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The Development of Piezoelectric Tiles for Efficient Energy Harvesting

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Abstract

This project outlines the design and development of an interactive piezoelectric tile system aimed at harvesting mechanical energy generated by footstep impacts and converting it into usable electrical energy. A prototype was developed utilising 20 piezoelectric ceramic discs, each with a diameter of 25 mm, configured in a series-parallel arrangement. In a controlled laboratory environment, the tiles were exposed to simulated foot pressure, resulting in the generation of AC voltage. This voltage was then rectified utilising a full-bridge rectifier made up of 1N4148 diodes. The output was stabilised and buffered with a 2.7 V, 0.8 F supercapacitor prior to being elevated to 5 V through a CE8301-based DC-DC converter. A regulated voltage was employed to partially charge a 3.7 V, 1200 mAh lithium-ion battery utilising a TP4056 charging module. Experimental testing evaluated three damper configurations such as spring-mounted, soft pad, and hard pad to determine their impact on output performance. The spring-mounted damper demonstrated superior performance compared to the alternatives, reaching maximum outputs of 3.72 V (AC) and 2.45 V (DC) during repeated steps. According to the measurements of current and voltage, each footstep produced around 26.75 µWh of energy. The total number of steps required to achieve a complete battery charge was estimated at 168,820, which corresponds to approximately 23.5 hours of uninterrupted stepping at intervals of 0.5 seconds. Upon complete charging with a DC power supply, the battery operated a 5W LED lamp for an estimated duration of 53 minutes. Simulations using MATLAB were performed on essential circuit stages, particularly the rectifier and boost converter, to assess their performance across different input conditions. The findings showed a strong correlation with the physical tests, with slight variations explained by diode voltage drops and inconsistent mechanical input. This investigation validates the practicality of combining piezoelectric energy harvesting with power conditioning and storage systems. The system, although not fully optimised for independent operation at this stage, exhibits significant promise for future implementation in public areas as engaging and sustainable energy alternatives.

1. Introduction

The increasing global demand for sustainable energy has driven interest in energy harvesting technologies, which convert ambient or wasted energy into usable electrical power. Among the various harvesting methods such as thermoelectric, photovoltaic, and electromagnetic systems. Piezoelectric energy harvesting utilized for its ability to convert mechanical stress into electricity, especially in environments with frequent physical interaction like public walkways [1], [2], [3].

This project proposes the development of a piezoelectric floor tile system designed to convert footstep energy into electrical power. The system includes key power management stages such as rectification, buffering, voltage boosting, and battery charging. The harvested energy will be used to power a low-power 5W LED lamp, offering a sustainable lighting solution while also raising public awareness of renewable energy technologies [4].

1.2 Problem Statement

In line with Malaysia's National Energy Transition Roadmap (NETR), the push toward innovative renewable energy solutions is growing. Public spaces such as parks, museums, and tourist walkways often depend on grid-powered lighting, resulting in higher costs and environmental impact. These locations also present a unique opportunity to harness footstep-induced mechanical energy through piezoelectric flooring [5],[6].

However, current piezoelectric systems suffer from several limitations—namely, intermittent and low power output, voltage instability, and inefficient storage. Without effective power conditioning, such energy remains unusable. Additionally, many designs lack the scalability or engagement potential required for public-facing installations.

This project addresses these challenges by integrating piezoelectric tiles with a rectification circuit, a supercapacitor buffer, a DC-DC boost converter, and a TP4056 charging module to create a robust system. The final output powers a 5W LED, providing both functional lighting and an engaging visual experience to promote awareness of sustainable energy use.

1.3 Objectives

- To design and build piezoelectric tiles capable of converting mechanical energy from footstep pressure into electrical energy.
- To integrate power conditioning circuits—including a rectifier and boost converter—for voltage stabilization and energy storage.

1.4 Scope of Study

This project focuses on the design, simulation, and experimental testing of a piezoelectric energy harvesting system for powering low-power lighting in public spaces. The specific scope includes:

1. Designing a prototype using 25 mm ceramic piezoelectric discs in series-parallel configuration.
2. Developing an energy storage system using a 3.7 V, 1200 mAh lithium-ion battery.
3. Simulating key components—rectifier, boost converter, and storage—in MATLAB.
4. Testing the energy output performance under spring, soft, and hard damping configurations.
5. Integrating a 5W LED lamp to demonstrate real-time energy utilization.
6. Evaluating the efficiency of the rectifier and boost stages using multimeter analysis.
7. Analyzing the system's performance under varying foot traffic and mechanical stress.

2. Literature review

2.1 System Overview

This chapter reviews relevant studies and concepts related to piezoelectric energy harvesting systems, highlighting their potential, limitations, and practical applications in low-power environments.

Fig 1 shows piezoelectric materials such as PZT (Lead Zirconate Titanate) and PVDF have been widely researched for their ability to generate voltage under mechanical stress. Ceramic piezoelectric discs, particularly the 25 mm type, are favored in energy harvesting due to their high voltage output and mechanical robustness. Prior studies have demonstrated their suitability in footstep-based applications, where dynamic pressure from human steps produces intermittent AC voltage [7],[8].

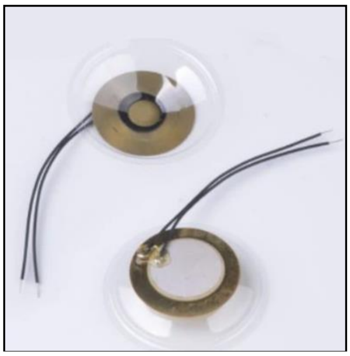


Fig. 1 *Piezoelectric*

2.2 Power Conditioning Circuitry

Because the output from piezoelectric tiles is AC and inconsistent, proper power conditioning is required. A full-bridge rectifier using 1N4148 diodes converts the AC signal into DC. However, this rectified signal still contains ripple, especially under fluctuating footstep pressure. To stabilize this output, a 2.7 V supercapacitor is introduced to smooth the voltage and serve as a short-term energy buffer. This setup ensures consistent voltage input to the voltage boosting stage of the system.

After rectification and buffering, the voltage remains too low to directly charge most storage systems. A DC-DC boost converter module based on the CE8301 IC is used to step up the voltage to a fixed 5V. Unlike traditional converters that require external tuning, the CE8301 integrates an internal feedback loop and fixed output voltage regulation, reducing design complexity. Proper voltage regulation is critical to protect the battery and maintain consistent system operation.

2.3 Energy Storage System

Energy harvested from footsteps is intermittent, so storing it effectively is essential for consistent usage. Lithium-ion batteries are well-suited for this purpose due to their high energy density and rechargeability. The TP4056 charging module is widely used in such systems for its ability to safely charge 3.7 V lithium-ion batteries, featuring built-in overcurrent, overvoltage, and thermal protection. Coupled with a supercapacitor, it helps mitigate rapid fluctuations and ensures smoother battery charging.

2.4 Summary

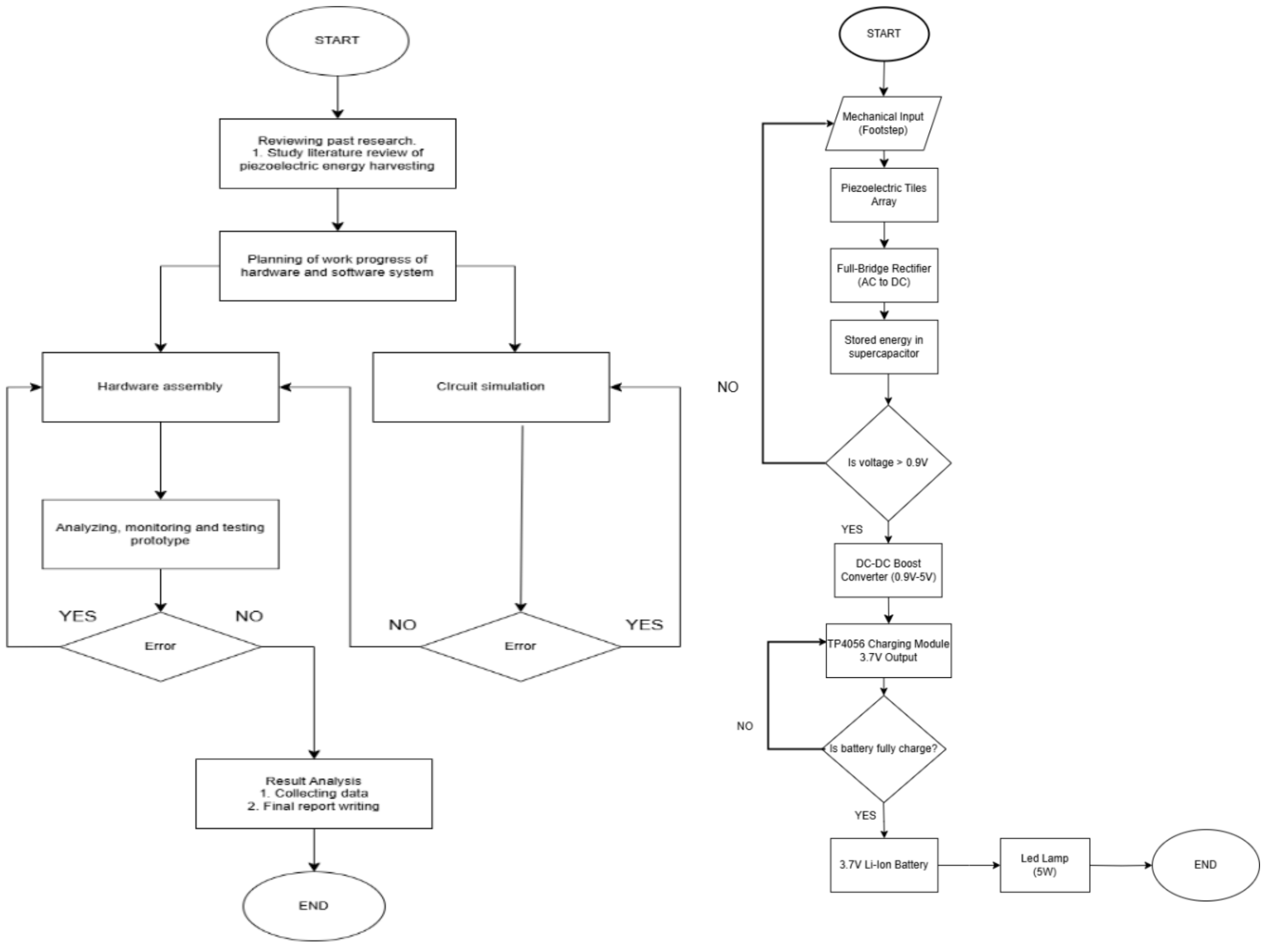
This review highlights the fundamental elements of piezoelectric energy harvesting: the use of ceramic sensors, the importance of power conditioning (rectification and voltage boosting), and integration of reliable energy storage systems. Through a combination of efficient mechanical-to-electrical conversion and optimized circuitry, such systems have proven their feasibility for small-scale, low-power applications particularly in interactive and educational public environments.

3. Methodology

This section outlined the specific methodology used for this project. The proposed methodology to implement the project involves energy generation through piezoelectric sensors as an alternative power source.

3.1 System Overview

In Fig. 2(a), the project begins with a literature review to understand piezoelectric principles, energy generation capabilities, and previous applications. This informs the design strategy, targeting the goal of generating sufficient energy to charge a 3.7 V lithium-ion battery and power a 5W lamp. Next, the planning phase involves designing the hardware system, including a series-parallel arrangement of 20 piezoelectric discs, a full-bridge rectifier, and a DC-DC boost converter for voltage regulation. Implementation includes assembling the hardware, integrating the components, and running circuit simulations under varying foot traffic conditions. Faults detected in this stage are corrected prior to testing. Finally, the prototype undergoes testing under both simulated and real-world conditions to evaluate energy generation, storage efficiency, and lamp illumination response to foot pressure.



(a) **(b)**

Fig. 2 *Flowchart (a) Project Flowchart; (b) Piezoelectric tiles flowchart system*

In Fig. 2 (b), The piezoelectric tiles system follows a structured flow to convert mechanical stress from footsteps into usable electrical energy. As shown in Figure 3.2, the process begins when a user steps on the tiles, applying force to the piezoelectric discs, which generate an AC voltage through the piezoelectric effect. To optimize stress transfer, three damping methods such as spring-mounted, soft pad, and hard pad were tested. Multiple piezoelectric discs are arranged in a series-parallel connection to enhance voltage and current output. The AC voltage is then rectified using a full-bridge rectifier and smoothed with a capacitor, which also acts as an energy buffer to help reach the 0.9V threshold required to activate the CE8301 boost converter. This converter steps up the voltage to 5V. The output is regulated using a TP4056 charging module to safely charge a 3.7V, 1200mAh lithium-ion battery, which stores the energy for later use. Finally, the stored energy powers a 5W LED lamp, demonstrating the system's capability in real-world applications. Each block in the flow represents a key stage from energy generation to storage and output delivery.

3.2 Block diagram

The system converts footstep pressure into electrical energy using piezoelectric discs arranged in series parallel. When stepped on, the discs generate AC voltage, which is rectified using a full-bridge rectifier and stabilized with a capacitor that also buffers energy. This DC voltage is then stepped up using a CE8301 boost converter to 5V, which is regulated by a TP4056 charging module to safely charge a 3.7V lithium-ion battery. The battery stores energy and powers a 5W LED lamp, showcasing the system's real-world application for low-power lighting. Fig. 3 is the block diagram of the proposed work.

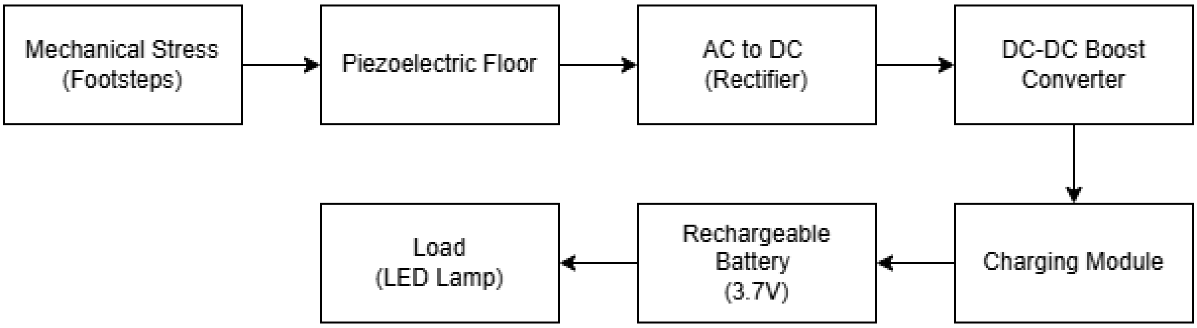


Fig.3 *Block diagram system*

3.3 Experimental Setup

The piezoelectric tile system depicted in Fig 4 was tested under controlled laboratory conditions using a footstep subject applying consistent footstep pressure. Footstep intervals were regulated at 0.5 seconds using a digital timer to ensure repeatability. The prototype comprised 20 ceramic piezoelectric discs with diameter of 25 mm arranged in a series-parallel configuration. Three damping configurations were evaluated: spring-mounted, soft pad, and hard pad. Each configuration underwent a series of trials, with 20 footsteps applied per trial, and this process was repeated three times. Measurements were performed in open-circuit mode utilising a digital multimeter to capture peak AC output, rectified DC voltage, and current.

System-level testing encompassed the complete energy conditioning configuration, utilising a 2.7 V, 0.8 F supercapacitor to buffer the rectified output. Upon reaching a voltage of 0.9 V, the CE8301-based boost converter elevated the voltage to 5 V. The TP4056 module regulated the charging process for a 3.7 V, 1200 mAh lithium-ion battery, which subsequently powered a 5W LED lamp to demonstrate energy utilisation. Fig. 3.2 showed the setup of experimental testing on the piezoelectric tiles.

Fig. 4 *Experimental testing setup*

4. Result and Discussion

The developed piezoelectric tile system in Fig.5 successfully demonstrates the conversion of mechanical energy from footsteps into usable electrical energy through a complete process involving energy generation, rectification, buffering, voltage boosting, and storage. The system incorporates 20 piezoelectric ceramic discs arranged in a series-parallel configuration, producing AC voltage which is rectified using a full-bridge rectifier with 1N4148 diodes. A 2.7V, 0.8F supercapacitor is used to smooth the rectified DC voltage and act as an energy buffer. This buffered energy feeds into a CE8301-based boost converter, stepping up the voltage to a stable 5V output, which is then regulated by a TP4056 module to charge a 3.7V, 1200mAh lithium-ion battery. The battery powers a 5W LED lamp as the load demonstration.

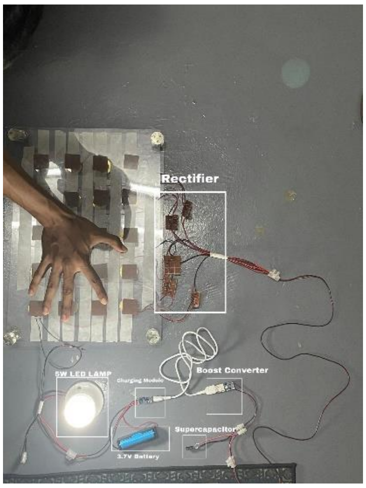


Fig. 5 *Piezoelectric tiles hardware*

To evaluate mechanical efficiency, three damping setups which are spring-mounted, soft pad, and hard pad were tested under controlled footstep input. The spring-mounted configuration yielded the highest output, with measured peaks of 3.72 V (AC) and 2.45 V (DC), followed by the hard pad and soft pad. Tables 1, 2 and 3 summarizes the average voltage outputs across all damping types.

Table 1 *Result piezoelectric floor with spring for average Vac, Vdc, Idc (Spring Damper)*

No of Steps.	V_{AC} (piezo output)	V_{DC} (Rectified)	I_{DC}
2	2.345	1.54	12.4uA
4	2.98	1.61	18.0uA
6	3.03	1.78	19.9uA
8	3.18	1.83	21.7uA
10	3.21	1.86	28.3uA
12	3.22	1.95	29.4uA
14	3.27	2.06	31.6uA
16	3.44	2.14	33.2uA
18	3.62	2.34	35.3uA
20	3.72	2.45	44.0uA

Table 2 *Result piezoelectric floor with soft pad for average Vac, Vdc, Idc (Soft-pad Damper)*

No of Steps.	V_{AC} (piezo output)	V_{DC} (Rectified)	I_{DC}
2	0.96	0.43	NA
4	0.97	0.55	NA
6	1.25	1.17	NA
8	1.27	1.19	NA
10	1.36	1.32	NA
12	1.41	1.45	NA
14	1.49	1.46	NA
16	1.83	1.47	NA
18	1.88	1.52	NA
20	1.85	1.65	NA

Table 3 *Result piezoelectric floor with hard pad for average Vac, Vdc, Idc (Hard-pad Damper)*

No of Steps.	V_{AC}, (piezo output)	V_{DC} (Rectified)	I_{DC}
2	0.70	0.43	6.2uA
4	1.13	0.55	7.0uA
6	1.26	1.17	8.3uA
8	1.41	1.19	8.7uA
10	1.45	1.32	9.2uA
12	1.56	1.45	11.3uA
14	1.71	1.50	13.6uA
16	1.75	1.53	15.4uA
18	1.99	1.60	16.1uA
20	2.03	1.65	16.8uA

In summary, the analysis conducted under open-circuit conditions indicated that the spring-mounted damper yielded the highest voltage output, succeeded by the hard pad and soft pad. The recoil of the spring improved the transfer of stress to the piezoelectric tiles, thereby increasing the efficiency of energy harvesting. Nonetheless, since the tests were conducted without any load, the recorded voltages indicate the maximum potential and are anticipated to diminish when subjected to actual load conditions. This analysis underscores the spring damper's enhanced efficiency in energy generation. Fig. 6 shows the experimental results.

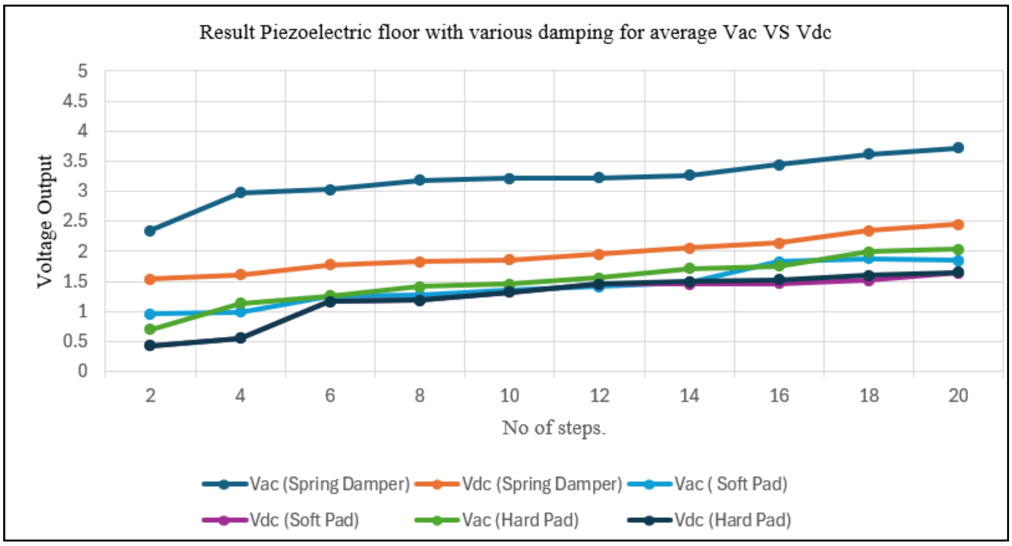


Fig. 6 *Damper configuration experimental results*

The supercapacitor was important in storing accumulated energy from repeated footsteps. The boost converter required a minimum input of 0.9 V to activate and it successfully provided a stable 5 V output, which continuously charged the lithium-ion battery via the TP4056 module. A fully charged battery was able to power the 5W LED lamp for approximately 53 minutes based on the calculation. Table 4 provides a breakdown of energy generation and charging analysis.

Table 4 Energy generation and charging analysis

Metric	Value
Energy per footstep (avg.)	26.75 µWh
Total battery capacity	4.44 Wh
Footsteps to fully charge	168,820
Time to charge (0.5 s/step)	23.5 hours
Runtime on full charge (LED)	53 minutes

4.1 Simulation Vs Experimental Result

Simulations of the rectifier and boost converter were conducted in MATLAB to evaluate circuit behaviour and validate hardware performance. The simulations were conducted under ideal conditions, utilising consistent voltage inputs obtained from experimental piezoelectric outputs.

However, the actual 1N4148 diodes exhibited a forward voltage drop of approximately 0.7 V, which led to a reduced DC output during hardware testing. The reduction of ripple voltage was observed in both scenarios utilising a 0.8 F supercapacitor. However, the experimental output showed an increase. The multimeter's ability to capture peak values during open-circuit measurements. The Boost Converter Simulation demonstrated an increase in voltage from 1.42 V to 3.7 V at optimised duty cycles. Experimental tests validated activation at an input voltage of 0.9 V however, real-world startup faced limitations due to inconsistent energy pulses generated by footsteps. The component response in hardware was influenced by limitations in gate drive, which is MOSFET switching and transient piezoelectric inputs, which do not completely align with the steady input modelled in the simulation.

Table 5 *Simulation vs Experimental results comparison*

Component	Parameter	Simulation Result	Experimental Result	Notes
Rectifier	VDC Output	2.07 V – 5.87 V	2.52 V – 6.80 V	Peak voltage higher in hardware due to open-circuit state.
Rectifier	Ripple Voltage	17.1 µV	Low ripple	Capacitor effective in both cases.
Boost Converter	Input Voltage Range	1.42 V – 1.5 V	0.7 V – 0.9 V	Hardware required ≥0.9 V to activate CE8301.
Boost Converter	Output Voltage	3.7 V – 3.71 V	3.7 V – 5.0 V	CE8301 outputs stable voltage once activated.
System Stability	Energy Input	Steady (constant pulse)	Pulsed (footstep-based)	Simulation idealized: Real input is intermittent.

Overall, both simulation and experimental results confirm the system's functionality, with expected discrepancies due to real-world losses and input variability. This validates the modeling approach while highlighting the importance of energy buffering and component selection in hardware design.

4.2 Applications

The piezoelectric tile system developed shows potential for low-power usage in areas with high foot traffic. The capacity to generate and store electrical energy from footsteps makes it appropriate for implementation in smart campus pathways, museum walkways, or metro station floors. The design's flexible features enable scalability through the interconnection of multiple tile arrays and the enhancement of battery capacity.

The system provides a passive, low-maintenance solution for off-grid lighting in developing regions, thereby decreasing reliance on conventional grid electricity. The system captures mechanical energy that would otherwise be wasted, thus contributing to sustainable infrastructure. It aligns with clean energy objectives and promotes environmental conservation by decreasing reliance on fossil fuels.

5. Conclusion

This project successfully demonstrated the design, development, and testing of a piezoelectric energy harvesting system using mechanical stress from footsteps. The main objective to convert kinetic energy into electrical energy and store it for low-power lighting applications was achieved. The system, built with 20 piezoelectric ceramic discs, a full-bridge rectifier, a 2.7V supercapacitor, CE8301 boost converter, and TP4056 charging module, effectively charged a 3.7V, 1200mAh lithium-ion battery to power a 5W LED lamp for 53 minutes. Among the three damping configurations tested, the spring-mounted setup produced the highest output up to 3.72V AC, 2.45V DC. Calculations showed that approximately 168,820 footsteps over 23.5 hours are required to fully charge the battery, confirming the cumulative but low-energy nature of piezoelectric generation.

Simulations using MATLAB supported these findings, although differences were observed in real testing due to diode losses and inconsistent mechanical input. Overall, the system successfully integrated energy harvesting, power conditioning, and energy storage for small-scale public applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception, design, data analysis and manuscript preparation:*** *Muhammad Luqmanulhakim Bin Mohamad Ariffin;* ***manuscript verification:*** *Suhaimi Bin Saiman @ Saim. All authors reviewed the results and approved the final version of the manuscript.*

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