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Evaluation of Energy Harvesting from Pedestrian Movement Using Piezoelectric Flooring in Urban Mobility Infrastructure: A Case Study of "Les Fusilles" Metro Station, Algeria †

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Abstract

Urban mobility infrastructure is a major energy consumer in rapidly growing cities. Piezoelectric flooring tiles offer a promising solution for harvesting energy from pedestrian movement and creating an eco-friendly path in public facilities with high-density occupancy. This study tests the hypothesis that installing piezoelectric tiles in high-traffic transit zones can generate an estimated amount of electrical energy. The Algiers metro station, Les Fusilles (LFU), was selected as the case study. The methodology is structured into three stages: first, collecting data on daily passenger numbers and electricity consumption at LFU; second, conducting in situ observations of pedestrian patterns; and third, selecting Waynergy tiles for this test based on their energy generation capacity, cost, and lifespan. Results show that installing the selected piezoelectric tiles in high-traffic zones could generate a modest but estimated amount of electrical energy directly correlated with daily pedestrian frequency. This harvested energy is sufficient to power a low-draw auxiliary application, such as an LED indicator or a wireless sensor node, or stored for later use. The findings confirm that Waynergy piezoelectric flooring is a viable solution for enhancing urban sustainability, reducing carbon emissions, and supporting smart transportation systems in metropolitan environments.

Keywords: urban mobility; energy harvesting; piezoelectric flooring; pedestrian movement

1. Introduction

Urban mobility infrastructure, such as metros, light rail, and bus networks, is widely recognised as a climate mitigation strategy because it reduces reliance on private vehicles and lowers per-passenger emissions; however, the systems themselves are substantial energy consumers and contribute significantly to cities' operational carbon footprints. A typical urban metro line consumes between 1.5 and 3.5 million kWh annually per kilometre for traction, station operations, lighting, ventilation, escalators, and passenger information systems [1]. These energy demands impose considerable operational costs on transit authorities and contribute to greenhouse gas emissions, particularly in regions where electricity generation remains dependent on fossil fuels. According to the International Energy Agency (IEA), Algeria's transport sector is responsible for approximately 34% of

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the country's total energy consumption and around 30% of its CO2 emissions [2]. This substantial energy footprint necessitates exploring innovative, decentralised energy generation solutions that can complement existing grid supply and contribute to national emissions-reduction targets. Among renewable energy technologies such as solar, wind, hydro, biomass, and geothermal, piezoelectric energy harvesting has emerged as a promising alternative for generating clean energy and creating an eco-friendly path within existing infrastructure without requiring extensive land acquisition or major structural modifications. The system captures wasted mechanical energy from pedestrian movement and converts it into usable electrical energy through the piezoelectric effect.

Numerous studies have investigated piezoelectric energy harvesting from pedestrian movement across diverse geographical contexts and infrastructure types [3–5]. These studies have demonstrated that high-density pedestrian traffic in transit hubs, shopping centres, and educational institutions can generate non-negligible electrical energy suitable for low-power applications. Despite these promising developments, significant research gaps remain regarding the application of piezoelectric energy harvesting in North African urban contexts, where climatic conditions, pedestrian demographics, and infrastructure characteristics differ substantially from the Asian, European, and North American contexts in which most studies have been conducted. Specifically, the Algerian context presents unique characteristics, including a predominantly natural gas-based electricity grid, distinct pedestrian demographics, and variable walking speeds that may affect energy yield. The absence of empirical research on piezoelectric harvesting in Maghreb region transit infrastructure represents a critical knowledge gap. This study addresses these gaps by providing empirical evidence from Algeria's first metro system, thereby contributing to the broader understanding of piezoelectric technology transfer in emerging-economy contexts. This paper aims to: (1) establish a quantitative relationship between pedestrian footfall frequency and estimated electrical energy output from commercially available piezoelectric tiles; (2) compare alternative piezoelectric tile products based on energy yield, capital cost, and operational lifespan; (3) evaluate the environmental benefits in terms of carbon emission reduction potential within the Algerian energy context. The findings are intended to provide infrastructure planners, transit operators, and urban policymakers with evidence-based guidance for integrating piezoelectric energy harvesting into sustainable mobility infrastructure.

2. Materials and Methods

The methodology is structured into three stages: (1) data collection on passenger flow and station electricity consumption; (2) site visit and visual observation of pedestrian movement patterns; and (3) comparative analysis and energy output calculation of commercially available piezoelectric tiles to be implemented in LFU. Figure 1 presents a schematic overview of the methodological framework.

2.1. Case Study Description

Algiers is the first city in the Maghreb region and the second in North Africa, after Cairo, to operate an underground metro system. The Algiers Metro network currently consists of 19 stations (Figure 1). Among them, Les Fusillés (LFU) Metro Station was selected as the case study due to its consistently high passenger flow, underground configuration, and strategic importance within the metro network. These characteristics make the LFU station an appropriate location to evaluate the feasibility of pedestrian energy harvesting via piezoelectric flooring.

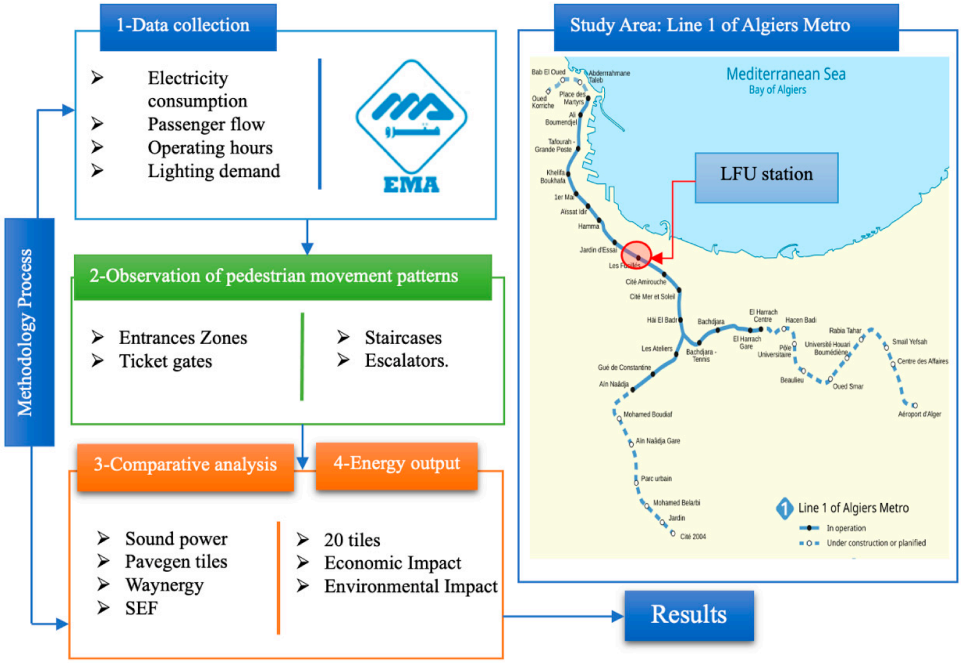

Figure 1. Overview of the methodological framework.

2.2. Data Collection

2.2.1. Passengers' Data

The daily average number of passenger entries at the LFU station during 2024 was obtained from ticket office records provided by Entreprise Métro d'Alger (EMA). This dataset represents a comprehensive record of paid entries over the year, accounting for seasonal variations and operational fluctuations. The station recorded a total of 5,013,923 passengers in 2024, averaging 13,710 passengers per day. This high passenger volume establishes LFU as one of the busiest stations in the Algiers metro network. Figure 2 represents the average daily number of passengers per month.

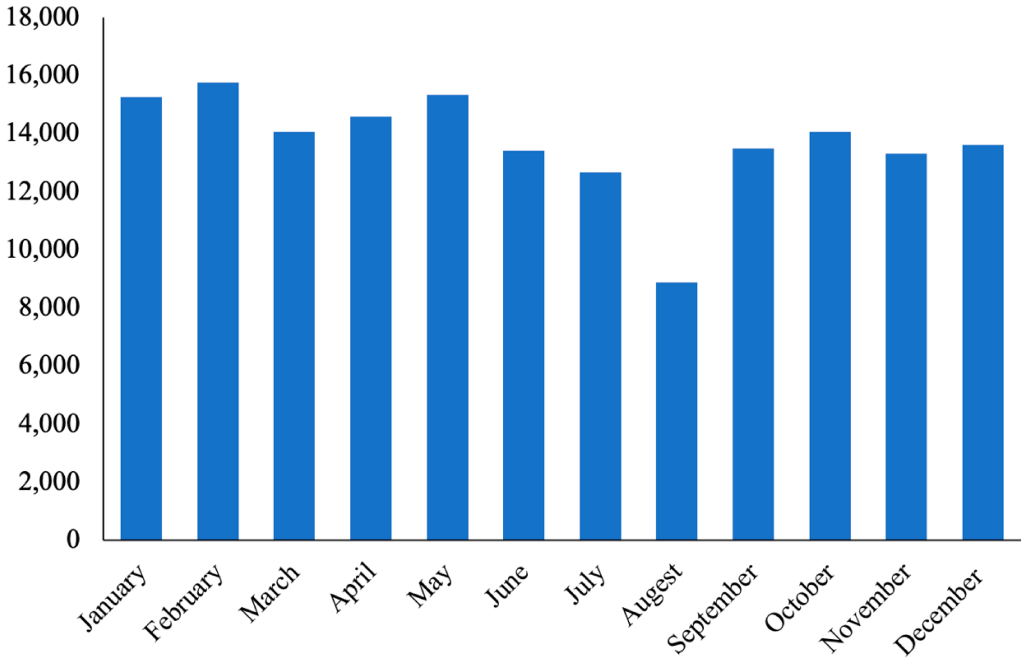

Figure 2. Average daily passengers by month, 2024.

2.2.2. Station Electricity Consumption

The electricity consumption data for the Algiers network were obtained from utility records provided by EMA, comprising detailed meter readings and load profiles for all stations. An attempt was made to calculate the electricity consumption for LFU (Table 1). The station consumes an average of approximately 8360.4 kWh per day for all operational functions, including lighting, ventilation, escalators, and other systems. The lighting consumption comes from several key areas: passenger corridors; escalators, stairs, and platform area; high-intensity lighting runs during operating hours; advertising and signage; illuminated advertising boards; and emergency and exit lighting systems that must remain operational at all times. The lighting system alone accounts for 37% of total electricity consumption [6]; consequently, it consumes 3093.3 kWh per day, corresponding to the largest category of electricity use and the primary target for offset through piezoelectric generation.

Table 1. Electricity consumption per station, 2024 data.

Stations	Factor	Consumption/Station	Daily Consumption (kwh/Day)
SAT	0.079739889	9759.828061	325.327602
GDC	0.502408385	61,492.67946	2049.755982
AIN	1.269204614	155,345.3223	5178.17741
SAB	1.037752296	127,016.5292	4233.884306
SPM	2.240227588	274,194.4622	9139.815407
HAC	1.228779654	150,397.4767	5013.249225
HAG	0.751685351	92,003.13475	3066.771158
BDH	1.021942949	125,081.5314	4169.384381
BDT	0.757356477	92,697.25679	3089.90856
KBK	1.317830964	161,296.9836	5376.566119
MAI	1.498931808	183,462.9674	6115.432248
AID	0.512277681	62,700.63989	2090.02133
HAM	0.398459948	48,769.82671	1625.66089
JES	0.614736814	75,241.20808	2508.040269
LFU	**2.049192055**	**250,812.5142**	**8360.41714**
CMS	0.533608569	65,311.45118	2177.048373
TGP	1.463132519	179,081.2846	5969.376152
HEB	0.706427919	86,463.81479	2882.12716
CAM	0.472163334	57,790.81198	1926.360399

Note: Bold text indicates LFU, the case study.

2.3. Pedestrian Movement Pattern Observation

A site visit was conducted at the LFU station to observe pedestrian movement patterns and confirm the areas with the highest pedestrian density. The visit focused on key passenger movement zones, including entrances, ticket gates, staircases, escalators, and platform access points, where pedestrian flow is naturally concentrated. The visual observation confirmed that the ticketing concourse and main access corridors consistently experience the highest passenger concentration, as these areas serve as mandatory passage points for all passengers entering and exiting the station. This site visit was qualitative and did not involve instrumented pedestrian counting; the total daily passenger volume used in this

study was obtained from EMA's gate-validated ticket records. Both of the station's access points share the same escalator configuration and landing dimensions, each consisting of two sequential escalators separated by an internal landing zone (Figure 3). Twenty tiles are proposed for this pilot-scale installation, arranged as two 10-tile clusters (2 × 5 grids, 0.8 m × 2 m each) paving the landing zone at each access point, ensuring that pedestrian footsteps at these mandatory passage points consistently land on a tile surface rather than a gap.

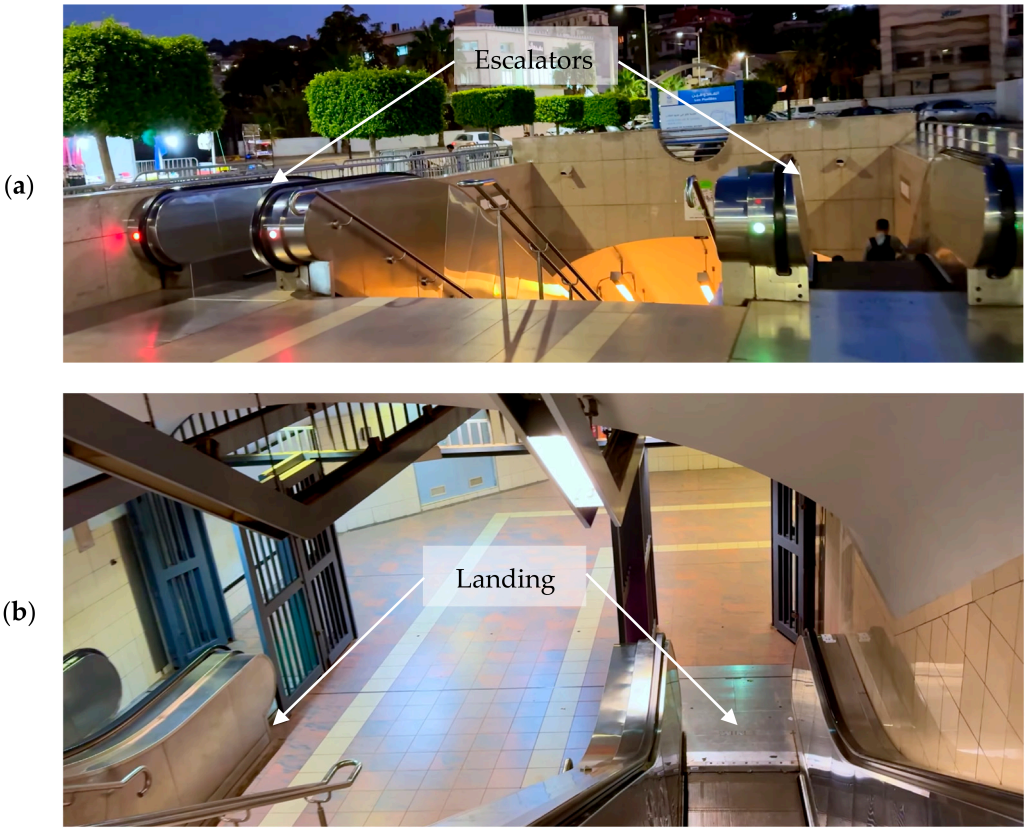

Figure 3. LFU station access infrastructure: (**a**) street-level entrance with twin escalators; (**b**) internal landing zone between the station's two sequential escalators.

2.4. Comparative Analysis and Energy Output Calculation

Selecting an appropriate piezoelectric tile technology is critical to this project. According to previous research [5], Waynergy tiles are identified as the best-performing piezoelectric tiles for use in public facilities. The technology has been developed since 2009 by the Waydip Company (Covilhã, Portugal) in collaboration with the Pavement Mechanics Laboratory at the University of Coimbra. The system consists of small paving blocks with an internal power-generation mechanism that responds to a small vertical displacement (3–5 mm) when a pedestrian or vehicle passes over the block. The technology is patent-protected [7].

The evaluation framework comprised four criteria: (1) energy generation capacity per footstep, (2) power density per unit area, (3) initial capital cost per tile, and (4) operational lifespan under continuous pedestrian loading. These criteria were prioritised based on their relative importance to infrastructure operators, with energy capacity and durability given greater weight than cost considerations. Table 2 presents a comparative assessment of commercially available piezoelectric tile flooring products, including the Sustainable Energy Floor (SEF), Pavegen, Waynergy systems, and Sound Floor, using the established multi-criteria framework. The Waynergy tiles were selected for this study due to their

superior energy conversion efficiency, proven track record in similar installations, and favourable lifecycle cost profile.

Table 2. Types of piezoelectric tiles and their characteristics.

Company	Shape	Size (cm)	Power per Step (w)	Price (USD)	Lifespan (Years)	Refs.
SEF	Square	75 × 75	7	1693	15	[5]
Pavegen	Triangle	50 × 50	5	395	20	[5]
Wayenergy	Square	40 × 40	10	254.4	20	[5,8]
Sound Floor	Square	50 × 50	0.1 w per 2 steps	270.9	20	[8]

Energy Output Estimation

Before this rating is used to estimate the station's daily energy output, its physical plausibility is first checked independently. When a person walks across a floor, the flooring undergoes a certain amount of deformation. Basic physics indicates that the mechanical energy stored in an object depends on both its deflection and the forces acting on it. This principle can also be applied to the section of flooring beneath a person's foot:

$$W_m = \int F \, d\gamma \tag{1}$$

where W_m represents the mechanical energy, F is the vertical force exerted on the floor, and γ is the average deflection beneath the foot. Because accurately measuring the relationship between force and deflection is not straightforward, the stored energy is estimated by assuming a linear increase. Under this assumption, the peak mechanical energy is given by:

$$W_{max} = \frac{1}{2} F_{max} \cdot \gamma_{max} \tag{2}$$

where W_{max} denotes the peak force and γ_{max} denotes the peak deflection. For an energy-harvesting floor, the maximum deflection is determined by the design limits. In particular, the deflection must be restricted to protect the active piezoelectric elements from excessive strain. This makes it possible to estimate the mechanical energy that can be generated during a typical step:

$$W_{max} = \frac{1}{2} (m \, g) \cdot \gamma_{max} = \frac{1}{2}(76.5 \times 9.82)(0.0063) = 2.35 \text{ J} \tag{3}$$

For a person with a typical mass of 76.5 kg, a floor deflection of 6.3 mm, and a stepping time of approximately 0.25 s, the mechanical energy generated per step can be estimated at approximately 2.36 J. This corresponds to an average power of approximately 9.4 W during the stepping interval:

$$P = W_{max}/t = 2.36 \text{ J} \; / \; 0.25 \text{ s} \approx 9.44 \text{ W} \tag{4}$$

As is known, a greater applied force or floor deflection results in more mechanical energy being available for conversion into electricity. Although this estimate assumes a linear relationship between force and deflection, it provides a reasonable indication of the order of magnitude of the energy that could be harvested during walking.

Manufacturer specifications for Waynergy flooring tiles report a nominal power of 10 W per step without specifying the activation duration or a validated energy-per-step value [8]. Because this figure expresses power rather than energy, it must be combined with the number and duration of tile activations to estimate daily output.

In this study, each 10-tile cluster spans approximately 2 m in the direction of pedestrian travel (five tiles of 0.4 m each); a passenger crossing this distance takes approximately 3 footsteps [9]. This calculation can be expressed through the following equations:

$$E_{step} = (P \times t)/3600 \quad (5)$$

$$C_{tile} = K/10 \quad (6)$$

$$E_{total} = C_{tile} \times N \times E_{step} \quad (7)$$

Here, P is the manufacturer's nominal power rating (10 W), t is the assumed footstep contact duration (0.2–0.5 s), and C_{tile} represents the number of footstep contacts on one individual tile per day. K is the total number of footstep contacts on one 10-tile cluster per day: since the station's daily passenger volume of 13,710 is divided evenly between its two access points, each access point serves approximately 6855 passengers per day; each passenger takes about 3 footsteps to cross the 2 m tiled cluster, giving $K = 6855 \times 3 = 20{,}565$ footsteps. Using the central contact duration ($t = 0.35$ s), $E_{step} = 0.00097$ Wh, so the total daily energy for the 20-tile installation ($N = 20$) is $E_{total} = 2056.5 \times 20 \times 0.00097 = 40$ Wh/day.

3. Results

3.1. Estimated Energy Generation and Economic Feasibility

The average daily energy consumption for the lighting system at the LFU station is 3093.3 kWh/day. Twenty Waynergy tiles are proposed for installation at the station's two access points, the zones with the highest and most consistent pedestrian footfall. Using the estimation method described in Section Energy Output Estimation, this configuration is estimated to generate approximately 40 Wh/day (0.040 kWh/day), with a range of 22.9–57.1 Wh/day depending on footstep-contact-duration assumptions (Table 3). This output, while several orders of magnitude below the station's total lighting demand, is broadly consistent with the modest per-activation energy yields reported in the piezoelectric tile literature [8] and is sufficient to power a very low-draw auxiliary application, such as a single LED indicator or an intermittently triggered wireless sensor node.

Table 3. Efficiency of the Waynergy tile implementation at the LFU station.

Type	Waynergy Tiles
Nominal power	10 W
Number of tiles	20
Initial cost for installing one tile	$254.4
Initial cost for installing 20 tiles	20 × 254.4 = $5088
Estimated energy output per tile	2 Wh/tile/day
Estimated daily generation, 20 tiles	20 × 2 = 40 Wh/day = 0.040 kWh/day
Sensitivity range (contact duration 0.2–0.5 s)	22.9–57.1 Wh/day
Lifespan (years)	20 years = 7300 days
Estimated annual energy generated	0.040 × 365 = 14.6 kWh/year
Estimated annual cost saving	0.29–0.73 $/

In Algeria, the initial cost of buying 1 kWh of electricity from the government is approximately 0.035 USD/kWh. Based on the central estimate, the 20-tile installation would generate approximately 14.6 kWh/year, corresponding to an estimated annual cost saving of approximately 0.51 USD/year; across the full sensitivity range, this varies between approximately 0.29 and 0.73 USD/year. Against an initial installation cost of

5088.0 USD (Table 3), this indicates that, at current tile costs and grid electricity prices, direct capital cost recovery through avoided electricity purchase would require a timeframe far exceeding the tiles' 20-year operational lifespan. Accordingly, the value of this installation should be understood primarily in terms of its measurable environmental contribution and technology-demonstration value, rather than as an economically self-sustaining energy source for the station's lighting system.

3.2. Calculating Carbon Emission Reduction

In Algeria, electricity generation comprises 0.4% from oil, 98.9% from natural gas, and 0.7% from solar PV, according to the most recent national energy statistics. Hence, natural gas is the predominant source of electricity, which produces approximately 94.97 million tonnes of carbon dioxide (Mt CO_2) annually at the national level.

The station's lighting system consumes 3093.3 kWh per day. At Algeria's natural-gas-dominated grid emission factor of 0.66 kg CO_2/kWh, baseline lighting-related emissions are therefore 3093.3 × 0.66 = 2041.6 kg CO_2 per day, equivalent to approximately 745.2 tonnes per year. The proposed 20-tile piezoelectric installation, generating an estimated 40 Wh/day, would offset approximately 0.0264 kg CO_2 per day, equivalent to approximately 9.6 kg CO_2 per year. Across the full sensitivity range (22.9–57.1 Wh/day), this offset varies between approximately 5.5 and 13.8 kg CO_2 per year. While negligible relative to the station's total lighting-related emissions, this reduction is achieved without additional land use, fuel input, or grid infrastructure, and represents a directionally consistent, modelled contribution to decentralised decarbonisation efforts.

4. Discussion

The results of this study demonstrate that piezoelectric energy harvesting is technically feasible at the LFU metro station, generating an estimated, if very modest, quantity of electricity directly attributable to pedestrian footfall. These findings demonstrate that pedestrian traffic in metro stations can be converted into a small but genuine renewable energy contribution, rather than allowing mechanical energy from footsteps to dissipate entirely, and are broadly consistent with the modest per-activation energy yields reported in the piezoelectric tile literature [8], in line with previous studies [3,5,10,11].

The economic analysis confirms that, at current tile costs and Algeria's grid electricity price, capital cost recovery would not occur within the tiles' operational lifespan, reinforcing that the installation's value lies primarily in its environmental and technology-demonstration contribution rather than direct cost savings.

The estimated carbon emission reduction, while very modest, is achieved with zero marginal land-use or fuel inputs and is broadly consistent with the environmental benefits reported in prior piezoelectric flooring studies. However, several important limitations must be acknowledged. The energy generation potential is inherently dependent on sustained passenger footfall, which exhibits significant diurnal, weekly, and seasonal variation. During periods of reduced passenger traffic, such as holidays, economic downturns, or public health emergencies, the energy harvesting capacity would correspondingly decline.

The technical performance of piezoelectric tiles is also influenced by pedestrian characteristics, including weight, walking speed, gait patterns, and footwear, all of which vary substantially across the passenger population. Algerian metro passengers are diverse demographic groups with different average body weights, and many wear flexible footwear that may reduce pressure transmission to the tile surface.

Maintenance requirements represent an additional operational consideration. The manufacturer specifies a 20-year operational lifespan, but this assumes regular inspection, cleaning, and component replacement schedules. In the Algerian urban environment,

dust accumulation, humidity, and thermal cycling may accelerate material degradation or reduce energy conversion efficiency. The cost of maintenance must be factored into lifecycle cost analyses to provide a complete economic picture.

5. Conclusions

This study evaluated the feasibility of implementing piezoelectric flooring at the Les Fusillés (LFU) Metro Station in Algiers as a source of decentralised, pedestrian-driven electricity generation, finding that a 20-tile installation can generate a modest but estimated quantity of electricity sufficient for low-draw auxiliary applications. Beyond the case study itself, the proposed estimation framework offers a reproducible basis for evaluating similar installations across the Maghreb region and other emerging transit contexts, where empirical data on pedestrian energy harvesting remain scarce. Future work should prioritise instrumented field validation of the contact duration and extend the framework to alternative station layouts and piezoelectric technologies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LFU	Les Fusillés
EMA	Entreprise Métro d'Alger

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