# Piezoelectric Energy Harvesting in Pedestrian walkaways: Design, Prototyping, and Feasibility Assessment for Lighting Applications

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## Abstract

Palestine's strong reliance on imported electricity, along with the small percentage of locally produced renewable energy, creates ongoing challenges for public institutions, especially universities with continuous lighting demands. Pedestrian walkways experience high human movement, which results in wasted mechanical energy. In order to support energy-efficient lighting applications, this research evaluates the feasibility of using piezoelectric technology to harvest pedestrian footstep energy.

A laboratory-scale prototype was developed using piezoelectric elements, rectification circuitry, capacitive energy storage, and an Arduino-based control system. Additionally, light-dependent resistors (LDRs) were integrated to reduce unnecessary energy use by enabling lighting only when ambient light is insufficient and harvested energy is available. Experimental observations confirmed voltage generation under mechanical loading and demonstrated progressive energy accumulation in the storage element. A feasibility study was conducted on a high-pedestrian-density street at Birzeit University to assess the potential contribution of harvested energy to building lighting. The results show that the proposed system can generate usable electrical energy and support controlled lighting operation, indicating that piezoelectric harvesting can function as a localized supplementary energy source within smart lighting applications.

## Introduction

Palestine's electricity sector continues to face structural difficulties due to its heavy reliance on imported electricity and the small amount of locally produced renewable energy. According to the Palestinian Energy and Natural Resources Authority, over 85–90% of Palestine's electricity is imported, with renewable energy making up a very small portion of the country's overall electricity supply. This reliance puts public institutions under financial strain, especially universities that depend on constant lighting.

University campuses have pedestrian corridors and streets with heavy daily foot traffic. However, the mechanical energy produced by human movement is completely wasted. While Palestine has seen an increase in solar energy projects, there is still a lack of research focused on small-scale and site-specific energy harvesting solutions appropriate for institutional and dense urban settings. In addition, academic buildings' lighting systems frequently run inefficiently, continuing to function even when areas are empty or adequately lit by natural light.

This research examines the feasibility of implementing piezoelectric energy harvesting as an additional energy source for energy-efficient lighting at Birzeit University. It also assesses the potential contribution of harvested energy to corridor lighting in university buildings using motion- and light-aware control strategies by combining experimental prototype validation with field measurements from a high-pedestrian-density street close to the Faculty of Arts. The goal is to determine whether, given practical operational limitations, such a system can effectively support smart lighting applications.

# I. Theoretical Background

Piezoelectric energy harvesting is based on the piezoelectric effect, which is the ability of certain materials to generate an electrical signal when mechanical force is applied to them. When a person walks over a piezoelectric element, the applied pressure causes a small mechanical deformation, which results in the generation of electrical charge.

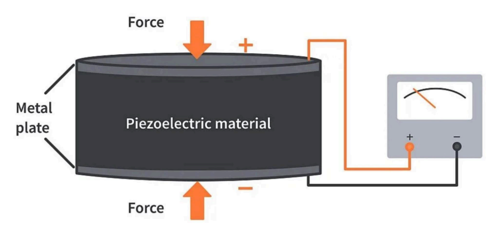


Figure 1. Principle of direct Piezoelectric effect

The relationship between mechanical stress and electrical output can be expressed using the direct piezoelectric equation:

$$D = d \, . \, \sigma$$

where

D represents the electric displacement (C/m²),

d is the piezoelectric coefficient (C/N), and

σ is the applied mechanical stress (N/m²).

This equation shows that the electrical response depends on both the applied force and the material properties of the piezoelectric element.

In practical energy harvesting applications, PZT (lead zirconate titanate) is commonly used because it produces relatively high electrical output, is mechanically stable, and can withstand repeated loading, making it suitable for pedestrian walkways and flooring systems.

The electrical output generated by piezoelectric elements is alternating and irregular, so it must be processed before use. After rectification, the harvested energy is typically stored in a capacitor. The energy stored in a capacitor is given by:

$$E = \frac{1}{2} \, C \, V^2$$

where

E is the stored energy (J),

C is the capacitance (F), and

V is the voltage across the capacitor (V).

This equation is used to estimate how much usable energy can be accumulated from repeated footsteps over time, forming the basis for evaluating the feasibility of piezoelectric energy harvesting in lighting applications.

# II. Methodology

### A. technical implementation and proof of concept

#### Proof-of-Concept Objectives

The technical phase of this research aimed to validate the feasibility of harvesting electrical energy from pedestrian-induced mechanical stress using piezoelectric elements and to demonstrate the practical integration of energy harvesting, storage, sensing, and control within a single low-power system.

Rather than maximizing power output at this stage, the objective was to: Verify electrical generation from piezoelectric elements, and Observe the effects of electrical configuration and conditioning,

#### Piezoelectric Element Configuration

The proof-of-concept prototype began with four piezoelectric discs arranged in series–parallel configurations. This arrangement was selected to balance: output voltage (enhanced through series connections), and output current (enhanced through parallel connections).

Mechanical pressure was applied manually to simulate pedestrian footsteps. Initial measurements confirmed that pressing the piezoelectric elements generated alternating electrical signals (AC) characterized by short voltage spikes corresponding to applied force.

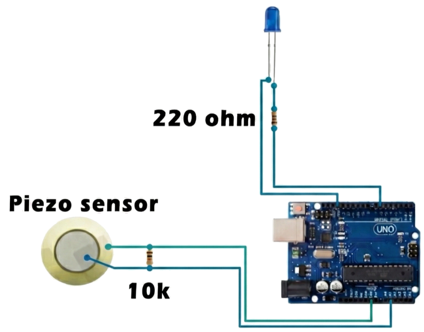


Figure 2.. Arduino-based piezoelectric energy harvesting and LED indication circuit

**Direct Load Connection and AC Limitation**

In the initial configuration, the piezoelectric array was directly connected to an Arduino microcontroller, and a light-emitting diode (LED) as a visual indicator.

When pressure was applied to the piezoelectric elements, the LED briefly illuminated. However, the emitted light intensity was extremely weak and unstable. This behavior is attributed to: the alternating nature of the generated voltage (AC), along with the short duration of voltage spikes, and the lack of energy storage or rectification.

This stage demonstrated that direct utilization of raw piezoelectric output is insufficient for powering electronic loads in a stable manner.

**AC–DC Conversion Using a Bridge Rectifier**

To address the limitations of alternating output, a full-wave bridge rectifier composed of discrete diodes was introduced. The rectifier converts the bidirectional AC signal produced by the piezoelectric elements into a unidirectional DC signal, allowing energy from both halves of the mechanical excitation cycle to be utilized.

Following rectification, the output voltage exhibited: Increased stability, Reduced polarity reversal, Improved suitability for charging storage elements.

**Energy Storage Using a Capacitor**

A capacitor was then added at the output of the rectifier to enable temporary energy storage. The capacitor accumulates charge during successive mechanical excitations, effectively smoothing voltage fluctuations and increasing the available energy over time.

The voltage across the capacitor terminals was monitored and displayed using an LCD screen connected to the Arduino. Experimental observations showed that:

Each applied pressure caused a measurable voltage increase,

Repeated pressing resulted in gradual capacitor charging,

The voltage decayed slowly when no further pressure was applied, indicating stored energy release.

This stage validated the energy accumulation capability of the system.

**Integration of the Sensor-Based Control Logic**

To demonstrate intelligent energy usage, the harvested and stored energy was integrated with a sensor-based lighting control subsystem. This subsystem consisted of:

1. A Light Dependent Resistor (LDR) for ambient light detection,

2. An LED representing a lighting load,

3. A current-limiting resistor to safely control LED power consumption.

The control logic implemented on the Arduino ensured that:

The LED activates only when sufficient voltage is present at the capacitor, and

Ambient light levels are below a predefined threshold (dark conditions).

This logic mimics a real-world smart lighting scenario, where energy is utilized only when both supply and demand conditions are met.

**Microcontroller Integration and System Monitoring**

All system components including the piezoelectric array, rectifier, capacitor, sensors, LED, and LCD were interfaced with an Arduino microcontroller. The Arduino served as: a monitoring unit for capacitor voltage, a decision-making unit implementing the sensor logic, and a visualization platform through the LCD display.

### B. Economic and Energy Feasibility Analysis

After the prototype development phase, a campus-level design scenario is presented to assess the applicability of the suggested piezoelectric energy harvesting system in an actual academic setting. A representative pedestrian area at Birzeit university is chosen as a case study to illustrate system deployment and energy generation potential.

#### 1. Selection of Piezoelectric Tile Technology

In order to choose the piezoelectric technology, a comparative evaluation of available options was conducted, and the chosen technology was : Sustainable Energy Floor (SEF), due to:

- Ability to cover continuous floors making it suitable for long walkaways like the ones in the chosen site in birzeit university unlike other discrete piezoelectric elements (ex: drum harvesters, piezo buzzers).
- Mechanical robustness and flexibility, resistance to repeated loading cycles, and low brittleness compared to PZT ceramics.
- Simple and inexpensive manufacturing
- Generates sufficient energy for low-power loads, especially for lighting applications and sensors
- Compatible for **Levelized cost of Energy (LCOE)** calculations, since they have defined unit cost per square meter, known lifetime, degradation behavior that can be predicted.

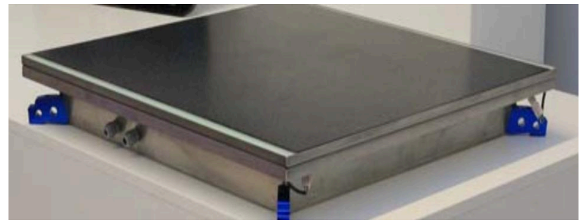

Figure 3.. SEF piezoelectric flooring structure

**Product dimension=** 75 * 75 cm

**Generated energy =** Typical power output for continuous stepping by a person lies between 1 and 10W nominal output per module (average 7W)

**Tile's Price (ILS) :** approximately 1020 shekels

**Estimated LifeSpan by years =** 15 years

#### 2. Case Study Area definition (Faculty of Arts street)

Birzeit university's faculty of Arts street has been chosen as the case study location. One of the busiest pedestrian streets on campus, this street links several academic buildings and acts as a main route for students and staff to move around, which is why it is known among university students for its high pedestrian density during academic hours. Thereby, making it a suitable choice for the insertion and evaluation of piezoelectric tiles energy generation.

The length and width of the street were measured using the palestinian Geographic information system (GeoMOLG) online measurement tool.

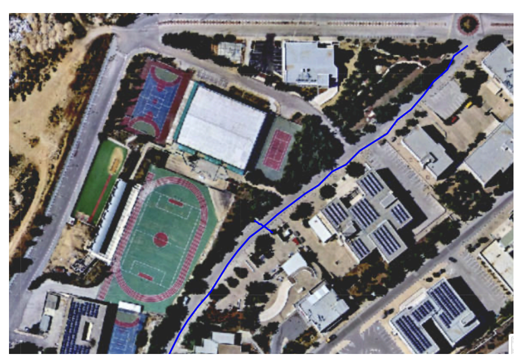

Figure 4.Faculty of Arts Street at Birzeit University, captured using the GeoMOLG

**Street's length (L)** *approximately = 390 m*

**Street's width (W)** *approximately = 12m*

**Total usable street area =** *L * W = 4680 (squared meters)*

3. **Tiles coverage and number of tiles**

**SEF tile area** *= 0.75 * 0.75 = 0.5625 (squared meters)*

**Number of tiles required =** *street area / tile area*

*= 4680/0.5625*

*= 8320 tiles*

4. **capital cost calculation**

**Tile procurement cost =** *number of tiles * cost/tile*

*= 8320 *1020 = 8486400 ILS*

***5. Time required to walk along the street***

According to typical walking speeds reported in pedestrian dynamics studies for adults. **The average pedestrian walking speed =** 1.4 m/s

The effective mechanical excitation time per pedestrian passage is defined as the **time required to walk along the full length of the piezoelectric floor:**

***T = street's length/ average speed***

*= 390/1.4*

*= 279 sec*

This time represents the period while the piezoelectric tiles are being subjected to dynamic loading by a pedestrian.

**6. Electrical energy generated per pedestrian passage**

According to the manufacturer specifications of SEF-type piezoelectric floor tiles, the **system produces a nominal electrical outpu**t of 7 W during stepping.

Electrical energy generated per pedestrian passage is (E pass ):

***E (pass) = P * t***

*= 7 * 279*

*= 1953 J*

Converting to Watts/hour:

*E (pass) = 1953 / 3600*

*= 0.54 Wh*

**7. Daily harvested energy**

The total energy harvested by the system is obtained by multiplying the energy per passage by the total number of pedestrian passages:

Based on campus movement observations provided by the project team, **the effective number of daily passages was taken as** : 6500 passes/day

***E (daily) = (number of people) * E (pass)***

*= 6500 * 0.54*

*= 3.51 kWh / day*

**8. Annual harvested energy**

Assuming continuous campus operation throughout the year, **the annual energy generation is:**

**E (annual) = 365 * E(daily)**

= 365 * 3.51

= 1.281 kWh / year

**9. Estimation of energy savings from the sensor-based lighting system**

The suggested system incorporates sensor-based lighting control in addition to energy harvesting to lower electricity usage in academic buildings close to Faculty of Arts Street, like the engineering building.. This contribution is regarded as an energy-saving mechanism, independent of piezoelectric energy generation.

**Description of the lighting control strategy :**

The lighting control system uses a Light Dependent Resistors (LDRs) for ambient light sensing, then it regulates the artificial lighting accordingly. This means, lighting fixtures are automatically switched off when there is enough natural light.

Assuming that the **number of controlled lighting fixtures** in the engineering building is approximately 30.

**Rate of power per fixture** = 30 Watts

Since these LED luminaires balance energy efficiency and illumination level, they are frequently used in academic buildings and hallways. This value is in line with common indoor lighting practices and is frequently used in campus lighting retrofits.

In the absence of sensor based control, lighting fixtures are expected to stay on throughout the academic day (from 8:00 am to 5: 00 pm) **so the Baseline daily operating hours without sensors (H)** = 9 hours

**Baseline annual lighting energy consumption (E baseline) :**

***E (baseline)*** *= Number of lighting fixtures * Power per fixture * operating hours * 365*

*= 30 * 30 * 9* 365*

*= 2956.5 KWh/ year*

For this study, we used a conservative 30% **lighting energy reduction factor**. This value matches a Lawrence Berkeley National Laboratory meta-analysis that found measured energy savings 28-48% for daylight-responsive control in commercial and institutional buildings. Our system uses ambient light sensing, so an intermediate percentage of 30% reduction factor is realistic and well-supported.

**Annual energy savings due to sensor based control (E saved) :**

***E (saved) = energy reduction factor * E (baseline)***

*= 0.3 * 3285*

*= 886.95 KWh / year*

Assumption for **electricity tariff (C)** according to the mean electricity tariff value for institutional consumers in palestine.

**Annual monetary savings from lighting control**

***S (lighting) = E (saved) * C***

*=886.95* 0.55*

*= 487.8225 ILS / year*

*Approximately 488 ILS / year*

**Annual monetary savings from piezoelectric energy generation**

***S (piezo) = E (piezo) * C***

*= 1281 * 0.55*

*= 705 ILS / year*

**10. Economic feasibility and LCOE framework**

**a. annual energy contribution of the system**

The total annual energy benefit combines: Piezoelectric energy generation, and energy savings from sensor-based lighting control**.**

*E (total annually) = E (piezo) + E(saved)*

*= 1281 + 886.95*

*= 2167.95 KWh / year*

**b. Capital cost of the system**

Number of tiles = 8320

Cost per tile = 1020 ILS

Cost of tiles = 8320 * 1020 = 8486400 ILS

**C. electronics and installation cost**

In large scale floor-integrated systems, power electronics, sensors, wiring, and installation typically represent 10% - 20% of the primary hardware costs .

A value of 15% is selected as a conservative mid-range estimate .

**Total installation cost = capital cost + installation cost**

*= 8486400 + 1273000*

*= 9759400 ILS*

**D. system lifetime assumptions**

The PVDF-based flooring systems are designed for high-cycle loading and public-space durability. Infrastructure-scale installations support a 15-year service life that is consistent with conservative lifetime assumptions in energy system feasibility studies.

**E. assumption for maintenance cost**

A 2-4 % annual maintenance rate is standard for mechanically integrated energy systems, so selecting 3% value is good enough for balancing needed routine inspections, sensor placement, and probable minor repairs.

***C maintenance = 3% of C installation annually***

*= 3% * 9759400*

*= 292782 ILS*

**F. Lifetime energy benefit**

***E (life time) = E (total) * T***

*= 2266.5 * 15*

*= 32519.25 KWh*

**G. levelized cost of energy**

$$LCOE = \frac{C\ install + C\ maintenance}{E\ lifetime}$$

*= 9759400 + 2927282 / 32519.25*

*= 390.128  ILS / KWh*

***11. Total annual Savings***

***S total = S piezo + S lightning***

*= 705 + 488*

*= 1193 ILS / year*

## III. Results and Discussion

**Prototype-Level Results (Proof of Concept)**

The laboratory scale prototype successfully demonstrated the full operational chain of the proposed system: mechanical excitation, electrical conditioning, energy storage, sensing, and load control.

When pressure was applied to the piezoelectric elements arranged in a combined series–parallel configuration, an alternating voltage signal was generated. Direct connection of the piezoelectric output to the LED resulted in weak and intermittent illumination, confirming the unsuitability of raw AC output for stable load operation. This behavior validates the necessity of electrical conditioning stages in practical implementations.

Following the introduction of a full-wave bridge rectifier, the output signal was converted into a unidirectional voltage suitable for storage. The addition of a capacitor enabled energy accumulation, evidenced by measurable voltage increments across the capacitor terminals during repeated mechanical excitation. The LCD module connected to the storage node displayed discrete voltage increases, directly correlating with the frequency and intensity of applied pressure. This confirms that the system is capable of converting intermittent mechanical inputs into cumulative electrical energy.

Integration of the light-dependent resistor (LDR) and LED load introduced conditional energy usage. The LED was activated only when two conditions were simultaneously satisfied: (i) sufficient voltage was available across the capacitor and (ii) ambient light levels were below a predefined threshold. This validated the effectiveness of the proposed control logic in preventing unnecessary energy discharge under non-demand conditions.

Overall, the prototype confirmed the technical feasibility of harvesting, conditioning, storing, and selectively utilizing pedestrian-generated energy using low-cost components and a microcontroller-based control system.

**Scaled Energy Generation Results for Faculty of Arts Street**

Using the validated prototype behavior as a functional reference, the system was analytically scaled to the selected case study site: the Faculty of Arts Street at Birzeit University.

Covering the full street area (approximately 390 m × 12 m), the installation of floor-integrated piezoelectric tiles enables continuous mechanical excitation due to high pedestrian traffic. Based on an average of 6,500 daily traversals of the street and a nominal power output of 7 W per tile under continuous stepping conditions, the system yields a non-negligible aggregate energy contribution.

Although the power generated per individual tile remains modest, the cumulative effect across a large surface area and sustained daily footfall results in measurable energy availability suitable for low-power applications. These findings align with prior large-area piezoelectric floor deployments reported in the literature, where distributed low-density generation compensates for limited per-unit output.

It is important to emphasize that the system is not intended to replace grid electricity but rather to provide localized supplementary energy, consistent with the role defined in the methodology.

**Results of Sensor-Based Lighting Energy Reduction**

Independent of piezoelectric generation, the deployment of sensor-based lighting control in secondary indoor spaces yielded significant projected energy savings.

For a single academic building equipped with 30 LED fixtures rated at 30 W each, baseline annual lighting consumption was calculated assuming continuous operation during academic hours. Applying a conservative 30% reduction factor—supported by empirical results from large-scale studies on daylight-responsive lighting control in educational buildings—the controlled system demonstrates a substantial reduction in annual electricity demand.

This reduction is particularly impactful in intermittently occupied spaces such as corridors, restrooms, and service areas, where conventional lighting systems are often left active despite low usage. The results confirm that intelligent control strategies provide immediate and reliable savings without dependence on energy harvesting performance.

**Economic Interpretation of Results**

From an economic perspective, the results highlight two distinct but complementary contributions:

1. Piezoelectric energy harvesting provides a localized, renewable energy source whose value increases with pedestrian density and installation scale. While the levelized cost of energy (LCOE) remains higher than conventional grid electricity, the system's durability, modularity, and long operational lifetime support its feasibility as a supplementary source.
2. Sensor-based lighting control offers direct and quantifiable electricity cost reductions. Unlike energy harvesting, these savings are independent of human activity levels and are realized immediately upon deployment. As demonstrated, even conservative reduction factors translate into meaningful annual cost savings, strengthening the overall economic viability of the combined system.

The integration of both approaches creates a hybrid efficiency framework in which harvested energy offsets a portion of demand, while intelligent controls reduce total consumption.

**Discussion and Practical Implications**

The results indicate that the primary value of the proposed system lies in its system-level integration, rather than in maximizing energy output from individual components. The prototype confirms that pedestrian-induced energy can be harvested and managed reliably, while the feasibility analysis demonstrates that the greatest economic impact arises when energy harvesting is paired with demand-side efficiency measures.

For university campuses in Palestine, where electricity costs, energy security, and sustainability are critical concerns, such hybrid systems are particularly relevant.

The approach supports gradual deployment, starting with high-traffic areas and secondary indoor spaces, allowing incremental investment and scalable impact.

Future work should focus on long-term field measurements, optimization of tile placement density, and detailed lifecycle cost analysis to further refine the LCOE estimates and validate real-world performance.

## IV. Future plans

Future development of this project will focus on improving efficiency, reliability, and real-world usability of the piezoelectric energy harvesting system. The rectification stage can be optimized by replacing standard diodes with low forward-voltage components such as Schottky diodes or dedicated energy-harvesting ICs to reduce power losses. Energy storage can be enhanced using supercapacitors or optimized capacitor values to provide longer operation time. Further improvements include experimenting with different piezoelectric configurations (series and parallel) to maximize output power and refining the LDR control using comparator-based circuits with adjustable thresholds for more stable LED operation. The system may be expanded for practical applications such as self-powered lighting, smart flooring, and remote low-power environments, with the possibility of integrating solar energy to increase reliability and sustainability.

## V. Conclusion

This work confirms that piezoelectric floor harvesting, when combined with sensor-based lighting control, can support localized energy efficiency in university environments. The prototype validated the technical operation of energy generation, storage, and controlled usage, while the feasibility analysis showed measurable reductions in lighting electricity consumption in intermittently used spaces. Although piezoelectric harvesting alone is not a primary energy source, its integration with smart control strategies provides a practical and scalable contribution to campus sustainability.

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