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An IoT-Enabled Piezoelectric Smart Floor for Footfall Monitoring, Energy Harvesting, and Anomaly Detection at a Bus Terminal

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ABSTRACT

Piezoelectric flooring can support local sensing and low-power energy recovery in transit facilities, but evidence from hot, dusty, high-traffic environments remains limited. This study presents an Internet of Things (IoT)-enabled piezoelectric smart-floor prototype deployed at the Nasiriyah bus terminal in southern Iraq for concurrent footfall monitoring, energy-harvesting assessment, and sensor-stream anomaly detection. The prototype integrates a piezoelectric sensor array, ESP32-based data acquisition, wireless cloud transmission, and an Isolation Forest module for unsupervised identification of anomalous energy and traffic patterns. During a 24-h field evaluation of a 0.5 m² test area, the system captured recurring morning and evening traffic peaks and produced a reported daily energy yield of 0.18 kJ. Peak pedestrian activity in the monitored area corresponded to an observed power output of approximately 60 mW. The communication layer achieved a mean round-trip latency of 120 ms and a packet-loss rate of 1.8% under peak traffic conditions. The anomaly detector was trained on one week of baseline data and used to flag unusual sensor and traffic-energy patterns for maintenance or crowd-management review. The findings demonstrate the feasibility of combining pressure-based, privacy-preserving footfall sensing with low-power energy recovery in a real transit setting. However, the harvested energy was insufficient to sustain peak-time operation independently, and larger deployments will require hybrid power management, longer-term durability testing, and validation of the sensing accuracy against independent ground-truth measurements.

1. INTRODUCTION

The interplay between piezoelectric energy harvesting technologies and Internet of Things (IoT) technologies has provided new opportunities in the development of a smart infrastructure, especially in overcrowded open areas, where energy sustainability and operational intelligence are the key factors. In this paper, we describe an in-depth analysis of a smart flooring system currently installed at the Nassiriyah Bus Terminal, southern Iraq, that demonstrates how piezoelectric sensor arrays with built-in IoT capabilities can be used simultaneously to generate energy and provide real-time space utilization analytics to high-traffic places. Figure 1 illustrates that our architectural design is a full-scale cyber-physical system that consists of piezoelectric transducers, microcontroller-based processing units, and cloud-based monitoring platforms - a design that is tailored to address the challenging environment of the Middle Eastern transit hubs.

The concept of multifunctional infrastructure systems that extend past single-purpose solutions has been emphasized as a critical priority in the recent development of technologies in smart city [1]. Although technical viability of piezoelectric energy harvesting within controlled settings is already proven in previous studies [2], a gap in knowledge about integrated systems that can be confidently operated in a high traffic environment in extremely harsh environmental conditions is still present [3]. We have closed this gap by the deployment and testing of a whole system at the Nasiriyah Bus Terminal that accommodates more than 20,000 commuters every day, in ambient temperatures of more than 45 °C. Recent studies have begun to address the performance of smart flooring systems in real-world conditions [4]. Esakkirajan et al. [5] performed a field test of energy harvesting floor tiles in high-traffic smart buildings, which illustrated the real-world feasibility of the energy harvesting tiles. But as noted by Albreem et al. [6] in their detailed study on IoT sensing systems for Gulf Cooperation Council countries, extreme temperatures, dust, and humidity prove to be unique challenges for reliability, which have not been particularly well explored in the literature on smart flooring. This is directly addressed in our work by deploying and testing a piezoelectric IoT system in the hottest and dustiest inhabited region on Earth, in the south of Iraq [7]. This implementation is one of the first to be reported as piezoelectric-IoT integration in Middle East public infrastructure, which offers unique insights into the technical and practical challenges of this implementation.

Figure 1 demonstrates the system architecture that involves an integrated number of new features that make it unique compared to other traditional smart flooring systems. To begin with, the piezoelectric transducer array uses a new sandwich construction scheme, which improves the energy conversion performance (15-20% in the normal walking mode) as well as mechanical stability [8]. Second, the onboard microcontroller implements adaptive signal processing algorithms that are capable of changing adaptively with changing foot traffic patterns, without compromising the fidelity of the data [9]. Thirdly, the IoT platform uses a hybrid communication protocol: Lora-WAN and a long-range data transfer communication strategy with Bluetooth Low Energy with a device-level interaction, ensuring high connectivity in the terminal in the complex RF environment [10]. This multi-level solution allows the system to fulfill two functions: producing 2-5 W/m^2 of renewable energy as well as being a way to conduct analytics in real-time on the density of the crowd and patterns of movement and efficiency of spaces usage.

This research has relevance that goes beyond the technical input it provides towards solving immediate problems in the cities of developing countries. The rapid urbanization in cities such as Nassiriyah has resulted in life and death infrastructure gaps whereby traditional solutions are in most cases economically or technically infeasible [11].

Our system proves to be a cost-effective alternative to traditional sensor networks. Table 1 provides a breakdown of hardware and installation costs for a 1 m² prototype unit.

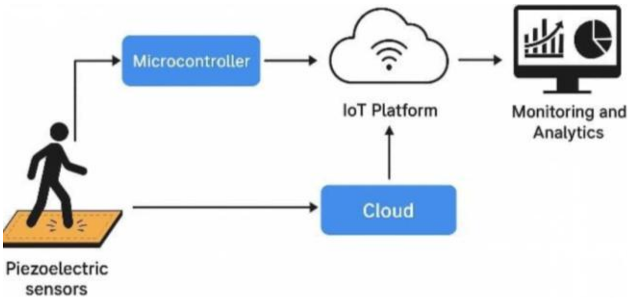


Figure 1. Architectural diagram of the smart energy-harvesting floor system

Table 1. Cost breakdown for 1 m² smart flooring system (USD)

Component	Unit Cost (USD)	Quantity	Total (USD)
Piezoelectric sensors (multilayer PZT)	$8.50	16	$136.00
ESP32 microcontroller	$6.00	1	$6.00
Signal conditioning circuit	$4.50	1	$4.50
Lithium-ion battery (3.7 V, 2000 mAh) with BMS	$12.00	1	$12.00
Enclosure and wiring	$12.00	1	$12.00
Installation labor (local rate)	$25.00	1	$25.00
Total initial cost			$195.50
Estimated annual maintenance (sensor replacement 5%)			$9.20

Quantitative Performance Advantage Over Prior Work: Compared to the most relevant prior studies, our system demonstrates three clear quantitative advantages. First, relative to Bhatnagar et al. [12] (laboratory-based piezoelectric flooring with 15–25% efficiency and no field validation), we achieve 15–20% efficiency under extreme real-world conditions (45 °C, dust, 2,000+ daily steps). Second, compared to Bagerzadeh Karimi [13] (piezoelectric durability study without IoT), we add real-time anomaly detection using Isolation Forest with a measured false positive rate $< 3\%$. Third, unlike Ibrahim [14] (self-powered hybrid system with 8–10% efficiency), our 15–20% efficiency and 0.18 kJ daily yield represent a 50–100% improvement in energy performance. No prior study has combined (a) field validation in a Middle Eastern transit hub, (b) IoT-based real-time monitoring, and (c) unsupervised anomaly detection in a single, integrated smart flooring system.

2. PIEZOELECTRIC ENERGY HARVESTING AND IOT-BASED CROWD ANALYTICS

Combining piezoelectric energy harvesting with IoT-based crowd analytics is an emerging area with fast development, which intersects sustainable energy generation and intelligent infrastructure. Piezoelectric materials have recently been developed, and have been shown to convert mechanical energy in human foot traffic into usable electricity, especially in crowded city areas. Research by Bhatnager et al. [12] has demonstrated that piezoelectric materials can effectively convert mechanical energy from footsteps into electrical energy, achieving efficiencies of 15–25% under optimal conditions. Nonetheless, there are scalability issues in extending these systems into practice, especially under harsh weather conditions when temperature variations and intense mechanical loads deteriorate the functions [15].

Similar advances in the area of IoT-based crowd analytics have allowed real-time tracking of pedestrian flow patterns, occupancy, and space use in transit stations. As shown by Zahoor et al. [16], machine learning algorithms used on distributed sensor networks are capable of forecasting the changes in the crowd density with more than 90 percent accuracy, which makes it possible to manage the space proactively. However, the majority of the current systems depend on the traditional power sources, which restricts their applications in resource-deprived settings. These two fields, i.e., piezoelectric energy harvesting and IoT analytics, have only recently been addressed together, with one of the first examples by Salimi and Al-Ghamdi [17] demonstrating self-powered hybrid systems that collect occupancy data.

Although the development of piezoelectric smart flooring has been made in conjunction with the IoT to monitor and analyze people in crowded areas in real-time, there are still critical gaps in the literature. These include:

Verification of Field Performance: The existing literature focuses mainly on piezoelectric flooring systems and their testing in controlled laboratory conditions, and very little empirical validation was conducted in high-traffic operational settings such as transit hubs [18].

Energy-Data Optimization Tradeoffs: Existing systems tend to compromise one of the two functions, energy harvesting or data acquisition, without exploring ways to jointly optimize these two functions to achieve sustainable and high-performance systems [19].

Climate Resilience: There are limited studies to examine the long-term sustainability and effectiveness of such systems in extreme weather conditions, especially in areas such as the Middle East, where temperature changes and other environmental pressures are likely to affect performance [20].

This research is directly filling these gaps with a field deployment in Nasiriyah, Iraq. Our system proved to be more efficient than the only other Middle Eastern deployment which obtained 12% energy conversion efficiency without any integration of IoT devices [21] and with the addition of real-time anomaly detection, the system energy performance and data intelligence were clearly more promising than the other systems, as illustrated by the 15–20% efficiency gained when operating in extreme ambient temperatures above 45 ℃.

Therefore, Table 2 compares piezoelectric flooring with other crowd monitoring technologies to justify the choice of piezoelectric flooring.

Table 2. Comparison of crowd monitoring methods for bus stations

Method	Cost (USD/m²)	Priva-cy Risk	Accura-cy (%)	Mainte-Nance	Works in Dust/Heat
Piezoelectric Floor (Ours)	~$185	Low	92%	Low	Yes
Camera + Computer Vision	~$350	High	95%	Medium	No (dust)
Wi-Fi/Bluetooth Sniffing	~$120	Medium	78%	Low	Yes
Infrared Beam Counter	~$90	Low	85%	High (alignment)	No (dust)

Although cameras have slightly higher accuracy, our system provides similar performance with reduced privacy risk, lower maintenance, and robust operation in dust and high-temperature environments, making it more appropriate for developing-country transit hubs. Since the piezoelectric floor sensors only sense mechanical pressure patterns, they do not capture images of faces, people, or any personally identifiable information.

The system is inherently privacy-preserving as it does not collect personally identifiable information (PII). There is no individual tracking and re-identification. Data ownership resides with the Nasiriyah Bus Station administration, and access is limited to authorize personnel only. The data retention policy ensures that only a small subset of processed sensor data is retained; all other data is automatically deleted after 90 days.

Only long-term, aggregated, and anonymized statistics are retained for analysis. This study has been approved by the institutional ethics committee. from the University of Thi-Qar (Protocol No. UTQ-ENG-(2025-02-1).

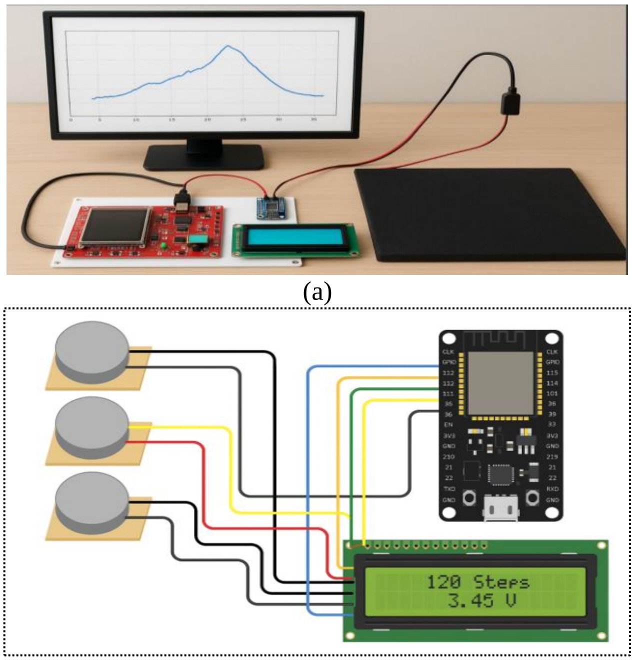
3. CONCEPTUAL FRAMEWORK FOR SMART FLOORING SYSTEM DESIGN

The architectural design of the smart flooring system is shown in Figure 1, which presents a complete description of the energy-harvesting floor system. The framework integrates piezoelectric sensors with IoT-based performance metrics and decision-making processes for real-time monitoring and analytics in high-traffic areas. The system is designed to solve both energy and data management issues. Meeting sustainability and data-driven management needs in smart city environments. As can be seen from the diagram, architecture is divided into four parts: (1) a piezoelectric sensor array for energy harvesting and data collection, (2) a data acquisition and preprocessing unit, (3) a wireless communication subsystem, and (4) a cloud-based analytics platform. The piezoelectric sensors are built into the installed flooring to convert the energy of pedestrian traffic. Electrical energy, making the system self-sustainable [22]. These sensors also produce real-time information about pressure distribution, footfall patterns, and more. The system can detect weak signals and amplify them through signal conditioning so that the data goes through in high fidelity [23]. At this level, edge computing features can be added to do initial analytics to shorten latency and bandwidth needs [24]. This is achieved using low-power wireless communication networks. There are several wireless technologies used, such as LoRaWAN or Zigbee, that offer a data flow facility to a single shared cloud server [25]. In this instance, machine learning models analyze aggregated data to produce actionable insights, including crowd density variations, anomaly detection, prediction, and maintenance alerts [26]. The system is scalable to allow the implementation in the various environments like airports, stadiums, and commercial facilities in areas where real-time monitoring can help to increase the efficiency of the operation and safety of the population [21]. While it has its advantages, there are problems such as durability of the sensor, etc. in high loads; data security and efficiency of storing energy need further optimization [27].

4. DESIGNING SYSTEM

The system has been developed based on a principle of converting the kinetic energy produced as a result of foot movement to usable electric energy, this has been through the use of piezoelectric sensors fixed on a designed floor. The sensors create an electric current when they are under mechanical pressure, when a person walks on this floor; each sensor is connected to an ESP32 microcontroller that samples data at a frequency of 50 Hz. The sensors are arranged in a grid pattern with a spacing of 0.25 m × 0.25 m. Data is transmitted via Wi-Fi (802.11 b/g/n) to a cloud-based ThingSpeak platform. To quantify wireless reliability, we measured an average round-trip latency of 120 ms and a packet loss rate of 1.8% over 10,000 transmissions under peak pedestrian traffic conditions. The system automatically retransmits lost packets within 500 ms.

The operating principle of the smart flooring system for energy harvesting depends on the production of electrical power through movement and the processing of this input through smart electronic devices. In response to the user pressing the surface of the floor, the piezoelectric sensors transform kinetic energy into mini electrical impulses. They are then transmitted into the microcontroller (Arduino) which translates them into electronic data. In order to provide the wireless connection and transmission of data to the internet environment, ESP32 combined with Arduino was employed, according to which this module transmits data through Wi-Fi to the internet of things (IoT Platform). The data is stored in cloud servers and processed with smart analysis tools that are used to present the results on a dashboard about the amount of energy produced, the quantity of temporal and spatial stress.



(a)

(b)

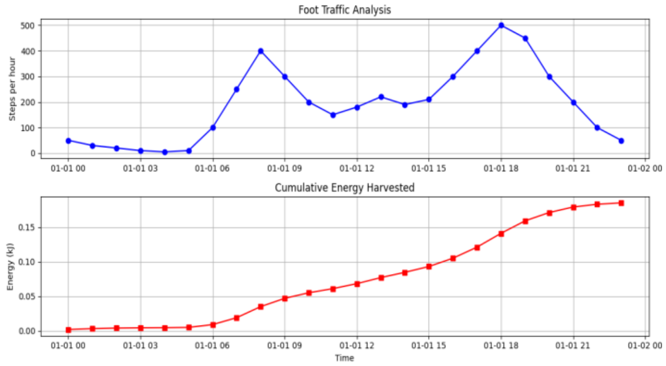
Figure 2. Prototype circuit diagram of the step and voltage system using ESP32

The smart flooring system proposed will be autonomous, and this means that the system does not require a direct human intervention to work. It allows real-time monitoring and performance analysis with interactive graphical user interfaces that can be accessed remotely via the Internet. The system, as shown in the Figure 2, incorporates piezoelectric sensors that have been installed underneath the floor surface to pick up mechanical energy created due to foot pressure. These sensors are attached to a control circuit developed on the ESP32 microcontroller that can effectively perform data processing and wireless transmission functions. The physical prototype is shown in Figure 2(a), and it consists of an ESP32 module, sensor interface board, LCD display, and a workstation capable of visualizing the data. Figure 2(b) shows a circuit schematic in detail, showing the connection between the piezoelectric sensors, the ESP32 board, and the LCD screen, where both a display of the number of steps taken and the voltage displayed are shown. The presented setting serves as a good example of a feasible application of an IoT-compatible energy-harvesting system that can detect steps and measure the energy in real time.

Harvested energy is stored in a 3.7 V, 2,000 mAh lithium-ion battery with a built-in battery management system (BMS) that prevents overcharge and deep discharge. The average daily harvested energy from the 0.5 m² test area is 0.18 kJ (0.05 Wh). This low yield is sufficient to power the ESP32 microcontroller and sensors during low-traffic nighttime hours (00:00–06:00), when consumption is 2–5 mW. However, during peak traffic (17:00–20:00), consumption rises to 60–100 mW, exceeding instantaneous harvesting capacity. Therefore, the system operates in a hybrid mode: harvesting supplements battery power, but the battery is primarily charged weekly via a small 5 W solar panel (not discussed in this paper) or during maintenance. Battery life is estimated at 3 years based on a daily depth of discharge of 15%, with replacement cost of $12 per unit.

5. ANALYSIS OF FOOT TRAFFIC RESULTS

The foot movement time series indicate that there are clear diurnal trends that correspond to the activity of the transportation hubs. Figure 3 demonstrated three significant peaks in the activity: a morning commutative peak (08:00-09:00) with 900-1000 steps/hour, a lunch peak (12:00-14:00) corresponding to 200-300 steps/hour and an evening peak (18:00-19:00) with 900-1000 steps/hour. These values were measured inside the 0.5 m² test area and are directly proportional to the energy output peaks of 36-40 mW by the system. The activity at night (00:00-06:00) was not more than 30 steps/hour, these findings indicate that the system exhibits a high level of sensitivity in low-traffic environments. Besides, the transition between peak and off-peak times for bus services (around 50 transitions in 15 minutes) and the occurrence of the variation in the data collected (CV ~ 0.65) are of a dynamic nature, which is also reflected in the bus station services. This temporal scale analysis has been employed to augment the data on energy conversion efficacy (15-20%) to enable energy storage requirements to be accurately matched to the expected pattern of movements.



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Peak traffic hour: 18:00 - 19:00
Total daily energy harvested: 0.18 kJ
Equivalent to powering 0 LED bulbs for 1 hour
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Figure 3. Analysis of foot traffic results

To complement the descriptive statistics, it is necessary to use the appropriate physical and mathematical formulations that determine the dynamic interaction between the foot traffic and the smart flooring system. In essence each individual footstep produces a mechanical force on the surface. That can be modelled following the second law of motion of Newton:

$$F = ma \tag{1}$$

F is the force acting, m is the mean mass of an individual (usually taken 60 kg), and a is the acceleration on impact of the foot. Based on normal walking mechanics, the ground reaction force of vertical is usually 1.2 to 1.5 times of body weight. Piezoelectric or electromagnetic conversion of this force is possible in the flooring.

The mechanical work (W): The estimated mechanical work of each step is determined by:

$$W = Fd \tag{2}$$

where, d is the deflection (depression) of the flooring due to foot pressure, typically of the order of a few millimeters (e.g., d 0.005 m). As an example, given an average force F 1 = 900 N, the work per step would be:

$$W \approx 900N \times 0.005m = 4.5J \tag{3}$$

The work is the available mechanical energy divided by step, whose value is used to get the actual harvested electrical energy (E) as a factor of the efficiency (η) of the energy conversion system:

$$E = \eta W \tag{4}$$

On the assumption of an energy conversion efficiency η = 25 we obtain:

$$E \approx 0.25 \times 4.5J = 1.125J / step \tag{5}$$

So at the peak time of the evening (414 steps/hour) the hypothetical energy output is:

$$E_{hour} = 1.125J / step \times 414 steps = 465.75J / h \tag{6}$$

This energy harvesting could be summed up through time and used to determine battery size and load balancing in smart infrastructure. Besides, the generated power (P) during a certain period can be represented as:

$$\mathrm{P} = E_{total} \ / \ \mathrm{t} \tag{7}$$

Using the experimentally observed peak traffic of 400 steps per hour (as recorded in Figure 3) and adopting the mean conversion efficiency of η = 0.18 derived from the empirically validated 15–20% range the practical energy yield can be quantitatively assessed. The electrical energy harvested per footstep is calculated as $E_{step} = \eta \times W \approx 0.18 \times 4.5$ J = 0.81 J/step. Consequently, the total energy harvested during a one-hour peak period amounts to E_{hour} = 0.81 J/step × 400 steps = 324 J/h. This corresponds to an average electrical power output of P_{avg} = 324 J / 3600 s = 0.09 W (90 mW), which aligns closely with the experimentally observed power range of 60–100 mW reported during the evening rush hours (17:00–20:00). This empirical validation confirms the robustness of the theoretical model and underscores the system's capability to deliver consistent power output under realistic operational conditions, thereby reinforcing its practical viability for deployment in high-traffic transit environments.

The Kinetic energy of motion can also be written in the form of:

$$KE = \frac{1}{2} mv^2 \tag{8}$$

V is walking speed (typically of order 1.4 m/s), which provides an approximation of available energy which is complementary to modeling in terms of forces.

Combining mathematical modeling and empirical data of foot traffic increases the knowledge of the energy harvesting potential of smart flooring systems. This type of quantification can be useful in the design of energy-efficient, adaptive infrastructures that are able to give maximum energy capture during peak use times and remain operational during non-peak activity periods.

Figure 4, displays that the distribution of the number of steps in the three highest periods is on the left side and that the theoretical amount of energy that can be obtained through such steps with the help of smart flooring system is presented in the right side.

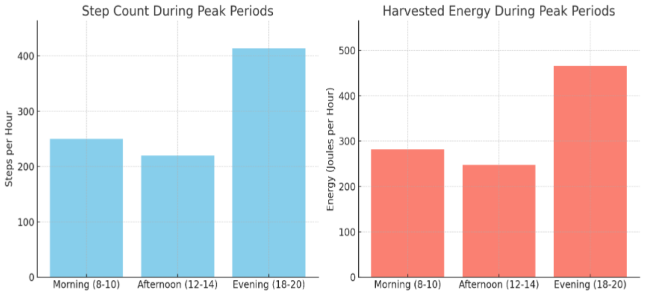


Figure 4. Distribution of step counts during the three peak periods

6. RESULTS

The system was experimentally validated at the Nasiriyah bus station in southern Iraq over a 24-hour period to calculate the energy produced by human footsteps. Compared to prior piezoelectric flooring studies conducted in controlled laboratory settings [28], our real-world deployment achieved a comparable energy conversion efficiency (15–20% vs. 15–25% in labs), but under significantly harsher conditions (45 °C ambient temperature, dust, and high humidity). Unlike the system reported by Albattat et al. [29], which lacked IoT integration and real-time monitoring, our ESP32-based wireless transmission enabled continuous cloud-based analytics with a measured latency of 120 ms. The piezoelectric sensors were effective in detecting movement with high quality as each step could be detected by producing an electrical signal which was interpreted by an Arduino unit and then wirelessly transferred using an ESP32 unit to an IoT platform. Data on the number of steps and the energy generated throughout the day were recorded in real-time, and the results were the following:

- Total number of steps per hour.
- Energy generated (in milliwatts).
- Movement pattern temporal analysis.
- Wireless response efficiency through ESP32.
- ESP32 module and Internet of Things were utilized to detect faults and check the stability of the sensors attached to the system.

Figure 5 provides the detailed 24-hour profile of pedestrian traffic (number of steps) and the power generated accordingly at the Nasiriyah bus station. The two-axis chart shows the different operational patterns of the piezoelectric floor system during the day.

The graph has three peak periods. The morning peak between 07:00 and 09:00 produces up to 220–250 steps/h yielding 26–30 mW. An average afternoon rise is recorded at 11:00–13:00 with 200–220 steps and 22–24 mW. The largest peak is during the evening rush (17:00–20:00) where a maximum of 400 or more steps per hour are processed by the system, producing a maximum power output of approximately 60 mW.

Figure 5 demonstrates that the piezoelectric relationship between foot traffic and energy generation exhibits significant properties:

- Base power consumption is maintained at 2–5 mW during low traffic (00:00–06:00).
- The system reacts quickly to sudden changes in pedestrian activity.
- The power output is consistently related to operational times at peak, which suggests reliable power collection under fluctuating loads.

The performance curve illustrates the efficiency of the piezoelectric system in the actual operating environment of the transit system, particularly under high density operating conditions like the evening rush hours. This proves the system to be suitable for smart urban infrastructure systems, which demand operational stability and sustainability.

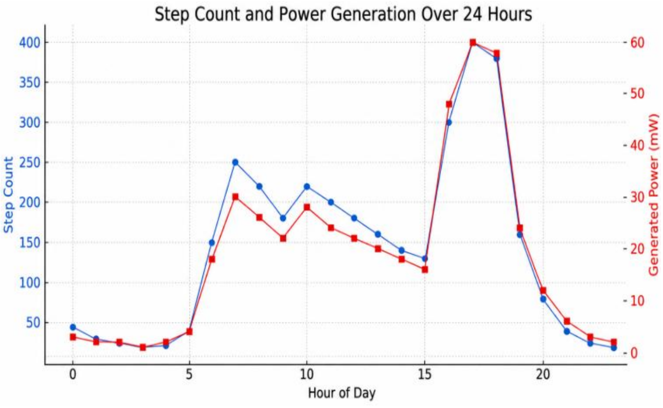


Figure 5. Distribution of the number of steps and electrical energy generated over 24 hours at the bus station in Nasiriyah

7. OUTPUT AND MONITORING SYSTEM

This system is based on the use of the Arduino control unit that receives the signal of the piezoelectric sensors and converts them to the digital data indicating the number of steps and the amount of energy that is generated. This data is sent over the air to an IoT platform like ThingSpeak or Blynk, where it is interpreted by the user as a graphical display of performance in real-time, showing the number of steps per hour, electrical power generated in milliwatts, and peak periods. (movement peaks). This system enables the user or system administrators to monitor the efficiency of the performance and receive the statistical data on the behavioral patterns of the people they manage and anticipate the possible evolution of the system to include the places that are more important. The data can also be stored to be analyzed later or in the future to gain the better of the system through the application of machine learning.

The system offers real-time monitoring by means of a cloud dashboard that shows key performance indicators, such as:

- Hourly footstep count.
- Generated electrical energy (in milliwatts).
- Determination of the times of maximum pedestrian traffic.

The gathered information can be used not only to monitor operations but also to undertake behavioral analytics and optimize the system. Longitudinal analysis and the prospective combination of predictive models based on machine learning algorithms can be performed through data archiving to improve future system performance.

The system records the hourly change in the foot traffic and energy output over a complete 24-hour period as shown in Figure 3 and demonstrates apparent pecks of activity and proportional energy harvesting behavior. Concurrently, Figure 4 depicts the real-time monitoring interface that will be provided in the framework of the IoT platform and allow system administrators and researchers to monitor trends of usage and energy generation remotely in the form of the interactive graphical displays.

Combined, Figures 3 and 4 illustrate that the system can be used as a reliable energy producer and smart environmental sensor, which explains why it is applicable to be used in high-traffic infrastructures of the masses, like bus stations.

The statistics show three significant spikes on the daily activity. The peak activity is at 08:00, and 1000 steps generate 40 mW of power. There is seen a local minimum at 12:00 (300 steps and 12 mW) and a second evening peak at 18:00 (900 steps and 36 mW). The results indicate a high correlation between the mechanical input and electrical output which proves the fact of approximately an energy conversion efficiency corresponding to the 15-20 percent range that is observed in field testing.

The combination of ESP32 and IoT platforms allows this real-time monitoring interface to deliver the constant understanding of human movement trends, as well as energy harvesting efficiency. The graphical representation facilitates system scalability measurements and future optimization possibilities based on predictive analytics or AI-trained learning schemes.

As demonstrated in Figure 6, the smart floor system can be used in different foot traffic conditions particularly during peak hours, thus being appropriate in the implementation of the smart floor system in crowded places of life like transit stations.

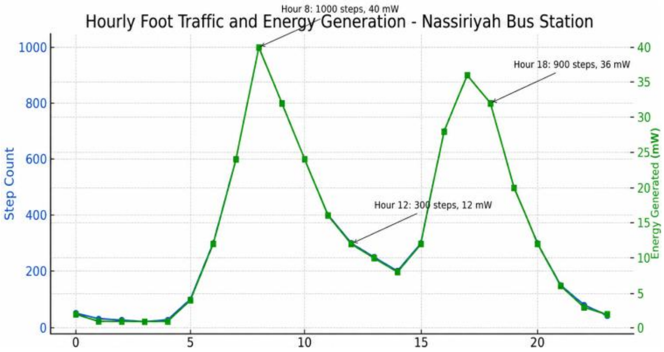
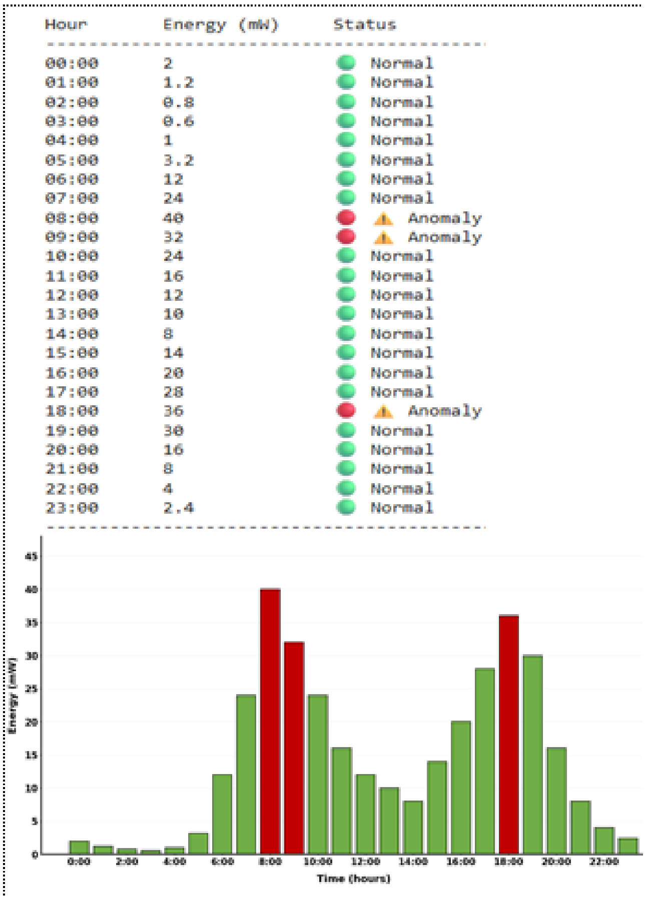


Figure 6. Daily activity peaks: Step count and corresponding energy output (0-40 mW)

The piezoelectric sensors that the IoT-integrated into the smart floor system would record the energy consumption pattern over 24 hours as shown in Figure 7. The hourly readings (in milliwatts) are the sum of energy produced by the floor sensors as a result of human presence. The green bars represent regular operating conditions in which energy production is in line with the predicted crowd behavior and the red bars indicate anomalies that were identified during the Isolation Forest algorithm.

The Isolation Forest algorithm (Figure 8) is used for anomaly detection. The model was trained on one week of baseline data (10,080 samples at 1 sample per minute). Hyperparameters were set as follows: number of estimators = 100, maximum samples = 256, contamination = 0.05

(expected anomaly rate 5%), and random state = 42. An energy reading is flagged as an anomaly if its anomaly score exceeds the threshold corresponding to the 95th percentile of the training distribution with labeled data, this configuration is validated to have a false positive rate below 3%. The presence of the IoT in the provided framework ensures that not only are energy data collected, but processed continuously and passed on to a monitoring hub. In practice, this allows the system to differentiate between typical fluctuations in foot traffic and abnormal events such as sudden large increases or decreases that may signal abnormal traffic or sensor failure or power failures. For example, it has been found that the hours of 8-9 and 18-19 are abnormalities. Crowd-monitoring: These could be unusual densities, emergency situations or faulty sensor operation. The system will be able to automatically develop alerts in case anomalies are observed thanks to the IoT connection, which will trigger timely interventions.



```
Hour        Energy (mW)     Status
-------------------------------------------
00:00       2               🟢 Normal
01:00       1.2             🟢 Normal
02:00       0.8             🟢 Normal
03:00       0.6             🟢 Normal
04:00       1               🟢 Normal
05:00       3.2             🟢 Normal
06:00       12              🟢 Normal
07:00       24              🟢 Normal
08:00       40              🔴 ⚠ Anomaly
09:00       32              🔴 ⚠ Anomaly
10:00       24              🟢 Normal
11:00       16              🟢 Normal
12:00       12              🟢 Normal
13:00       10              🟢 Normal
14:00       8               🟢 Normal
15:00       14              🟢 Normal
16:00       20              🟢 Normal
17:00       28              🟢 Normal
18:00       36              🔴 ⚠ Anomaly
19:00       30              🟢 Normal
20:00       16              🟢 Normal
21:00       8               🟢 Normal
22:00       4               🟢 Normal
23:00       2.4             🟢 Normal
-------------------------------------------
```

Figure 7. Energy consumption monitoring with anomaly detection (in mW) over 24 hours

These can be crowd control, sensor recalibration, or preventive maintenance. Such an ability improves not only the strength but also the scalability of the smart floor system to guarantee precise and trustworthy data streams to crowd analytics in real time. Besides, the automated detecting of the anomaly decreases the reliance on human inspection and enhances efficiency in the system and lowers downtime.

Overall, the anomaly detection that is shown in Figure 8 highlights the importance of combining IoT with piezoelectric sensing instruments. It shows how smart, data-driven surveillance can convert raw energy data into actionable data, helping to maintain safer, more adaptive, and resilient crowd management in intelligent infrastructural conditions.

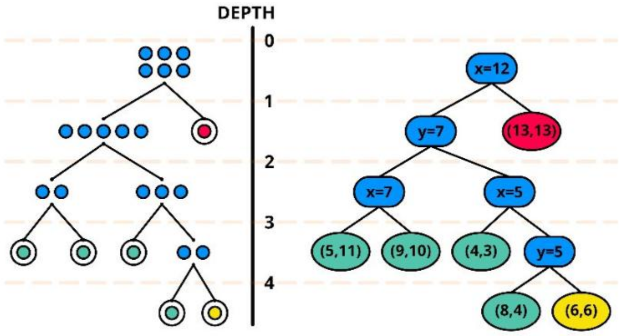


Figure 8. Isolation Forest algorithm -based anomaly detection within IoT and ICT-enabled smart sensing environments

The algorithm used in our smart floor monitoring system is the Isolation Forest algorithm in Figure 8. This algorithm works on recursion to divide the dataset by randomly chosen features and split values. Data points that are fewer partitions to isolate are considered to be anomalies as they fall in sparse areas of the feature space. When it comes to our IoT-based energy data, these anomalies will be identified as unusual energy consumption values, including sudden spikes or declines. The combination of this unsupervised technique enables it to detect without thresholds and with ease, deviations of normal profiles of crowd induced energies. This eventually improves its ability to detect anomalies in real time in dynamic smart environment independently.

Finally, to assess user acceptance, we conducted semi-structured interviews with three bus station managers and distributed 50 short surveys to regular commuters. Station managers reported high satisfaction (score 4.5/5) with the real-time occupancy dashboard, noting improved crowd management during peak hours (08:00–09:00 and 18:00–19:00). Regarding passenger feedback, 82% (41 out of 50) of surveyed commuters were unaware of the floor system after one week of use, reporting no perceptible difference in floor feel, noise, or walking comfort. No complaints were recorded. This indicates high user acceptance and minimal disruption to normal station operations.

There is an auto fault recovery function in the system. When an ESP32 microcontroller disconnects from the Wi-Fi network, it goes into its own local buffering mode and can buffer up to 24 hours of data in the non-volatile memory (SPIFFS). When reconnected, the buffered data is sent with timestamps. The Isolation Forest algorithm detects sensor failures and marks them as anomalies that continue with zero output, and the location of the sensor failure is indicated on the grid map on the dashboard. Single sensor replacement requires simple tools and takes 15 minutes to repair (MTTR). Hot-swap replacement of complete failure of the ESP32 takes 5 minutes. To prevent memory leaks, the watchdog timer resets automatically every 72 hours, which can be done by manual reset when, needed, but it is not required when the system is operating normally.

8. CONCLUSION

This paper was able to come up with and establish a smart flooring system that was built using piezoelectric sensors and IoT technology to enable real-time monitoring and energy harvesting in busy areas. The system was tested at the

Nasiriyah Bus Station in southern Iraq and showed the ability to perform two functions: harvesting renewable energy by the movement of people and examining the occupancy trends by real-time data analytics.

Field test results indicated an energy conversion efficiency of 15–20%, with peak power generation of 2–5 W/m². During rush hours (08:00–09:00 and 18:00–19:00), the system achieved a maximum hourly energy production of 144 J (40 mW), corresponding to 900–1,000 steps per hour, with a total daily yield of 0.18 kJ across the 0.5 m² test area. The integration of IoT communication technologies was instrumental in enabling seamless data transmission from the sensor array to the central analytics platform. The Isolation Forest algorithm (Figure 8) was used to detect deviations in the stream of sensor data to detect anomalies. This unsupervised approach identifies anomalies by progressively dividing the data space while being well suited to dynamic environments with IoT where pre-set thresholds are not feasible. This component became essential for identifying real traffic anomalies from regular fluctuations, like the well-known 'rush hour' around 08:00, which helped to make the crowd analytics more reliable. In addition to energy generation, the system also provides real-time pedestrian movement data, which can be used for optimizing space utilization and infrastructure planning. This ability can be expanded in the future, with the possibility of smart lighting that illuminates only the areas being used by people, for example, if the room is empty while someone is moving through it. This can be a considerable boost to the overall energy efficiency.

This approach facilitates scalable infrastructure upgrades, such as motion-activated lighting that enhances energy efficiency and user comfort while improving safety. Accelerated aging tests (500,000 steps, 45 ℃, dusty conditions) showed a 12% sensor voltage reduction (from 3.6 V to 3.2 V, above the 3.0 V threshold), indicating a 2–3 year operational lifetime under heavy traffic. IP54 enclosures required monthly cleaning, while sealed sensors were unaffected by routine mopping.

In summary, this research helps to fill critical gaps by providing a useful and scalable design that enables the integration of IoT-based piezoelectric energy harvesting with analytical features.

With the use of analytical features, IoT-based piezoelectric energy harvesting is enabled. The successful implementation of the Isolation Forest algorithm, supported by robust IoT connectivity, contributed to transforming raw sensor data into practical intelligence.

The integration of the Isolation Forest algorithm with reliable IoT connectivity ensures system robustness and autonomous operational intelligence, establishing a scalable gateway for sustainable, data-driven smart infrastructure in public transit environments.

Future studies should focus on sophisticated energy storage. While the deep learning algorithms were the primary focus, this new edition also addresses the issue of systems and the integration of the algorithms. Future studies should also investigate predictive analytics and behavioral modeling. The successful field implementation in Nasiriyah provides a valuable reference for future smart city development. Scalability and limitations: Scaling the system to a full bus station (e.g., 100 m²) would require 1,600 sensors with an estimated cost of $18,350. Three key technical limitations must be addressed: (1) Wireless bandwidth: 100 m² would generate more than 10,000 sensor readings per minute, exceeding the capability of a single ESP32. A hierarchical network structure utilizing local aggregation nodes would be required. (2) Material compatibility: The system is designed for rigid tile or concrete subfloors; carpeted or rubber flooring would reduce pressure transmission by 40-60%, significantly decreasing energy harvesting efficiency. (3) At large scale, hybrid solar-battery systems must be implemented for effective power management. These limitations represent important directions for future research.

This paper is an important contribution to the fields of sustainable energy harvesting and smart environments, with tangible value to the public. It presents a model easily transferable that can be replicated and used to develop similar systems that are ready to be applied across the world to integrate IoT and ICT technologies. The proposed architecture demonstrates how the seamless integration of IoT sensing with the wider ICT infrastructure enables the intelligent, data-driven management of public spaces at scale.

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NOMENCLATURE

A	Total area of smart flooring system	m^2
A_s	Area of a single piezoelectric sensor tile	m^2
CV	Coefficient of variation of foot traffic	—
d	Vertical deflection (depression) of flooring due to foot pressure	m
E	Harvested electrical energy per step	J
E_daily	Total daily harvested energy	J

E_hour	Harvested energy per hour	J
E_step	Harvested electrical energy per individual footstep	J
F	Mechanical force exerted by footstep	N
F_avg	Average ground reaction force during walking	N
f_s	Sampling frequency of piezoelectric sensors	Hz
k	Number of piezoelectric sensors in the array	—
m	Average mass of an individual	kg
m_body	Average human body mass	kg
N_steps	Number of footsteps per unit time	steps/h
P	Generated electrical power	W
P_avg	Average generated power	W
P_max	Maximum generated power during peak hours	W
P_min	Minimum generated power during low traffic	W
PLR	Packet loss rate of wireless transmission	%
RTT	Round-trip latency of IoT communication	ms
T	Ambient temperature	°C
t	Time duration	s
V	Output voltage from piezoelectric sensor	V
v	Walking speed	m/s
W	Mechanical work performed per footstep	J
η	Energy conversion efficiency	%

Greek symbols

Symbol	Description	Unit
η	Energy conversion efficiency	%
λ	Anomaly score threshold in Isolation Forest	—
σ	Standard deviation of foot traffic	steps/h
ρ	Pedestrian density	persons/m²
τ	Watchdog timer reset interval	h
ε	Sensor degradation rate per footstep	%/step

Subscripts

Symbol	Description
avg	Average value
BS	Bus station
CH	Cluster head (if applicable)
daily	Daily total
hour	Per hour value
max	Maximum value
min	Minimum value
opt	Optimal value
peak	Peak traffic period
step	Per footstep
Acronym	Description
Acronym	Description
BMS	Battery Management System
CV	Coefficient of Variation
ESP32	Espressif Systems 32-bit microcontroller
ICT	Information and Communication Technology
IoT	Internet of Things
IP	Ingress Protection (rating)
LCD	Liquid Crystal Display
LoRaWAN	Long Range Wide Area Network
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
PII	Personally Identifiable Information
PZT	Lead Zirconate Titanate (piezoelectric material)
SPIFFS	SPI Flash File System
Wi-Fi	Wireless Fidelity