Materials Research Proceedings 64 (2026) 218-223 https://doi.org/10.21741/9781644904091-27

Smart Piezoelectric Sensing Tile for Force Monitoring in Home Applications

Amina ALLAM

School of Science and Engineering. Al Akhawayn University in Ifrane. Ifrane, Morrocco

Am.Allam@aui.ma

Keywords: Piezoelectric Energy, Smart Energy Management, Ambient Lighting, Residential Lighting

Abstract. This work represents a smart household energy system based on piezoelectric tiles designed to harvest mechanical energy from footsteps and allocate it intelligently according to ambient lighting conditions .Electricity demand in Morocco increased by 4% in 2023 to reach 44 TWh, while the country still imports almost 90% of its primary energy, which underlines the immediate necessity for efficient micro-generation solutions. Simulation results indicate that the voltage generated by the piezoelectric tile rises from 130 mV to 891 mV for an increase in the load resistance from 1.12 to 7.51 kΩ and that a 1 μF capacitor charges from 0 to 3 V in about 60 footsteps. These results show that piezoelectric energy harvesting combined with simple control logic can indeed yield a reliable supplemental source of power for low-power residential applications.

Introduction

Energy availability and sustainability are central to the economic growth and social development of rapidly advancing nations like Morocco. National electricity demand has been on a continuous rise, increasing by 4% in 2023 and reaching about 44 TWh [1]. While continuous investments have been made in developing solar, wind, and hydropower infrastructures, Morocco still relies on external sources for around 90% of its primary energy needs [2]. Such high dependence on external sources places utmost importance on domestic energy conservation and distributed micro generation. Households themselves range from 13 to 37% of national electricity consumption, and therefore the development of Smart Home Energy Management Systems or SHEMS has become more urgent to better energy efficiency and reduce wastage [8].

Recent literature features the promising role of piezoelectric energy harvesters within smart residential systems. Indeed, piezoelectric materials possess the ability to convert mechanical strain directly into an electrical charge in an efficient manner, without any external power supply. According to existing studies, dynamic loads induced by footsteps may produce voltages that are measurable and adequate to power low-power devices, sensor networks, and lighting [5,7]. Moreover, impedance matching, SSHI, and MPPT advanced power-conditioning strategies raise the efficiency of energy extraction from piezoelectric elements significantly [4]. This brings together support for the integration of piezoelectric harvesting within intelligent home environments where autonomous control algorithms can handle the distribution of intermittently generated energy.

To this extent, the proposal of this paper is to design a smart piezoelectric sensing tile intended for residential energy management. The proposed system can convert the mechanical energy produced by footsteps, transmit this energy through the rectification and conditioning process, and finally distribute the converted electricity to residential lighting loads or to the storage capacitor in the supercapacitor bank. This process is decided and managed by an Arduino-controlled switching algorithm that assesses the ambient lighting intensity through the photoresistor,

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings 64 (2026) 211-217 https://doi.org/10.21741/9781644904091-26

switching between the illumination of the light-emitting diodes and the storage of the converted electrical energy depending on the need for illumination.

PIEZOELECTRIC THEORY

The piezoelectric sensing element used in the proposed system converts dynamic mechanical loads generated by footsteps into electrical energy. When the tile undergoes mechanical deformation (strain), the material produces an electric displacement that appears as a voltage across its terminals. The description of this type of electromechanical behavior is based on the linear stress-charge relation as shown in **Eq. (1)** [3]:

$$D = eS + \varepsilon E \quad (1)$$

In this **Eq. (1)**, D stands for electric displacement, S is applied strain, e the piezoelectric coefficient and ε is the permittivity of the material. This displacement is directly responsible for the electrical charge generated each time the tile is compressed.

Because footsteps are dynamic loads, the piezoelectric element does not output a constant voltage; it produces short-duration AC voltage spikes whose amplitude depends on the applied force. The element also has an inherent internal capacitance,Cp ,which affects the open-circuit voltage; greater generated charge increases the voltage, while larger capacitance reduces the voltage. Physical attributes like tile thickness, surface area, and mechanical stiffness influence peak voltage.

MATERIALS AND METHODS

A.Performance characterization and energy harvesting

The first goal was to understand how the electrical energy released from a piezoelectric surface is connected to the mechanical force applied to it. Using a Tinkercad simulation, and varying levels of force that were applied to the piezo surface through a Force Sensor, the resulting voltage outputs were observed. As a result, Graphs were generated to show how voltage and electrical power change as the applied force increases. The analog voltage that comes from the Force Sensor was processed by an Arduino Uno R3, and then it was converted into digital data that could be interpreted. At This stage the amount of usable electrical power produced by each footstep along with the corresponding voltage was then measured.

B. Smart Logic Validation for Residential Energy Management

The second phase of our study evaluates the feasibility of integrating a piezoelectric system into a residential environment, with the objective of autonomously powering low energy household loads represented in this prototype by Red, White, and Blue Led. The proposed system is designed to be placed in high traffic indoor areas such as hallways, entryways, or kitchens where frequent footsteps can be reliably converted into electrical energy. Placing this system in these locations increases energy generation and allows everyday human movement that are normally wasted to contribute directly to improving household energy efficiency.

This system uses smart switching logic controlled by the Arduino Uno R3, which acts as the main decision-making unit. The Arduino continuously reads ambient light levels from the photoresistor to determine how the harvested energy should be used .When the LDR detects low light(below the set threshold), the system enters spend mode , sending generated piezoelectric energy directly to LEDS to provide illumination and improve safety in dark conditions .When sufficient light is present (LDR above the threshold), the system switches to the store mode , directing the energy to the 1 μF capacitor to save power for late use.

Materials Research Proceedings 64 (2026) 211-217 https://doi.org/10.21741/9781644904091-26

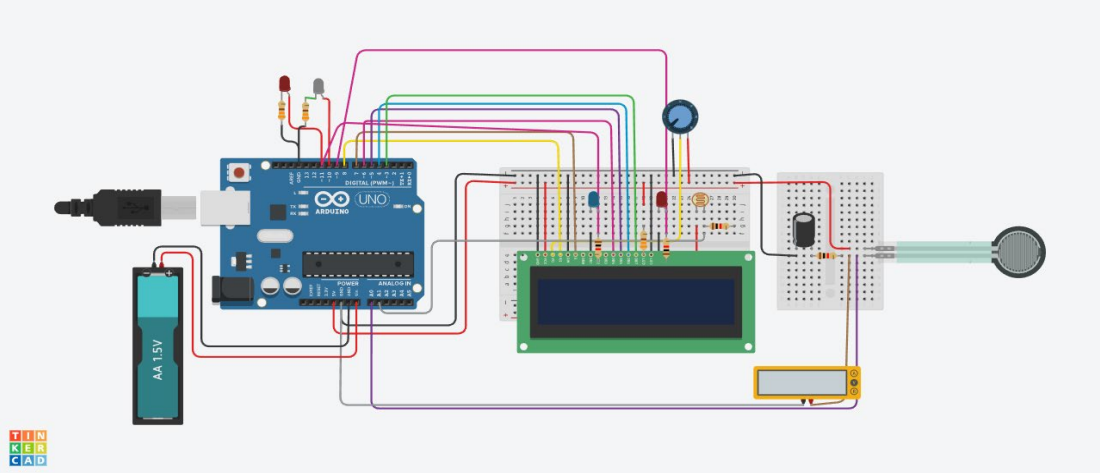


Fig. 1. Piezoelectric energy simulation using Thinkercard

By combining piezoelectric energy harvesting with a simple efficient control strategy, the system transforms everyday footsteps into a practical energy source. This demonstrates how piezoelectric flooring and smart energy management can reduce waste, improve efficiency, and support sustainable energy use in residential settings.

- **Arduino Uno R3:** control unit that executes the smart switching logic for power management.
- **Force Sensor:** Simulates the Piezoelectric Tile converting footsteps to Voltage.
- **Photoresistor:** Measures ambient light to inform the spend/store decision.
- **1 uF, 16 V Capacitor:** stores harvested energy during the store state.
- **LCD 16 x 2**: Interface that displays system state, power and sensor reading.
- **Red, White, Blue LEDs**: Load indicators that represent the low power residential lightning load.
- **AA Battery, Resistors, Potentiometer**: Provides baseline power and regulates current/ voltage.

RESULTS AND DISCUSSIONS

A.Validation of Footstep-to-Electrical Energy Conversion

1.Analysis of Input Force (Steps) with Respect to Output Voltage

Figure 2 illustrates the relationship between the simulated mechanical input (Force Sensor) and the electrical output Voltage. The Analysis of piezoelectrical Transformer in this case successfully demonstrates the non-linear relationship between the applied force and the electrical voltage.

This phenomenon usually has been reported in piezoelectric systems of energy conversion. The behavior can be mainly explained by considering the relationship between the generated output power and the applied strain/force expressed as: $P\ out \propto Fn\ cos(t), n > 1$.

One crucial factor contributing to the observed rise in output voltage is the overcoming of the forward-voltage drop across the assumed rectifier circuit. Once this threshold is exceeded, the electrical pathway becomes significantly more efficient, thereby improving the conversion of mechanical energy as the applied force F approaches the maximum mechanical stress corresponding to a full footstep.

The results obtained have effectively established the fact that mechanical energy from footsteps can be converted efficiently into usable electrical energy. The high output voltage levels achieved

Materials Research Proceedings 64 (2026) 211-217 https://doi.org/10.21741/9781644904091-26

under high simulated force conditions indicate that reaching or approaching the maximum applied force can significantly improve the energy generation capability of the piezoelectric device.

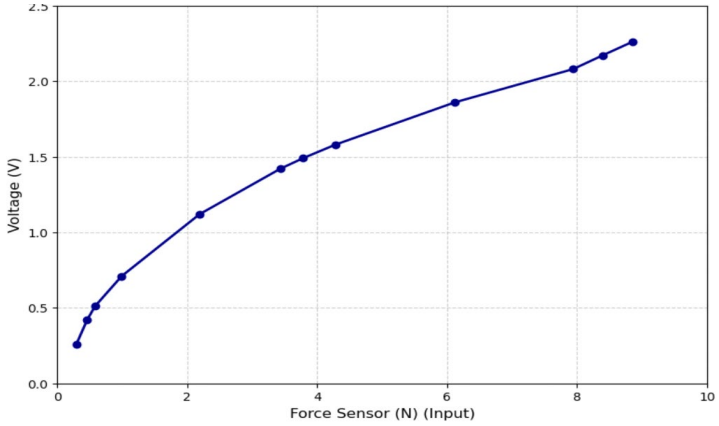


Fig. 2. The input force applied using piezo sensors versus voltage output

2.Analysis of Input Force (Steps) with Respect to Output Power

Indeed, the graph in Figure 3 of Power Spent (Output) vs. Force Sensor (N) in the range 0-10 N serves to clearly demonstrate the nonlinear behavior typical of piezoelectric energy harvesting systems**.** While increasing force from 0 to 10 N corresponds to an increase in power output, it does so in a non-linear fashion. Within the low-force region of 0-1 N, the curve climbs steeply to indicate that even small increases in force result in disproportionately large increases in electrical power; this reflects the high electromechanical sensitivity of the piezoelectric material when under low mechanical strain.

From around 2 to 6 N, power output increases but with a slope that decreases with increasing force, indicating that conversion efficiency starts to fall as the applied force approaches mid-range values. Beyond 6 N and up to 10 N, the curve noticeably levels out, confirming a sublinear response whereby extra applied force leads only to marginal increases in power. Such saturation-like behavior is to be expected while the piezoelectric element approaches its upper limits of mechanical stress and internal electrical constraints, such as the threshold forward-voltage of the rectifier and intrinsic material stiffness start to dominate.

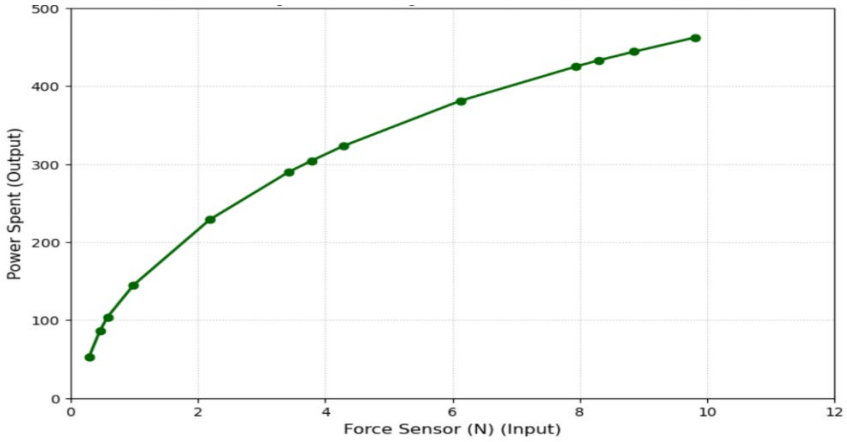


Fig. 3. *the input force applied using piezo sensors versus power output.*

3.Analysis of the electrical output voltage as a function of the load resistance connected to the harvesting circuit

The observed behavior (Fig.4) aligns with theoretical expectations for piezoelectric harvesters operating under the variation of load conditions: when low resistance, significant current flows leading to lower terminal voltage. At intermediate resistance, the device approaches its optimal power transfer region, yielding sharper voltage increases. At high resistance, the load approximates an open circuit condition causing voltage to approach the harvester's maximum open circuit output. This confirms that the system exhibits correct electromechanical characteristics and that the load resistance plays a crucial role in shaping the measurable voltage output.

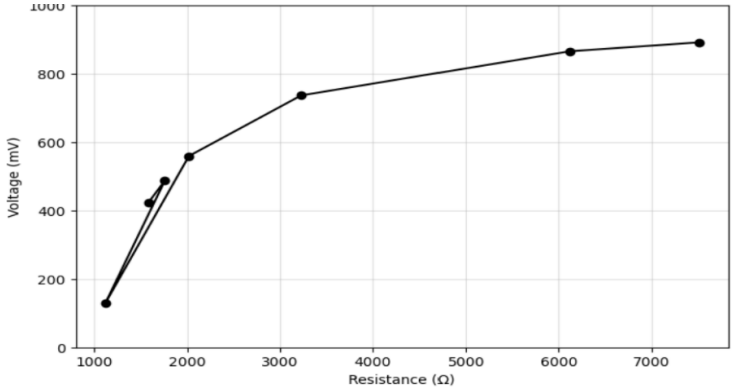


Fig. 4. The resistance and the voltage output correlation

4.Analysis of storage of the piezo electric energy through capacitors

The characteristic curve of capacitor voltage accumulation versus accumulated footsteps (Fig.5) gives important verification of the energy management performance during the STORE state. As expected, the plot displays a nonlinear charging profile consistent with an RC circuit whose input is an intermittent mechanical energy source. In the initial region (roughly 0 to 15 steps), the voltage increases steeply: this means that when the capacitor voltage is low, the piezoelectric tiles and conditioning circuitry operate at high energy-transfer efficiency.

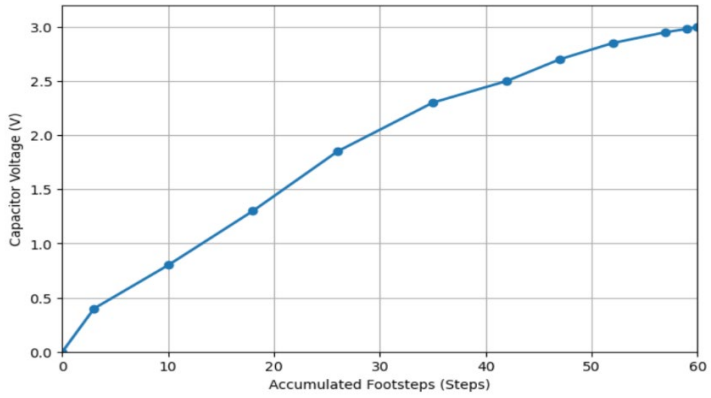


Fig. 5. Storage case of electric energy with respect to footsteps

Conclusion

This paper presents a smart piezoelectric energy-harvesting system, which is validated through high-fidelity simulation. The results indicated that footstep-like mechanical forces can convert into electrical voltage and power effectively, suggesting the feasibility of piezoelectric tiles in micro-generation. Key insights to optimize the power transfer were drawn from a load-dependent

analysis, whereas the implemented switching algorithm based on Arduino successfully managed the harvested energy either for powering an LED in low-light conditions or charging a storage capacitor. A practical short-term energy accumulation has been demonstrated: with approximately 60 footsteps, the capacitor reached 3 V.

This work showcases how piezoelectric harvesting could support energy conservation, especially in Morocco, by converting wasted kinetic energy into useful power for small household applications. Since this work is simulation-based, on-site validation is yet to be performed to account for material efficiency, circuit losses, and long-term durability.

References

[1] ANRE, "The National Agency for Renewable Energy (ANRE) Report on Moroccan Electricity Demand," 2024.

[2] ITA, "International Trade Administration (ITA) Report on Moroccan Primary Energy Imports," 2024.

[3] Z. Mahmood, N. Javaid, and S. H. Bouk, "A Survey on Residential Demand Side Management in Smart Grid," Renewable and Sustainable Energy Reviews, vol. 50, pp. 1102-1115, Oct. 2015.

[4] S. Priya and D. J. Inman, Eds., Energy Harvesting Technologies. Springer, 2009. https://doi.org/10.1007/978-0-387-76464-1

[5] E. Lefeuvre, A. Badel, C. Richard, and D. Guyomar, "A comparison between several power harvesting devices for wiring-free applications," Sensors and Actuators A: Physical, vol. 126, no. 2, pp. 405-416, Feb. 2006. https://doi.org/10.1016/j.sna.2005.10.043

[6] Y. K. Tan and S. K. Panda, "Synchronous Switch Harvesting on Inductor (SSHI) and Maximum Power Point Tracking (MPPT) for Piezoelectric Energy Harvesting," IEEE Trans. Power Electron., vol. 35, no. 1, pp. 192-205, Jan. 2020.

[7] S. A. Gholap, "Basic Piezoelectric Theory and Applications in Energy Harvesting," J. Smart Mater. Struct., vol. 20, no. 12, pp. 125016, 2021.

[8] S. Priya and D. J. Inman, Eds., Energy Harvesting Technologies. Springer, 2009. https://doi.org/10.1007/978-0-387-76464-1

[9] H. A. Sodano, G. Park, and D. J. Inman, "Estimation of Electric Charge Output for Piezoelectric Energy Harvesting," Strain, vol. 40, no. 2, pp. 49-58, 2004. https://doi.org/10.1111/j.1475-1305.2004.00120.x