

IoT-Enabled Dual-Model Piezoelectric Energy Harvesting System for Real-Time Footstep Power Generation and Monitoring

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Abstract— This paper is a practical study about an IoT-enabled dual-model piezoelectric energy harvesting system designed to convert mechanical energy from human footsteps into electrical power that can be used. The system consists of two prototypes: a public infrastructure model, where piezoelectric sensors are embedded under high-footfall areas to power LED streetlights, and a wearable model integrated into footwear for charging low-power electronic devices. Arduino UNO and ESP32 microcontrollers is used by both these models for data collection and wireless transmission, with the collected energy data synchronized with Firebase and is visualized using a Flutter mobile application. The study showcases real-time monitoring and data tracking for both models. According to experimental analysis, the public model produces approximately 11 W of energy that can be used from 4,456 footsteps, while the wearable model generates around 0.48 W from 475 steps. The suggested system provides a cost-effective, portable, and eco-friendly solution for local energy generation, supporting smart infrastructure and sustainable urban development.

Index Terms— Piezoelectric energy harvesting, Piezoelectric sensors, Footstep power generation, Public infrastructure, Off-grid renewable energy, Footstep energy, ESP32, Arduino UNO, Firebase, Flutter Mobile Application.

I. INTRODUCTION

The rising demand for sustainable and decentralized energy systems has emerged as a global challenge. This is due to rapid urban growth, population increases, and a greater reliance on portable electronic devices. Traditional energy grids often struggle to meet this growing demand, especially in rural and off-grid areas. As a result, alternative energy sources that are renewable, affordable, and eco-friendly have received considerable attention.

Among these alternatives, piezoelectric energy harvesting stands out as a promising technology that converts mechanical stress or vibrations into electrical energy. Everyday human activities, such as walking or running, produce a lot of kinetic energy that often goes to waste. By placing piezoelectric sensors in surfaces or wearable items, we can convert this kinetic energy into usable electrical power, aiding in localized and sustainable energy production.

The connection between the Internet of Things (IoT) and piezoelectric systems further improves their usefulness. It allows for real-time data monitoring, energy tracking, and analysis via cloud platforms. This creates opportunities for smart, interactive energy systems that can effectively capture and share data.

Although there has been research on piezoelectric systems, most previous studies have focused on either fixed infrastructure, such as floor tiles or pavements, or wearable devices, but rarely both. Additionally, few studies have looked at IoT-based synchronization and real-time visualization of collected energy across multiple prototypes. To fill these gaps, this work introduces a dual-model IoT-enabled piezoelectric energy harvesting system that functions in two complementary ways:

1. A public infrastructure prototype that generates power in busy pedestrian areas.
2. A wearable prototype integrated into footwear for charging personal devices.

Key Contributions

This paper's main contributions are:

- Designing and implementing a dual-prototype piezoelectric energy harvesting system that powers both public and wearable applications.
- Integrating Arduino UNO and ESP32 microcontrollers for synchronized real-time data collection and wireless transmission.
- Developing a Firebase–Flutter mobile platform for live visualization and monitoring of energy data.
- Comparing both prototypes regarding power generation efficiency and feasibility.
- Presenting a low-cost, scalable, and environmentally friendly method for localized energy production.

This paper aims to show how combining mechanical energy harvesting with IoT-driven analytics can foster smart, energy-efficient, and self-sustaining environments for both urban infrastructure and portable device ecosystems.

II. LITERATURE SURVEY

During the last two decades, the integration of piezoelectric energy harvesting and IoT technologies has taken center stage in finding a solution to modern energy sustainability challenges. Piezoelectric systems essentially convert mechanical stress into electrical energy and, because of that, are very suitable for capturing energy from ambient vibrations or human motions. However, the efficiency of these systems remains limited due to variations in force, material properties, and conversion circuitry. Previous works, such as Gautschi (2002) and Priya & Inman (2009), laid the basic principles of piezoelectric sensorics and the mechanisms of energy conversion that initially enabled the exploration of fixed and wearable harvesting platforms.

Advances in microcontrollers and low-power electronics have hastened the deployment of energy-harvesting systems integrated with IoT capabilities. The most recent research on this subject by Todorov and Zaki (2021) presented ESP32-based wearable harvesters with real-time voltage monitoring and wireless data transmission. Similarly, other research explored the use of aluminum nitride materials for vibration-based energy harvesting (Elfrink et al., 2009), while Tan and Panda designed shoe-integrated piezoelectric systems to power mobile electronics (Tan & Panda, 2009). Yet most implementations remain single-purpose in either infrastructure-based harvesting or personal wearables, without a unified platform that bridges both applications.

IoT-driven monitoring platforms have bestowed the capability for real-time visualization, tracking of energy, and data synchronization through cloud-based services like Firebase and mobile applications such as Flutter, hence providing intelligent energy management and user engagement opportunities. However, literature shows very few research works that compare public infrastructure and wearable piezoelectric models under a single IoT framework.

Besides, circuit refinement for system performance optimization by using Schottky diodes, supercapacitors, and efficient rectifier configurations has been discussed in works such as those by Horowitz and Hill (2015) and Khaligh et al. (2010), underlining the importance of hardware-software co-design for improving conversion efficiency. Yet, the two issues of voltage stability and real-time synchronization across heterogeneous prototypes remain major challenges. In this paper, two IoT-enabled piezoelectric energy-harvesting systems are proposed—a combined model addressing both the public and wearable prototypes. The system accomplishes the capability for real-time monitoring of harvested energy, cost-effective scalability, and portability by synchronously driving microcontrollers, Arduino UNO and ESP32, respectively, with cloud-based data visualization. The convergence of mechanical energy harvesting with IoT analytics in this work presents a leap forward to sustainable, decentralized, and intelligent energy infrastructures for smart cities and personal devices.

III. RELATED WORK

Piezoelectric energy harvesting has been an active research area for over two decades. Researchers have studied materials, circuit optimization, and integration into wearable and structural systems. Gautschi (2002) first established the basic principles of piezoelectric sensors. Priya and Inman (2009) further explored their use in embedded and wearable electronics. These studies laid the foundation for converting ambient mechanical energy into electricity.

Recent advancements have focused on integrating with IoT, enabling smarter and connected energy systems. Todorov and Zaki (2021) proposed an IoT-based wearable energy harvester that achieved real-time voltage monitoring using microcontrollers. Elfrink et al. (2009) investigated vibration-based harvesting using aluminum nitride materials. Tan and Panda (2009) demonstrated a shoe-integrated piezoelectric generator for low-power devices.

However, most of these studies concentrated on single-mode systems, either fixed installations or personal wearables. There is still limited work on dual-use frameworks that combine public and individual energy applications within a unified IoT architecture.

At the same time, the adoption of low-power microcontrollers like ESP32 and Arduino UNO has made real-time monitoring more feasible for small-scale energy systems. Recent IEEE studies (2021-2024) highlight the growing trend of combining piezoelectric harvesting with cloud computing, mobile interfaces, and smart data logging. These developments improve the system's accessibility and scalability.

Despite these advancements, few implementations compare public infrastructure-based and wearable piezoelectric models. This research addresses that gap by developing and analyzing a dual-model IoT-enabled system. It leverages Firebase for cloud synchronization and a Flutter-based mobile app for real-time energy visualization.

IV. MOTIVATION

With rapid urbanization and technological growth, global electricity demand is rising sharply. According to international energy projections, electricity consumption is expected to increase by nearly 50% by 2050. Meeting this demand with traditional energy sources presents challenges such as fossil fuel depletion, high costs, and pollution. This situation requires the exploration of renewable and decentralized energy solutions that are sustainable and cost-effective.

One promising yet underused source of renewable energy is the mechanical energy from human movement. Every step taken in busy places like bus stations, sidewalks, or shopping centers generates kinetic energy that usually gets wasted. Capturing this energy with piezoelectric materials, which convert mechanical stress into electrical charge, offers a simple and eco-friendly way to produce power.

Additionally, the growing reliance on mobile and portable electronic devices, especially in rural or remote areas with limited grid access, highlights the need for self-sustaining energy generation systems. A small, wearable energy source that can recharge essential devices like phones or sensors could greatly improve convenience and access.

By incorporating Internet of Things (IoT) technologies, these energy harvesting systems can be monitored and tracked in real time. Cloud-based databases and mobile applications can display power generation, efficiency, and usage patterns, raising awareness among users about sustainable energy practices.

This research is driven by three main goals:

- To capture unused mechanical energy from human footsteps for power generation.
- To create a dual-mode system that supports both public infrastructure and individual portable devices.
- To enable real-time IoT-based monitoring that encourages user participation and data-driven improvement.

This approach connects renewable energy generation, IoT analytics, and user interaction, providing a new solution for smart and sustainable energy systems.

V. PROBLEM DOMAIN

With the increase of global electricity demand predicted to increase by nearly 50% by 2050 due to rapid urbanization and population growth^[3], there is a vital need for alternative source of renewable energy. A substantial amount of environmental mechanical energy- particularly from footsteps in high-density urban areas-remains untouched.

Already available urban infrastructure lacks mechanisms to utilize this kinetic energy, leading to new opportunities for sustainable power generation. At the same time, the widespread use of mobile devices has proportionally increased the demand for portable, autonomous energy sources mainly in off- grid or in-transit scenarios.

This project addresses these issues by utilizing sensors to capture mechanical stress and convert it into electrical energy. When integrated with pathways and wearable devices, the sensors offer a decentralized and low-maintenance energy solution. This approach matches smart infrastructure initiatives and supports localized and renewable energy management.

VI. PROBLEM DEFINITION

The main aim of this project is to develop a system that captures mechanical energy generated from human locomotion into usable electrical energy. The converted energy has two main uses: powering public infrastructures and charging personal electronic devices.

To make it practical, the solution must incorporate real-time data monitoring through cloud-based IoT platforms. Optimal energy conversion, reliable storage, cost-effective deployment and minimal maintenance should be ensured. The solution should support all possible use cases and should be scalable in a variety of settings.

VII. PROBLEM STATEMENT

In today's rapidly urbanizing world, a huge amount of mechanical energy generated by human footsteps remains unutilized. High-traffic public spaces withstand thousands of steps daily, but the current infrastructure lacks the capability to utilize it fully. With the global energy demand projected, recovering this lost energy is both a necessity and an opportunity. The main challenge is to develop a scalable, dual- prototype energy harvesting system. The first prototype targets public environments to capture energy and the second prototype focuses on personal wearables to provide portable, user-specific energy generation.

To be effective, the proposed system should ensure the real-time energy monitoring via Internet of Things (IoT) platforms, maintain cost-efficiency, support easy deployment and operate with minimal maintenance. It must be adaptable to various kinds of environments including both urban and rural environments.

By addressing the issues of urban energy wastage and rising demand for electricity, the main aim of this project is to provide a practical approach for sustainable energy generation.

VIII. INNOVATIVE CONTENT

The novelty of this work lies in integrating two piezoelectric energy harvesting prototypes, a public infrastructure system and a wearable system, under a single IoT-enabled monitoring platform. Most earlier studies have looked at fixed (floor-based) or wearable piezoelectric systems separately. In contrast, this project presents a hybrid dual-framework that connects both prototypes through cloud-based monitoring, addressing community-level and personal energy needs.

The first prototype embeds piezoelectric sensors beneath high-footfall areas, like bus stands or pavements. These sensors convert the pressure from footsteps into electrical energy. The produced power is rectified, stored in supercapacitors, and used to run 12 V LED streetlights, creating a local, self-sustaining lighting system.

The second prototype is a wearable model integrated into footwear. It uses compact piezoelectric discs connected to a lithium-ion battery via a rectifier and voltage regulator circuit. This setup can charge small portable devices through a 5 V USB

output. The energy data, including step count, voltage, and battery status, is managed by the ESP32 microcontroller, which sends real-time data to Firebase.

Both systems synchronize through an IoT framework that includes Arduino UNO and ESP32 modules, a Firebase Realtime Database, and a mobile application built with Flutter. The app shows live power output, energy usage, and system status, improving transparency and user engagement.

From a technological standpoint, this innovation also encompasses:

- The dual-use design, which combines public and wearable prototypes under a single monitoring structure.
- Scalable, low-cost hardware made with off-the-shelf components like Arduino UNO and ESP32.
- Real-time cloud synchronization using Firebase for efficient data logging and visualization.
- User interaction and feedback through a mobile interface that encourages energy awareness.

This dual-framework system illustrates how merging mechanical energy harvesting with IoT data analytics can support smart infrastructure, personal energy independence, and sustainable urban living. By showcasing both scalability and portability, the proposed system offers a model for the next generation of decentralized renewable energy technologies.

IX. SYSTEM ARCHITECTURE AND DESIGN

The two primary parts of the Energy Under Foot concept are a wearable shoe prototype and a stationary public infrastructure unit. Both are designed to use piezoelectric technology to capture human kinetic energy, and integrated Internet of Things microcontrollers are used to store and track the energy.

A. Public Infrastructure Model

In the first prototype, piezoelectric sensors are placed under platforms where the population density is high, such those found at bus stops. Lead Zirconate Titanate (PZT) sensors receive mechanical force when a user steps on the surface, producing an alternating voltage. The physics underlying this method, force-to-voltage conversion in piezoelectric sensorics, is explained by Gautschi^[1]. As Elfrink et al.^[8] showed, the usual voltage output ranges from 10 to 30 V AC, depending on frequency and foot pressure because of their low voltage drop.

Once the AC is generated, a full-wave bridge rectifier is used to correct the raw AC generated and capacitors are used for stabilization of the AC. Low-power devices are provided with energy by a set of supercapacitors which have the capacity to store regulated DC voltage in the 5–12 V range. Schottky diodes are used to increase the efficiency of the system. This infrastructure provides clean, locally harvested power, reducing dependency on the grid. The idea is comparable to that put out by Ramya and Bhuvana for real-time energy monitoring on public walkways^[10].

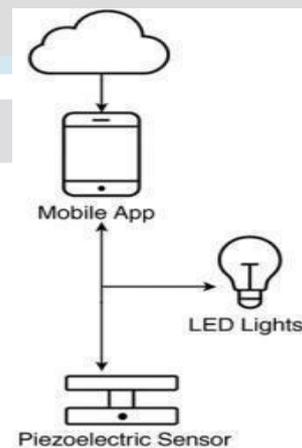


Fig. 1. Block Diagram of Bus Stand Energy Harvesting System

B. Wearable Shoe-Based Model

The second prototype is focused on wearable energy harvesting. Piezoelectric PZT discs are arranged under the sole of the shoe. With each step, the material is strained and generated voltage spikes, as studied earlier by Ferrar et al.^[6] and Tan and Panda^[14]. These voltage spikes are transmitted through a low-dropout rectifier to a lithium-ion battery.

A step-down DC-DC converter regulates the battery to 5V, which is suitable for charging small electronic devices. Paradiso and Straner^[9] explored the use of harvested energy in mobile devices.

To improve interactivity and real-time data monitoring, the prototype used ESP32 microcontroller, which stores the step count, voltage generation and battery status. It was chosen because of its integrated ADC and wireless capabilities, as documented in Espressif's technical documentation^[12]. The generated real-time data is transmitted to Firebase Realtime Database^[13], which helps in enabling cross-device tracking and visualization.

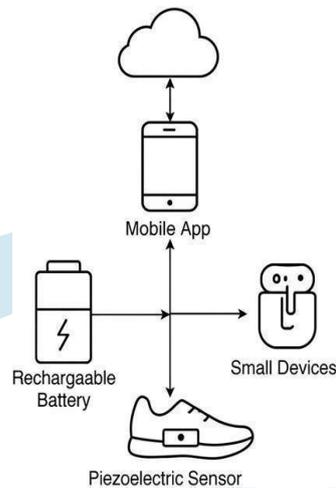


Fig. 2. Wearable shoe circuit and energy flow

C. Microcontroller Synchronization and Data Feedback

The public infrastructure model uses an Arduino UNO and the wearable model uses the ESP32 because of its dual-core processing and integrated Wi-Fi. Todorov and Zaki ^[7] highlights the importance of lightweight, embedded architectures in wearable energy systems. The data is visualized through a Flutter-based mobile app that retrieves the data from the Firebase and presents the real-time insights on step-count, energy harvested, and charge levels and also improves user awareness and participation in sustainability ^[13].

D. Circuit Optimization and Performance

The key components of the prototypes such as a diode type, capacitor ratings, and voltage regulation are used to improve the energy conversion efficiency and system stability. Ceramic buffer capacitors are used to manage voltage spikes and fluctuations in walking behavior, matching with the design recommendations of Horowitz and Hill ^[5]. The use of Schottky diodes and careful tuning of the voltage regulator has minimized conversion losses, as advocated by Khaligh et al. in their review on kinetic energy harvesting techniques ^[11].

X. SOLUTION METHODOLOGY

The solution technique is to harness kinetic energy via piezoelectric sensors in series- parallel configurations to generate maximum energy. In the case of the bus stand model, the sensor array is interfaced with an Arduino UNO which samples analog voltages and transfers the data serially to a PC where it is uploaded by a Python script to Firebase. The stored energy is used to power adjacent LED lights, and step and energy data are observed in real time through a mobile app.

In the shoe prototype, piezoelectric sensors embedded in the insole are wired to an ESP32 microcontroller, which manages real-time voltage reading, step counting, and Firebase synchronization. Energy is stored in a small rechargeable battery and tapped through a USB output for charging devices. This wearable system provides energy independence, mobility, and real-time user feedback, all in a compact and portable package.

A. Bus Stand Model

In a static public place, PZT sensors are placed under a raised platform. When the humans walk across a mechanical pressure is applied to the sensor array that generates alternating current. Series and parallel combinations of PZT units are used to enhance the voltage and current output, based on studies by Gautshi ^[11] and Ferrari et al. ^[6]. Generally, the output from each sensor ranges from 10-30 V, depending on the force applied and the frequency stride ^[8].

An Arduino UNO reads these analog voltages, samples the information, and sends it directly to a PC that is attached. The sampled voltage data is uploaded to Firebase for remote monitoring via a Python script running on the PC. Concurrently, the captured energy is adjusted, controlled, and kept in a bank of supercapacitors that supply power to nearby 12 V/3 W LED lamps, establishing a self-sufficient, grid-independent lighting system. This configuration's statistics, such as energy levels and step count, are shown in real time through a Flutter-developed mobile application that uses Firebase for backend data ^[13].

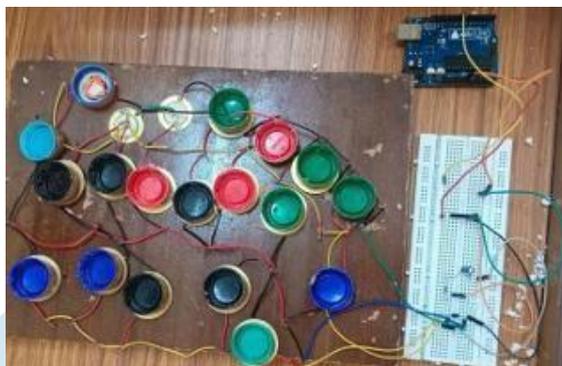


Fig. 1. Circuit Connection for Bus Stand Prototype

B. Wearable Shoe Based Model

Compact PZT discs are integrated into the insole of the wearable prototype. A low-dropout rectifier is used to condition the voltage spikes caused by mechanical deformations that occur as the user moves. The 2200 mAh, 3.7 V lithium-ion battery stores the energy and can be used to charge portable devices using a USB port. Strategies similar to wearable energy collection were documented in earlier studies by Tan and Panda^[14], with consistent production ranging from 1 to 2 W during moderate exertion.

The model uses an ESP32 microcontroller for multiple purposes such as using pulse frequency mapping to count the digital steps, syncing the data to Firebase wirelessly, and to record voltage readings in real time. The ESP32 is best suited for small, portable energy applications due to its integrated Wi-Fi and ADC capabilities^[12].

The final product is a portable, small, self-sufficient energy harvesting system that gives customers real-time activity insights and energy utility.



Fig 4. Circuit Connection for Shoe Prototype

| Component | Specification | Used in |
|----------------------------|--------------------------------------|-----------------|
| Piezoelectric Sensor | 27 mm disc, resonant freq ~6 kHz | Both Models |
| Arduino UNO | 10-bit ADC, USB interface | Bus Stand Model |
| ESP32 Microcontroller | Dual-core, Wi-Fi, ADC, Bluetooth | Shoe Prototype |
| Lithium-Ion Battery | 3.7 V, 2200 mAh | Shoe Prototype |
| Supercapacitor Bank | 10 F, 2.7 V units | Bus Stand Model |
| Full-Wave Bridge Rectifier | Silicon diodes / Schottky (low-drop) | Both Models |
| LED Light | 12 V, 3W | Bus Stand Model |
| Mobile App (Flutter) | Firebase integrated | Both Models |

Table 1. Component List for Both Subsystems

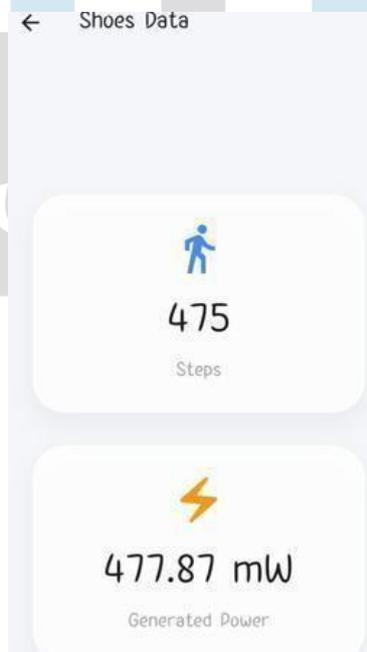


Fig 5. Mobile Application Home Page Screen

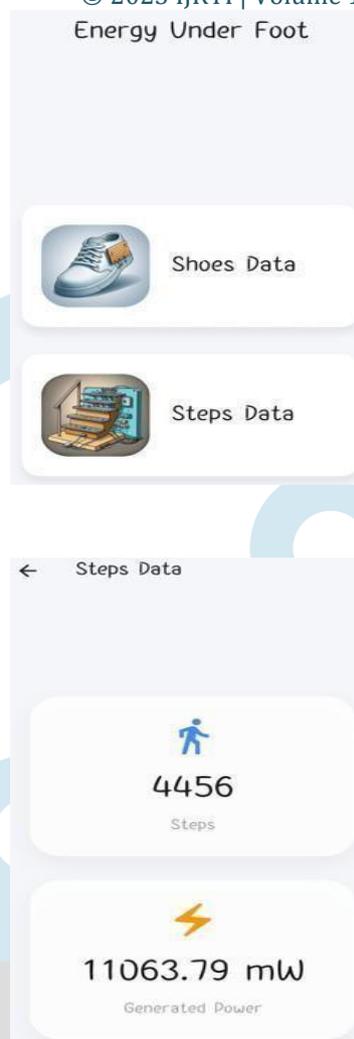


Fig 6. Mobile Applications Screens for Steps and Shoes

XI. DATA MODEL

The above prototypes, includes project's Firebase database's NoSQL structure allows real-time updates, lightweight querying, and efficient data management. The data is separated into high-level nodes that represent the several types of shoes and step (public unit) devices and child nodes that store energy and use information.

Figure 7 illustrates the structure of the Firebase database; it provides the steps and watts as the two primary fields for each node. This format enables continuous data logging, future analytics, and fast access to mobile applications.

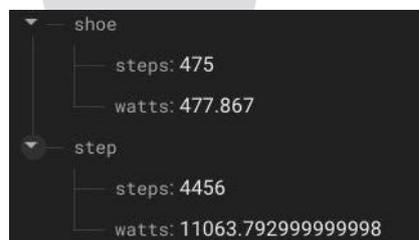


Fig 7. Firebase Data

Using Firebase Realtime Database ensures smooth integration with the mobile application and provides fast data read/write speeds. This cloud-backed architecture supports instant feedback, robust user management and easy scalability of the system ^[13].

XII. PERFORMANCE EVALUATION

To evaluate the efficiency of both prototypes, we conducted a comparison based on step count, voltage generation, and total power output. We performed controlled experiments where we recorded the number of footsteps and applied pressure for both models under similar conditions.

The bus stand model produced an average voltage output between 10 V and 30 V AC per piezoelectric sensor, depending on the applied force. The total energy from 4,456 footsteps was about 11 W, enough to power 12 V / 3 W LED lamps for short periods. The wearable shoe model generated lower power levels, producing an average regulated output of 5 to 12 V DC, which translated to 0.48 W from 475 steps. The energy was stored in a 3.7 V, 2200 mAh lithium-ion battery, allowing it to charge small electronic devices for 10 to 15 minutes.

These results show that the public model is more effective for generating energy collectively, while the wearable prototype is better for personal, low-power uses. We minimized voltage fluctuations from irregular walking pressure by improving the rectifier and capacitor configurations. Table 2 summarizes the findings from both prototypes, confirming that piezoelectric materials can be used in hybrid IoT-based energy systems.

| Feature | Bus Stand System | Footwear System |
|-----------------------|---------------------------------|------------------------------------|
| Application | Street Lighting | Mobile device Charging |
| Sources of Energy | Public Footstep | Individual Walking |
| Energy Output | ~11,063.79W from 4,456 steps | ~477.87W from 475 steps |
| Voltage Generated | 10–30V AC (per sensor unit) | ~5-12V regulated DC |
| Storage Device | Capacitor + Battery Combination | 3.7V, 2200mAh Rechargeable Battery |
| Communication | Arduino UNO → Python → Firebase | ESP32 Wi-Fi → Firebase |
| Output Device | 12V/3W LED Streetlights | 5V USB Charging Por |
| Real -Time Monitoring | Yes | Yes |
| Target Users | Public Infrastructure Utilities | Individual Mobile Users |
| Installation Cost | Moderate | Low |

Table 2. Performance Comparison between Bus Stand and Footwear-Based Energy Harvesting Systems

XIII. CONCLUSION

This project shows the development of the two prototypes: a public platform to power LED streetlights and a wearable shoe-based system for mobile device charging. It generates the electrical piezoelectric unit producing 10–30 V AC. The shoe-based wearable system generates 477.87 m W from 475 steps, storing energy in a 3.7 V, 2200 mAh lithium-ion battery, supporting a 5 V USB output with a charging time of 10–15 minutes.

Real-time data visualization was achieved through Firebase and a Flutter-based mobile app which allows users to utilize and monitor energy generation. Major challenges such as voltage fluctuation and sensor variability were managed by refining rectifier circuits, capacitor configurations, and microcontroller logic.

This research shows the design and setup of an IoT-enabled dual-model piezoelectric energy harvesting system that effectively turns human footsteps into electrical power. The proposed system brings together piezoelectric sensors, microcontrollers, cloud-based data syncing, and mobile monitoring for real-time energy generation visualization. Experiments confirmed that both prototypes worked well. The public infrastructure model produced about 11 W of usable energy, while the wearable model generated 0.48 W of power. Both models are suitable for off-grid and personal device applications.

The study points out the potential of combining mechanical energy harvesting with IoT for sustainable, decentralized energy solutions. However, the current system faces limitations due to the efficiency of the piezoelectric sensors and variability in energy output from inconsistent step force. Future work will concentrate on improving energy conversion efficiency, using high-performance piezo materials, refining power storage circuits, and expanding the IoT analytics platform for large-scale smart city deployment.

REFERENCES

- [1] G. Gautschi, *Piezoelectric Sensorics: Force, Strain, Pressure, Acceleration and Acoustic Emission Sensors, Materials and Amplifiers*, Springer, 2002.
- [2] M. S. Priya and D. J. Inman, *Piezoelectric Energy Harvesting*, Springer, 2009.
- [3] A. Khaligh and O. C. Onar, *Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems*, CRC Press, 2009.
- [4] A. Bahga and V. Madiseti, *Internet of Things: A Hands-On Approach*, VPT, 2014.
- [5] P. Horowitz and W. Hill, *The Art of Electronics*, 3rd ed., Cambridge University Press, 2015.
- [6] M. Ferrari, V. Ferrari, D. Marioli and A. Taron, "Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems," *IEEE Sensors J.*, vol. 6, no. 5, pp. 1315–1322, Oct. 2006.
- [7] M. H. Todorov and T. A. Zaki, "Design of IoT- Based Wearable Devices for Energy Harvesting," *IEEE Access*, vol. 9, pp. 11023–11035, 2021.
- [8] R. Elfrink et al., "Vibration energy harvesting with aluminum nitride-based piezoelectric devices," *J.Micromech. Microeng.*, vol. 19, no. 9, 2009
- [9] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan. 2005.

- [10] K. Ramya and R. S. Bhuvana, "Real-Time Monitoring of Energy Using Piezoelectric Sensors in Public Footpaths," in Proc. IEEE Int. Conf. Comput., Intell., Commun. Technol. (ICCICCT), 2019, pp. 589–593.
- [11] A. Khaligh, P. Zeng and C. Zheng, "Kinetic Energy Harvesting Using Piezoelectric and Electromagnetic Technologies—State of the Art," IEEE Trans. Ind. Electron., vol. 57, no. 3, pp. 850–860, Mar. 2010.
- [12] ESP32 Technical Reference Manual, Espressif Systems, 2024. [Online]. Available: https://documentation.espressif.com/esp32_technical_reference_manual%20_en.pdf
- [13] Firebase Realtime Database, Google Firebase, 2024. [Online]. Available: <https://firebase.google.com/docs/database>
- [14] Y. K. Tan and S. K. Panda, "Energy Harvesting From Body Motion of a Wearable Shoe System," IEEE Trans. Ind. Electron., vol. 56, no. 1, pp. 428–436, Jan. 2009.

