smart cities.

## IX. CONCLUSION

Footstep power generation is a promising renewable energy technology that converts human mechanical energy into electrical energy using piezoelectric sensors. This system provides a sustainable and low-maintenance solution for powering low-energy devices, particularly in high-footfall areas such as railway stations, airports, shopping malls, and educational institutions. The integration of power electronics, energy storage devices, and voltage regulation ensures stable and usable output, while IoT-based monitoring allows real-time tracking, optimization, and predictive maintenance. Recent research trends emphasize hybrid energy harvesting, smart energy management systems, advanced storage solutions, and integration with smart city infrastructure to improve efficiency and reliability. Real-world implementations, including those by Pavegen Systems and at Shibuya Station, validate the feasibility, durability, and scalability of this technology. Future developments in high-efficiency piezoelectric materials, modular designs, and wearable energy-harvesting devices could further enhance energy output and broaden applications. Overall, footstep energy harvesting represents a viable, sustainable, and innovative approach to supplement urban energy needs and contribute to smart, energy-efficient cities.

## X. REFERENCES

- [1] S. Priya and D. J. Inman, *Energy Harvesting Technologies*, 1st ed., New York, NY, USA: Springer, 2009.
- [2] C. Dagdeviren, Z. L. Wang, "Energy Harvesting — A Review," *IEEE Trans. on Industrial Electronics*, vol. 61, no. 3, pp. 1148–1157, Mar. 2014.
- [3] Q. Dong and L. Cheng, "Piezoelectric Energy Harvesting From Human Motion," *IEEE Sensors Journal*, vol. 18, no. 23, pp. 9539–9549, Dec. 2018.
- [4] A. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," *Computer Communications*, vol. 26, no. 11, pp. 1131–1144, July 2003.
- [5] P. Tiwari and A. Kumar, "Power Generation Using Footstep Energy Harvesting," *International Journal of Renewable Energy Research*, vol. 12, no. 4, pp. 900–910, 2022.
- [6] V. Jeevan Kumar, S. N. Mishra, and R. K. Singh, "Footstep Based Power Generation: Design and Implementation," *International Journal of Engineering and Science Research*, vol. 15, no. 2, pp. 45–49, Feb. 2025.
- [7] K. R. H. Rao and B. N. Kumar, "Piezoelectric Footstep Power Generation Using Multiple Sensor Array," *International Journal of Recent Advances in Multidisciplinary Topics*, vol. 9, no. 4, pp. 123–130, 2024.
- [8] M. Haroon et al., "Footsteps Power Generation Using Piezoelectric Energy Harvester," *Sustainable Energy Systems Journal*, vol. 7, no. 1, pp. 78–85, Jan. 2025.
- [9] Y. Zhou and X. Zhang, "Hybrid Energy Harvesting Systems: A Review," *IEEE Transactions on Power Electronics*, vol. 35, no. 9, pp. 9582–9599, Sept. 2020.
- [10] J. Lee, J. Kim, and S. Lee, "IoT-Enabled Smart Energy Management for Distributed Renewable Systems," *IEEE Internet of Things Journal*, vol. 8, no. 14, pp. 11438–11449, July 2021.
- [11] L. M. Ramos et al., "Advanced Energy Storage for Hybrid Harvesting Applications," *IEEE Access*, vol. 9, pp. 98765–98778, Nov. 2021.
- [12] P. K. Sharma and R. Gupta, "Urban Energy Harvesting Using Piezoelectric Flooring," *International Journal of Smart Infrastructure Systems*, vol. 3, no. 2, pp. 115–123, 2023.
- [13] "Footstep Energy Harvesting Technology at Metropolitan Stations," Technical Report, Japan Renewable Energy Association, 2026.
- [14] "Piezoelectric Floor Energy Generation — Case Study: Shibuya Station," *Energy Insights Journal*, vol. 14, no. 6, pp. 68–75, 2025.