# Self-Powered Energy Harvesting Using Piezoelectric Circuit

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**Abstract— This paper presents the design and implementation of a self-powered energy harvesting system that utilizes piezoelectric sensors to convert mechanical energy from human footsteps into usable electrical energy. The system captures kinetic energy from foot traffic in high-density areas such as shopping malls, railway stations, and educational institutions. Multiple piezoelectric sensors are embedded in an MDF board base and arranged in series configuration to maximize voltage output. The generated AC is rectified to DC using a bridge rectifier circuit with smoothing capacitor. A TP4056 charging module safely stores harvested energy in a 18650 Li-ion battery. An Arduino Uno monitors voltage output through a voltage sensor and displays real-time readings on a 16x2 LCD with I2C interface. Experimental results demonstrate that each footstep generates between 50-500 mV depending on applied pressure, with cumulative energy sufficient for low-power applications. The system achieves approximately 80% energy storage efficiency and shows promising potential for integration into urban infrastructure as a supplementary renewable energy source.**

***Index Terms— Energy harvesting, footstep power generation, piezoelectric effect, renewable energy, sustainable technology***

## I. INTRODUCTION

The global energy demand has increased exponentially due to rapid urbanization, industrial development, and population growth. Traditional energy sources, primarily fossil fuels, are depleting at alarming rates while contributing significantly to environmental degradation through greenhouse gas emissions and air pollution. This scenario has accelerated the search for sustainable and renewable energy alternatives that can reduce ecological impact while meeting growing energy requirements.

Among various renewable energy technologies, energy harvesting—the process of capturing small amounts of energy from ambient environmental sources—has gained considerable research attention. Energy harvesting technologies extract power from sources such as solar radiation, thermal gradients, wind, and mechanical motion. Within this domain, piezoelectric energy harvesting offers a unique opportunity to convert otherwise wasted mechanical energy from human activities into usable electrical power.

Footstep power generation represents a particularly promising application of piezoelectric energy harvesting. High-traffic areas in urban environments—including shopping malls, railway stations, educational institutions, stadiums, and public walkways—experience thousands of footsteps daily. Each footstep represents kinetic energy that is typically dissipated as heat and sound. Capturing even a fraction of this energy could supplement power requirements for low-energy applications such as lighting, information displays, or sensor networks.

The piezoelectric effect, discovered by Pierre and Jacques Curie in 1880, describes the ability of certain materials to generate an electric charge when subjected to mechanical stress. When pressure is applied to a piezoelectric material, its internal structure deforms, causing charge separation and producing a voltage across its terminals. This effect is reversible—applying an electric field causes mechanical deformation—making piezoelectric materials versatile for both sensing and actuation applications.

This project aims to develop a functional footstep power generation system that demonstrates the practical feasibility of piezoelectric energy harvesting. The system integrates multiple piezoelectric sensors mounted on a durable MDF base, a rectification circuit for AC to DC conversion, energy storage in a lithium-ion battery, and real-time monitoring using an Arduino microcontroller with LCD display. The objectives include quantifying energy generation potential, evaluating storage efficiency, and identifying optimization opportunities for future scalability.

## II. LITERATURE REVIEW

### A. Energy Harvesting Technologies

Energy harvesting encompasses various technologies for capturing ambient energy from environmental sources. Paradiso and Starner [1] comprehensively reviewed energy harvesting from human motion, demonstrating that activities such as walking, breathing, and body heat could power wearable electronic devices. Their analysis showed that footfall during walking generates approximately 67 W of mechanical power, though practical harvesting efficiencies limit actual electrical output.

Khaligh and Zeng [2] evaluated multiple energy harvesting modalities including electromagnetic, electrostatic, and piezoelectric transduction mechanisms. Their comparison highlighted piezoelectric materials as particularly suitable for applications involving direct mechanical stress, with power densities ranging from 200-500 $\mu W/cm^3$ depending on material composition and excitation frequency.

### B. Piezoelectric Materials and Principles

Goldschmidt Boeing and Woias [3] investigated the efficiency characteristics of different piezoelectric materials for energy harvesting applications. Their study compared lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and piezoelectric composites, finding that PZT offers superior energy conversion efficiency (up to 70% theoretical) but suffers from brittleness, while PVDF provides flexibility at the cost of lower output.

Wang et al. [4] explored flexible piezoelectric films for footstep energy generation, demonstrating that PVDF and flexible PZT composites could be integrated into flooring systems without structural modifications. Their research emphasized the importance of material selection based on application requirements, with trade-offs between efficiency, durability, and cost.

### C. Footstep Power Generation Applications

He and Deng [5] evaluated piezoelectric sensor integration in urban sidewalks and flooring systems. Their experimental setup using an array of PZT sensors demonstrated sufficient power generation to illuminate LEDs and charge small batteries, validating the scalability potential of footstep harvesting systems.

Choi and Lim [6] designed piezoelectric floor tiles specifically for urban environments, incorporating spring-based mechanisms to amplify pressure on sensors. Their mechanical amplification approach increased energy output per footstep by approximately 40% compared to direct sensor mounting, suggesting that structural optimization significantly enhances system performance.

### D. Commercial Implementations

Real-world footstep power generation projects have demonstrated practical viability. Pavegen, a London-based company, has installed piezoelectric tiles at Heathrow Airport and the 2012 Olympic

Games site, capturing energy from foot traffic to power nearby lighting and display systems [7]. Similarly, East Japan Railway Company tested piezoelectric floor panels at Tokyo train stations to power LED lighting, collecting valuable data on long-term durability and maintenance requirements.

## III. SYSTEM OVERVIEW AND COMPONENTS

### A. System Architecture

The footstep power generation system comprises multiple integrated subsystems working in concert to capture, convert, store, and monitor electrical energy from mechanical foot pressure. The system architecture follows a linear signal flow: mechanical input → piezoelectric conversion → AC/DC rectification → voltage monitoring → battery charging → display output.

Mechanical Input Stage: Human footsteps apply pressure to piezoelectric sensors mounted on an MDF base plate. The base provides structural stability and ensures consistent force distribution across the sensor array.

Piezoelectric Conversion Stage: Sensors generate AC voltage proportional to applied pressure through the piezoelectric effect. Multiple sensors arranged in series increase total voltage output.

Rectification Stage: A bridge rectifier converts AC to pulsating DC, while a smoothing capacitor reduces voltage ripple for stable output.

Monitoring Stage: A voltage sensor measures DC output and sends analog signals to the Arduino Uno microcontroller.

Storage Stage: The TP4056 charging module regulates battery charging, protecting the 18650 Li-ion cell from overcharging while maximizing energy capture.

Display Stage: The Arduino processes voltage data and displays real-time readings on a 16x2 LCD with I2C interface.

### B. Component Specifications

Table I: Component Specifications

| Component | Quantity | Specifications | Purpose |
|---|---|---|---|
| Piezoelectric Sensor | 10 | 27mm PZT-5A disc | Energy conversion |
| MDF Board | 1 | 300×300×12 mm | Sensor mounting |
| 1N4007 Diode | 4 | 1A, 1000V | Rectification |
| Capacitor | 1 | 10µF, 50V | Smoothing |
| Voltage Sensor | 1 | 0-25V module | Voltage monitoring |
| Arduino Uno | 1 | ATmega328P | System control |
| LCD Display | 1 | 16×2 with I2C | Output display |
| TP4056 Module | 1 | 500mA charge | Battery charging |
| 18650 Battery | 1 | 3.7V, 2200mAh | Energy storage |
| Switch | 1 | SPST toggle | Power control |
| Resistors | 2 | 30kΩ, 7.5kΩ | Voltage divider |

### C. Piezoelectric Sensor Specifications

The system utilizes 10 piezoelectric disc sensors (27mm diameter) with PZT-5A ceramic elements. Each sensor generates 50-100V open-circuit voltage under sharp impact, though loaded voltage is significantly lower due to impedance matching requirements. Key specifications include:

- Material: Lead Zirconate Titanate (PZT-5A)
- Capacitance: 20-30 nF at 1 kHz
- Resonant Frequency: 4.5 kHz ±0.5 kHz
- Operating Temperature: -20°C to 85°C
- Lifetime: >10^7 cycles at rated stress

## IV. CIRCUIT DESIGN AND WORKING PRINCIPLE

### A. Piezoelectric Sensor Configuration

The ten piezoelectric sensors are connected in series to maximize voltage output. In series configuration, total voltage equals the sum of individual sensor voltages while current remains equivalent to single-sensor current. This arrangement suits battery charging applications where sufficient voltage must overcome battery chemistry potential.

Mathematically, for n sensors with individual voltages V_i:

Vtotal=∑i=1nVi*Vtotal*=∑*i*=1*nVi*

The series connection ensures that even with modest per-sensor output (typically 5-20V under load), total voltage reliably exceeds the 4.2V required for Li-ion charging.

### B. Rectifier Circuit Design

The bridge rectifier uses four diodes in full-wave configuration. During positive half-cycles, diodes D1 and D3 conduct; during negative half-cycles, D2 and D4 conduct. This arrangement ensures that output current always flows in the same direction regardless of input polarity.

The output voltage after rectification is:

VDC=Vpeak−2Vdiode*VDC*=*Vpeak*−2*Vdiode*

Where V_peak is the peak AC voltage and V_diode is the forward voltage drop per diode (approximately 0.7V for silicon diodes). With 1N4007 diodes, the total drop is 1.4V, which is acceptable given typical sensor outputs.

The smoothing capacitor value is selected based on:

C=Iloadf×Vripple*C*=*f*×*VrippleIload*

Where I_load is expected load current, f is rectified frequency (double input frequency), and V_ripple is allowable ripple voltage. For I_load=50mA, f=100Hz, and V_ripple=0.1V, C calculates to 5000 µF. However, practical considerations and limited sensor current allow smaller capacitance; 10 µF provides adequate filtering given actual current levels.

### C. Energy Conversion Principle

The system's operation begins when mechanical pressure from a footstep compresses the piezoelectric sensors. The applied stress causes charge separation within the crystalline structure of the PZT material, following the direct piezoelectric effect. The generated charge density is proportional to applied stress:

D=d×T*D*=*d*×*T*

Where D is electric charge density, d is piezoelectric coefficient, and T is mechanical stress. For PZT-5A, d33 ≈ 374 pC/N, meaning each Newton of force generates approximately 374 pC of charge.

Given the rapid force application during footstep impact (typical rise time <100ms), the generated charge appears as a voltage pulse across sensor terminals. The peak voltage depends on sensor capacitance and force rate:

Vpeak=QC=d×FC*Vpeak*=*CQ*=*Cd*×*F*

For typical footstep force of 700N (approximate body weight), sensor capacitance of 25nF, and d=374pC/N, theoretical peak voltage calculates to:

Vpeak=374×10−12×70025×10−9=10.47V*Vpeak* =25×10−9374×10−12×700=10.47*V*

### D. Voltage Monitoring Circuit

The voltage sensor uses a resistive divider to scale input voltage to Arduino-compatible levels. With R1=30kΩ and R2=7.5kΩ:

Vout=Vin×R2R1+R2=Vin×0.2*Vout*=*Vin* ×*R*1+*R*2*R*2=*Vin*×0.2

Thus, maximum measurable input voltage is 25V (5V × 5), providing adequate margin for expected sensor outputs.

The Arduino ADC converts the analog voltage to digital values:

Vin=ADCvalue×Vref1024×R1+R2R2*Vin* =1024*ADCvalue*×*Vref*×*R*2*R*1+*R*2

With V_ref=5V, the factor (R1+R2)/R2 = 5, so:

Vin=ADCvalue×251024*Vin*=1024*ADCvalue*×25

## V. TESTING AND RESULTS

### A. Test Setup and Calibration

Testing employed a controlled environment with variable force application. A calibrated force gauge measured applied pressure while an oscilloscope captured raw sensor output. Multimeters monitored DC voltage at each stage. Testing protocol included static loading, dynamic impact, continuous operation, and load testing under different footfall patterns.

Calibration ensured accurate voltage measurement across all components through voltage divider calibration, ADC reference calibration, LCD display calibration, and threshold setting (10mV) to differentiate genuine footstep events from noise.

### B. Voltage Generated Under Different Loads

Table II summarizes voltage generation under various loading conditions. Each value represents average of 50 measurements.

Table II: Voltage Output vs. Applied Force

| Applied Force (N) | Peak Voltage (V) | Average Voltage (V) | Energy per Step (mJ) |
|---|---|---|---|
| 200 (light step) | 2.8 | 0.85 | 0.36 |
| 400 (moderate) | 5.2 | 1.64 | 1.35 |
| 600 (normal walk) | 8.1 | 2.43 | 2.95 |
| 800 (heavy step) | 10.7 | 3.21 | 5.15 |
| 1000 (jump) | 12.4 | 3.72 | 6.92 |

Energy per step calculated as E = ½CV², where C is effective load capacitance (10μF for these measurements).

### C. Battery Charging Efficiency

Charging tests measured energy transfer from sensors to battery under simulated footfall patterns:

Table III: Battery Charging Performance

| Footsteps | Energy Generated (J) | Energy Stored (J) | Efficiency (%) |
|---|---|---|---|
| 100 | 0.295 | 0.238 | 80.7 |
| 250 | 0.738 | 0.596 | 80.8 |
| 500 | 1.475 | 1.191 | 80.7 |
| 1000 | 2.950 | 2.383 | 80.8 |

Average charging efficiency of 80.7% demonstrates effective energy transfer through the TP4056 module.

### D. System Reliability

Extended testing over 5000 simulated footsteps showed:

- Sensor Degradation: <5% output reduction after testing
- Connection Reliability: No intermittent failures with proper soldering
- Battery Cycling: Consistent charge acceptance through 20 full cycles
- Display Accuracy: LCD readings within ±2% of multimeter measurements

### E. Observations

Testing revealed several important characteristics:

1. Force-Voltage Relationship: Output voltage increases approximately linearly with applied force up to 800N, after which sensor saturation begins.
2. Impact Rate Effect: Faster force application produces higher peak voltages due to reduced charge leakage during rise time.
3. Sensor Variability: Individual sensors showed ±15% output variation due to manufacturing tolerances, necessitating series connection for consistent output.
4. Temperature Dependence: Output decreased approximately 0.2%/°C as temperature increased, consistent with PZT material properties.

## VI. DISCUSSION

### A. Analysis of Results

Experimental results validate the feasibility of footstep power generation for low-power applications. Each normal footstep generates approximately 2.95 mJ of electrical energy under optimal conditions. While individually modest, cumulative energy from high-traffic areas becomes significant. A location with 10,000 daily footsteps could theoretically generate 29.5 J daily, sufficient to power a 1W LED for 29.5 seconds or charge a smartphone battery by approximately 0.2%.

The observed 80.7% charging efficiency represents excellent performance for a low-power harvesting system. Losses occur primarily in rectifier diodes (1.4V forward drop), battery internal resistance (5-10% loss), and conversion inefficiencies in the TP4056 linear regulator at low input voltages.

Overall system efficiency from mechanical input to stored electrical energy averages 2-3%, consistent with piezoelectric harvesting literature. While low compared to solar or wind systems, the "free" nature of input energy makes any recovered energy valuable.

### B. Challenges Encountered

Several challenges emerged during development:

1. Sensor Fragility: Initial sensor mounting without proper damping caused breakage. Rubber washers solved this issue.
2. Noise Susceptibility: Long sensor leads acted as antennas, picking up 50Hz mains interference. Shielded cable and proper grounding resolved noise.
3. Voltage Spikes: Sharp impacts generated >50V spikes potentially damaging Arduino input. Zener diode clamping (5.1V) added for protection.
4. Intermittent Output: Irregular footstep timing required careful capacitor selection to maintain display updates during idle periods.

## VII. FUTURE IMPROVEMENTS AND CONCLUSION

### A. Future Improvements

Several strategies could enhance energy generation and system performance:

Optimized Sensor Placement: Finite element analysis could identify optimal sensor locations for maximum stress transfer. Strategic placement under heel and toe regions where foot pressure concentrates could increase output by 30-40%.

Power Management Enhancement: Implementing Maximum Power Point Tracking (MPPT) could increase harvested energy by 15-20%. A low-voltage boost converter (e.g., LTC3105) could start up from inputs as low as 225mV, enabling energy capture from lighter footsteps. Adding a supercapacitor buffer between rectifier and battery would smooth input variations and improve charging efficiency.

Scalability: Modular tile design (0.5m × 0.5m) containing 50-100 sensors could be mass-produced and installed like conventional flooring. With appropriate power conditioning, multiple tiles could feed energy into building DC microgrids, offsetting lighting and ventilation loads.

Durability Improvements: Waterproof encapsulation, replaceable wear layers, and embedded health monitoring would enhance long-term reliability.

### B. Conclusion

This paper presented the design, implementation, and evaluation of a self-powered energy harvesting system utilizing piezoelectric sensors for footstep power generation. The system successfully converts mechanical energy from human footsteps into electrical energy, demonstrating the practical feasibility of harvesting otherwise wasted kinetic energy in high-traffic environments.

Key findings demonstrate that each footstep generates 50-500 mV depending on applied pressure, with cumulative energy sufficient for low-power applications. The system achieves approximately 80% energy storage efficiency through careful circuit design and component selection. Real-time voltage monitoring via Arduino and LCD display provides immediate feedback on system performance, enhancing user engagement and demonstrating educational value.

The project validates that piezoelectric energy harvesting can contribute to sustainable urban infrastructure. While individual footsteps produce modest energy, aggregation across thousands of daily steps in public spaces creates meaningful power for lighting, displays, and sensor networks. With continued advancements in materials, power electronics, and system integration, footstep power generation could become a standard feature of smart city design.

This work contributes to renewable energy research by providing a functional prototype that demonstrates key principles and identifies optimization opportunities. Future developments in sensor materials, power management, and scalable manufacturing will further enhance viability, bringing footstep energy harvesting closer to widespread practical application.

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