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Piezoelectric Plate Prototype for Rural Power: Design, Testing, and Traffic-Based Simulation

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Abstract

Access to electricity in rural Peru remains uneven, while conventional renewables face cost and siting constraints. This study designs and evaluates a piezoelectric plate prototype that converts vehicular loads into electrical output and links laboratory results to a traffic-based simulation. Press tests recorded voltage spikes up to 73.5 V, and the Arena model—parameterized with one hour of counts (5,861 vehicles; 120 replications)—yielded an average of 19.7333 V per axle and a total of 232,020 V. Converting to a stable metric, the prototype produced 32.24 watt-hours. The contribution is a bench-to-traffic translation that quantifies energy under realistic load patterns and clarifies deployment conditions. Findings indicate feasibility for low-demand devices with appropriate conditioning and storage, informing siting along high-throughput corridors and guiding material and measurement improvements. Academically, the work connects PEH testing to traffic realism; socioeconomically, it outlines a pathway for micro-supply near underserved areas. Further pilots and durability studies are encouraged.

Keywords
Piezoelectricity, Energy sources, Rural areas, Electric power, Renewable energy.

1. Introduction
For some time, large amounts of particulate matter have been evident, this being the main risk factor for health (Ruiz, L. 2019) and a cause of the greenhouse effect. In Peru, 11 regions have exceeded the World Health Organization's permissible limits, placing it as one of the countries with the worst air quality. To mitigate pollution, renewable energy sources such as hydropower, wind, solar, etc., have been adopted (Konieczma et al. 2022). In Peru, 63% of electricity generation is hydropower, 34% is thermal, and the remainder is wind and solar. However, these sources present complications for installation and maintenance. Hydropower requires large areas with abundant water flow and is costly. Solar is only available during the day. Wind depends on strong airstreams, so it is variable. And tidal energy is the most expensive alternative (Lino, G. 2022). Despite the available resources, there is still a portion of the population without access to electricity. According to the Peruvian Statistic and Information National Institute, in

2020 it was recorded that 94.6% of all households had access to electricity through the public grid. In 2021, this figure decreased to 94.1%. Of these, only 82.6% of households in rural areas have access, compared to 97.1% in urban areas. To understand the sector's macroenvironment, a PEST analysis of the electricity sector in Peru was conducted. Politically, there is a lack of government support for new investors due to limitations such as regulations or laws. Economically, according to Energy and Mining Ministry, electricity consumption is centralized in Lima and Arequipa. Socially, the sector does not create many jobs due to automation in electricity generation, although it does promote employment in electricity transmission and maintenance. Finally, from a technological point of view, the infrastructure of hydropower plants is old and lacks investment for modernization.

According to Algarni et al. (2023), no energy source should be viewed as "bad," but many imply negative impacts on the world. Lino (2022) notes that while some alternatives generate substantial energy, they are expensive to install and maintain. The search for new sources must consider several factors. The social factor implies that progress depends on access to electricity. Next is the environmental factor, since large amounts of particulate matter are an evident major health risk (Ruiz, L. 2019) and greenhouse gases are present (Algarni et al. 2023). Although these energy sources were adopted to mitigate pollution and the greenhouse effect (Konieczma et al. 2022), this is not enough. The technological factor suggests that implementing new ways of producing electricity promotes innovation in society. Finally, from an economic perspective, current sources are costly to install. For these reasons, this research is based on identifying a feasible technology for producing electricity that is environmentally friendly, flexible, economical, and immediately available.

1.1 Objectives
The purpose of the research is to develop a piezoelectric plate prototype that converts the mechanical energy produced by the pressure of an external force into electrical energy and generates a voltage above 5 V.

2. Literature Review
2.1 Piezoelectricity
Recent studies have been made with the objective of find an alternative energy source as part of ongoing technological advances (Anitha et al. 2023). Within this context, the concept of piezoelectricity has emerged as a source to be used. It is a natural physical conversion found in certain solid materials such as crystals, quartz, wood, and bone (Wu et al. 2021). When subjected to external pressure, either directly or through vibrations, mechanical stress is generated and the internal atomic positions change, resulting in an electric charge (Sawane and Prasad 2023). However, some cement and quartz materials do not have sufficient capacity to collect energy (Chen et al. 2019), and they produce little energy due to low electrical conductivity (Ogbonna et al. 2022). Even so, recent years have seen efficiency increase from microwatts to milliwatts (Mishra et al. 2018). This gives rise to PEHs (Piezoelectric Energy Harvesters), systems that include piezoelectric material connected to other components for energy collection and distribution (Mahajan et al., 2021), varying according to the area where pressure is applied. Zheng et al. (2023) note that more structural types for generating energy through piezoelectricity have appeared. Therefore, background studies for this research can be grouped by their different applications.

2.2 Energy harvesting
Uchino (2017) explains the three phases of energy harvesting in PEHs. Covaci and Gontean (2020) present a review of different applications of piezoelectricity, their advantages and disadvantages, and the materials that can be used in PEH systems. Additionally, Shahrukh et al. (2019) provide a technical analysis of piezoelectric energy capture. Thainiramit et al. (2020) compare piezoelectric and triboelectric energy harvesting, finding that the piezoelectric approach has higher power and energy density. Calautit et al. (2022) discuss technologies for harvesting energy in small devices. Liu et al. (2021) describe different types of energy harvesting and present prototype examples. Perez-Alfaro et al. (2022) analyze energy harvesters under different conditions.

2.3 Typologies
Other studies examine alternative materials. Sandoval-Rodríguez et al. (2023) fabricated piezoelectric sheets with conventional materials and compared capacity, efficiency, and durability. Shaukat et al. (2023) explore transforming ambient energy into useful energy by connecting devices and piezoelectric materials for capture in electrochemical systems. Cha and Seo (2017) designed an energy-harvesting mechanism in shoes, which yielded a low electrical output; they conclude that better results could be obtained with materials having more stable properties. Similarly, Qian et al. (2018) designed a prototype boot with piezoelectric stacks in the heel that generate electricity depending

on speed and the stacks used. More recently, Norabuena (2020) studied the feasibility of generating electricity using sensors in shoe insoles, concluding that the energy produced was insufficient for conventional current.

Evans et al. (2019) studied floor platforms that produce electricity from people walking and found that walking produces less energy than running. In Guadalajara, Barragán et al. (2019) presented a theoretical investigation of a piezoelectric system in the urban train. Forero et al. (2018) and Sharma et al. (2022) designed piezoelectric plates/tiles to maximize collection. He et al. (2019) designed a prototype floor tile to power low-demand devices. Panthongsy et al. (2018) evaluated piezoelectric plates for energy collection from human footsteps. Yingyong et al. (2021) experimentally analyzed harvested energy under different pedestrian conditions.

Regarding piezoelectric pavement, Wang et al. (2020) developed a system based on CPEH (Conventional Piezoelectric Energy Harvester) and reported that vibrations from vehicle motion could collect up to 3.14 mW. Wang et al. (2022) investigated piezoelectric power generation for roads using cantilever-type and stacked-type devices, achieving a maximum output voltage of up to 128 V. Yuan et al. (2022) and Guo and Qing (2017) designed devices compatible with high traffic loads; the latter proposed a pavement design for piezoelectric energy collection. Wang C. et al. (2018) designed pavement prototype plates that achieved up to 2.92 mW at 0.2 MPa and 10 Hz. Wang C. et al. (2019) developed two pavement PEH prototypes and compared them, with effective results. Finally, Liu et al. (2021), Wang et al. (2021), and Wang C. et al. (2019) studied piezoelectricity in pavements for traffic monitoring; one study combined piezoelectric transducers with solar panels for higher efficiency and power; and another evaluated PEH adaptability under different traffic conditions.

3. Methods

Based on the above, it was proposed a prototype capable of generating electricity from the concept of piezoelectricity. The proposed methodological model can be seen in Figure 1 and enabled us to understand the piezoelectric effects and develop the prototype. The process included literature and materials review, verification, pilot tests, final tests, and analysis of all results, with iterative back-and-forth among components to improve the prototype as part of the experiments.

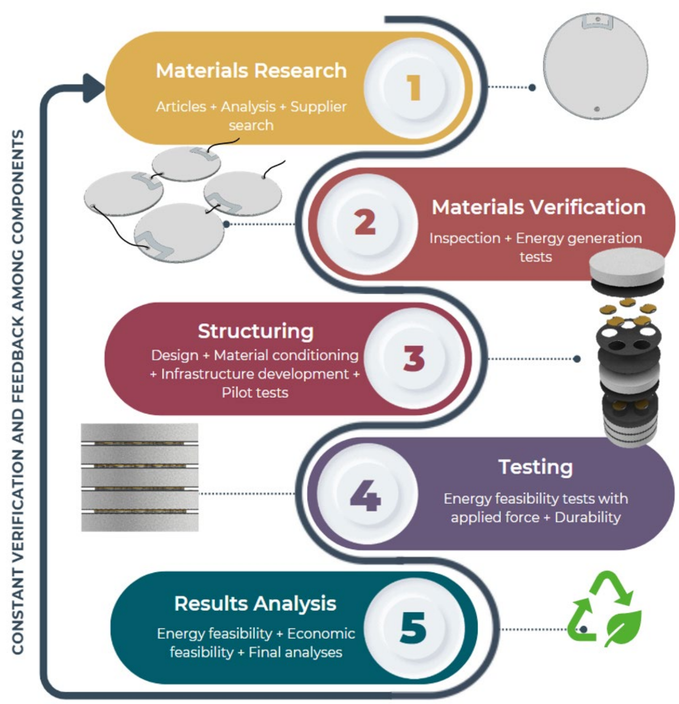

Figure 1. Methodological model

Within the model above, and as shown in Table 1, were the materials needed for the prototype parts.

Table 1. Materials

Material	Quantity
Powdered cement	6 kg
Cofitillo (rocks)	2.5 kg
Sand	3 kg
Ø 8" tube	1 m
1/4" mesh	1 m
Piezoelectric ceramic	20
Ø 9 cm brass bars	3 kg
Copper cables (m)	4
Adhesive	1 bottle
1/8" rubber	2 m²

The following equipment and instruments were also required:

- Multimeter: to measure generated voltage.
- Vernier caliper: to take dimensions.
- Soldering iron: to solder the wires.
- Lathe: to shape the brass reinforcement pieces.
- Milling machine: to shape the brass reinforcement pieces.
- Hydraulic press: to carry out the tests.

The prototype was built with a diameter of 20 cm and a length of 18.42 cm. These measurements varied through experimentation until the final version. In total, four versions were made, exploring different materials and ways to assemble them. The number of ceramics per layer evolved from 2 to 5, and the number of layers was reduced from 8 to 4. Reinforcement was introduced because the ceramic is fragile and was complemented by rubber, used as a gasket. Layered rubber also replaced suction cups.

First, the ceramics were soldered together with copper wires, connected in groups of five in series. After shaping the brass reinforcement, it was bonded on top of each ceramic. Cement disks were produced next, including a 10-day curing process. In parallel, flat rubber layers and gasket pieces were cut to size. Once the main components were ready, the rubber layers were bonded to the disks, the ceramics were inserted into the gasket, and all layers were stacked. Finally, excess material was trimmed (Figure 2).

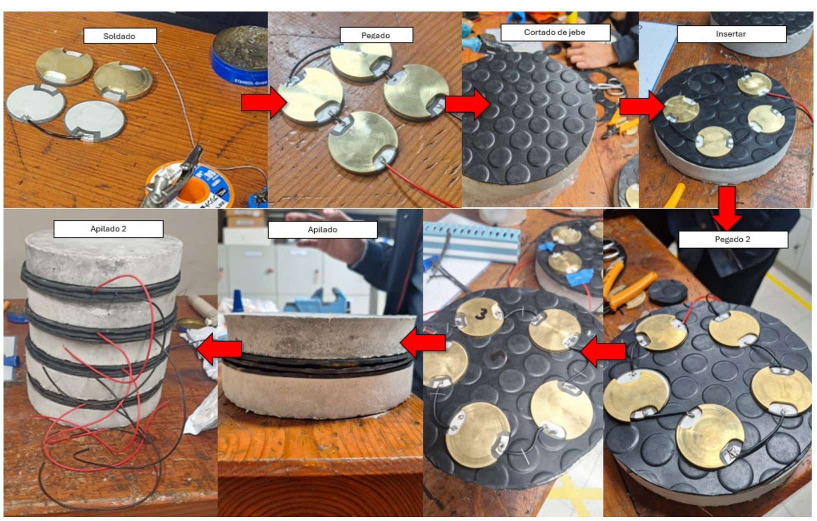

Figure 2. Layer conditioning and unfinished prototype

4. Data Collection

4.1 Data for simulation

Along with the prototype, a vehicle-counting study was required to conduct the final tests and associate the loads applied to the prototype with real-world operation. The intersection of Javier Prado Avenue and Olguín Avenue (Lima, Perú) was selected to scale the simulation. The vehicle count was carried out for one hour, from 9:00 to 10:00 p.m. (GMT-5), and vehicles were classified by weight (Figure 3).

Figure 3. Counting area

Additionally, interarrival times and weights were considered. Interarrival times were determined using the exponential distribution, which is commonly applied to this type of variable.

$$Estimated\ time = \frac{1}{(\lambda)}$$

Also, for the exponential distribution was considered the next expression:

$$f(t) = \lambda e^{-\lambda t}$$

For the weight variables, since it was not possible to obtain enough data from the press machine, and given that it was an analog press with imprecise and hard-to-observe readings, sample size calculations were performed and random data aligned with observed ranges were generated using the following, where a is the upper bound and b is the lower bound of the data:

$$= -a + (a - b) * Aleatory$$

Also, a 95% confidence level and 10% error were considered to compute the sample size.

$$Sample\ Size = (\frac{Standard\ deviation * Z}{Error})^2$$

4.2 Prototype data collection

Using the simulation inputs, final tests were performed by applying force with a press, so that the voltages obtained at given loads could be linked to predefined vehicle categories.

5. Results and Discussion

5.1 Manufacturing results (Figure 4)

Figure 4. Manufacturing result (completed prototype)

5.2 Numerical results

Based on the collected data, the vehicle types circulating on the roadway were classified by weight ranges and number of axles (Table 2).

Table 2. Vehicle classification and count

Category	Type
A	Motorcycles and small mobility vehicles
B	Cars and Pickup trucks
C	Mini-vans and Vans
D	Small trucks
E	Buses
F	Trucks

With this, the final tests were conducted. There were 57 results in which the prototype generated voltage. The peak measured value was 73.5 V (Table 3).

Table 3. Laboratory results

Voltage	**Ton**	**Category**	**Voltage**	**Ton**	**Category**
36.84	2.56	Category B	12.61	12.81	Category C
12.88	12.81	Category C	13.14	19.22	Category D
63.16	19.22	Category D	4.3	6.41	Category C
6.03	1.28	Category B	21.4	25.63	Category E
4.013	6.41	Category C	6.189	2.56	Category B
30.57	19.22	Category D	9.56	6.41	Category C
36.33	25.63	Category E	57.17	32.03	Category F
23.28	25.63	Category E	3.138	2.56	Category B
3.904	3.84	Category B	1.503	1.28	Category B
15.58	12.81	Category C	1.709	3.84	Category B
20.37	12.81	Category C	57.67	19.22	Category D
2.789	6.41	Category C	56.77	25.63	Category E
6.41	2.56	Category B	23.57	12.81	Category C
37.67	19.22	Category D	18.49	12.81	Category C

Voltage	**Ton**	**Category**	**Voltage**	**Ton**	**Category**
25.89	19.22	Category D	50.35	19.22	Category D
14.03	3.84	Category B	56.56	25.63	Category E
2.184	6.41	Category C	57.08	32.03	Category F
30.01	19.22	Category D	73.5	19.22	Category D
51.72	25.63	Category E	1.438	6.41	Category C
1.975	6.41	Category C	9.43	12.81	Category C
10.57	12.81	Category C	27.51	19.22	Category D
22.98	19.22	Category D	5.46	12.81	Category C
17.96	19.22	Category D	19.23	6.41	Category C
1.355	2.56	Category B	25.39	12.81	Category C
25.51	12.81	Category C	29.79	19.22	Category D
36.95	25.63	Category E	18.65	3.84	Category B
3.078	3.84	Category B	47.54	25.63	Category E
19.1	19.22	Category D	12.18	12.81	Category C
63.15	32.03	Category F			

Using this data, the simulation diagram in Arena software was built to represent the number of vehicles by type based on the laboratory results.

5.2 Graphical Results

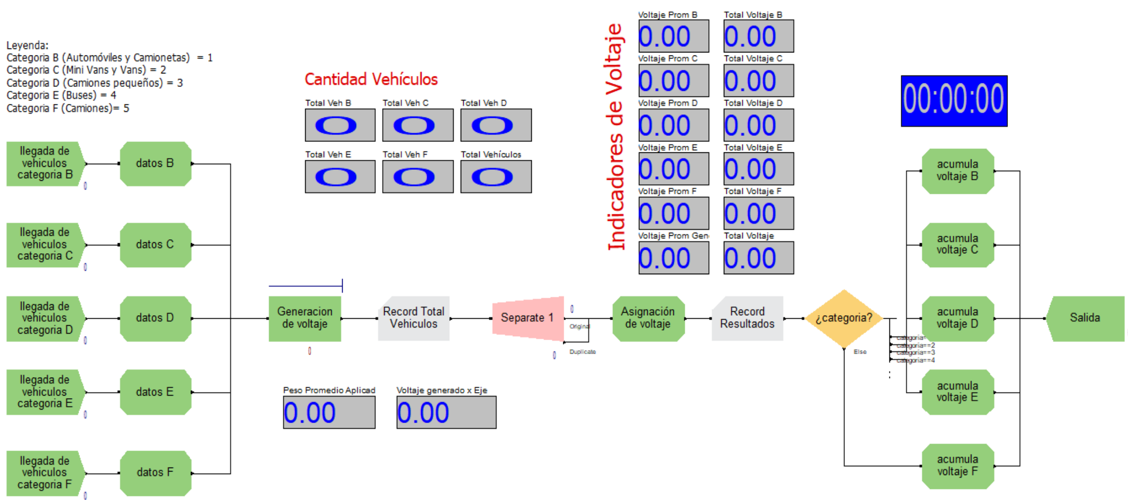

Figure 5. Simulation diagram

A one-hour simulation with 120 replications showed an overall average voltage per axle of 19.7333 V (Figure 5). Another important indicator is the total voltage generated by 5,861 vehicles: 232,020 V.

ARENA Simulation Results
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Output Summary for 120 Replications

Project: Unnamed Project — Run execution date : 6/ 9/2024
Analyst: desconocido — Model revision date: 6/ 9/2024

OUTPUTS

Identifier	Average	Half-width	Minimum	Maximum	# Replications
Total Voltaje	2.3202E+5	533.50	2.2323E+5	2.3913E+5	120
vehF.NumberIn	122.05	3.5892	72.000	183.00	120
vehF.NumberOut	122.05	3.5892	72.000	183.00	120
vehD.NumberIn	18.450	.98468	6.0000	38.000	120
vehD.NumberOut	18.450	.98468	6.0000	38.000	120
vehE.NumberIn	121.89	2.9108	84.000	156.00	120
vehE.NumberOut	121.88	2.9083	84.000	156.00	120
vehB.NumberIn	11425.	22.488	11096.	11657.	120
vehB.NumberOut	11425.	22.475	11096.	11656.	120
vehC.NumberIn	73.583	2.1223	48.000	102.00	120
vehC.NumberOut	73.583	2.1223	48.000	102.00	120
dispositivo.NumberSeized	5860.8	11.362	5681.0	5970.0	120
dispositivo.ScheduledUtilization	.13566	2.6286E-4	.13150	.13818	120
System.NumberOut	11761.	22.767	11403.	11971.	120

Simulation run time: 0.40 minutes.
Simulation run complete.

Figure 6. Simulation results

To translate the harvested energy to other devices, it is first necessary to compute it in a stable unit such as watt-hours (Figure 6). For the conversion, the overall average voltage per vehicle axle, the number of axles (categories B–E were assumed to have two axles and category F three axles), the duration of each impulse, and the amperage (theorical for this work) were considered (Figure 6).

$$Watts - seg = Average\ Voltage\ (V) \times Impulse\ time\ (s) \times amperage\ (A)$$
$$\sum Watts - seg = Watts - seg\ x\ axle\ q$$
$$Watts - h = \frac{T\ Watts - seg}{3600}$$

Thus, the total watt-hours was 32.24.

The main differences with previously cited studies lie in the prototype's form and output voltage. Although the prototype can generate electricity, it would likely have performed better with other materials. It should also be noted that the tools used can affect prototype performance and the interpretation of results.

Although the translation of harvested energy is beyond the scope of this work, preliminary experiments indicated that one or two modules may be required between the prototype and the load device. Storage and distribution are left for future research.

5.3 Proposed Improvements

Looking at how our results compare to other studies; there are a improvements that could be made.
First off, the prototype's design itself could use some refinement. Its shape really dictates how pressure spreads across the ceramics, which directly impacts the voltage we get.

In that same line, while PZT ceramics were a good starting point, other options like polymers or newer composite ceramics might be tougher and more flexible, handling the stress of a more realistic scenario without sacrificing too much power output.

On the testing side, having access to more modern equipment would make a big difference. A digital press and automated data loggers would give us much cleaner, more reliable numbers than our current analog setup, where reading the results was often tricky.

Finally, the most important test would be to take this out of the lab. Installing a few prototypes in a real road to know how it holds up under daily traffic and what it can truly generate outside of ideal conditions.

6. Conclusion

The prototype achieved voltage spikes above the 5 V design objective, reaching a maximum of 73.5 V under controlled press loads, and exhibited an average of 19.7333 V per axle when scaled through a traffic-based simulation of 5,861 vehicles and 120 replications. Translating performance into a stable energy metric, the system yielded 32.24 watt-hours, providing a quantitative basis for assessing feasibility in low-demand applications. These outcomes confirm functional energy harvesting from vehicular mechanical pressure while revealing variability inherent to impulsive loads and low current output. The study is important because it operationalizes a bench-to-traffic bridge that supports decision-oriented evaluation of piezoelectric harvesters in urban Peruvian conditions. It contributes a coupled design–test–simulation pathway that complements prior PEH research focused primarily on voltage or device typologies, and it clarifies siting implications for corridors with high axle throughput. Final observations point to material and geometry optimization, digital instrumentation for cleaner load–response traces, and in-situ pilots to observe durability and conditioning needs in real pavement environments. Future research should quantify energy stabilization and storage, examine alternative ceramics or composites for robustness under repeated stress, and validate long-term output under seasonal traffic variation and maintenance constraints without altering the core design premise.

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