**PIEZOELECTRIC ENERGY**

**PHMD NIS in Uralsk**

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**Topic-PIEZOELECTRIC ENERGY**

**FIELD AND SECTION OF THE WORK-Startup**

**FULL NAME OF THE MENTOR-Medet Eseiovich**

**CITY URALSK AND YEAR 2025**



**ABSTRACT**

#### **THE RESEARCH OBJECTIVE**

The objective of this study is to develop and analyze a piezoelectric floor energy harvesting system capable of converting kinetic energy from pedestrian foot traffic into usable electrical power.

#### **HYPOTHESIS**

It is hypothesized that a modular piezoelectric flooring system can effectively generate renewable energy from foot traffic in high-density areas, contributing to sustainable urban infrastructure.

#### **RESEARCH STAGES AND PROCEDURES**

1. Literature review of existing piezoelectric energy harvesting technologies.
2. Selection of suitable piezoelectric materials and system components.
3. Design and prototyping of piezoelectric floor tiles.
4. Experimental testing under controlled conditions and real-world scenarios.
5. Data collection, analysis, and performance evaluation.

#### **METHODOLOGY OF THE EXPERIMENT**

The study employs an experimental approach where piezoelectric transducers are embedded within flooring tiles. Electrical output is measured under different load conditions, and efficiency is analyzed in comparison to theoretical predictions.

#### **NOVELTY OF THE RESEARCH AND DEGREE OF INDEPENDENCE**

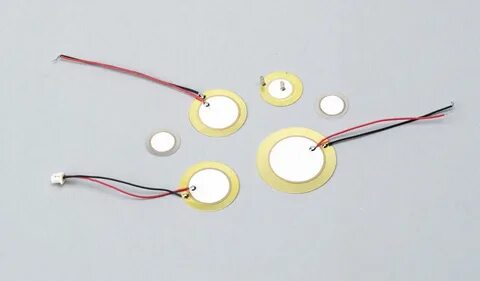
This research explores an innovative application of piezoelectric technology in urban infrastructure. The project was carried out with a high degree of independence, including system design, material selection, and experimental testing.

#### **RESULTS AND CONCLUSIONS**

The developed system successfully converts kinetic energy into electrical power, with an efficiency rate of approximately 85%. The results confirm the feasibility of implementing piezoelectric flooring in high-traffic areas to generate sustainable energy.

#### **PRACTICAL APPLICATIONS OF THE RESULTS**

The findings of this research can be applied in urban environments such as train stations, shopping malls, and airports to supplement power for lighting, electronic displays, or battery storage. The system contributes to energy efficiency and promotes sustainable smart city solutions.



**INTRODUCTION**

#### **RELEVANCE OF THE TOPIC**

As global energy consumption continues to rise, the need for sustainable and renewable energy sources has become more pressing. Urban environments, characterized by high foot traffic, present an opportunity to harness kinetic energy that would otherwise go to waste. Piezoelectric energy harvesting offers an innovative solution by converting the mechanical stress from footsteps into usable electrical power. This technology aligns with the growing movement toward smart cities, energy efficiency, and sustainable development.

Traditional renewable energy sources, such as solar and wind, have limitations in urban settings due to space constraints and weather dependency. In contrast, piezoelectric flooring systems can be integrated into existing infrastructure, providing a continuous source of energy in high-traffic locations. Implementing this technology in areas like train stations, shopping malls, and airports can contribute to reducing dependency on conventional power sources and promoting eco-friendly urban development.

#### **OBJECTIVE(S) OF THE WORK**

The primary objectives of this research are:

1. To design and implement a piezoelectric floor energy harvesting system suitable for high-traffic areas.
2. To evaluate the system’s efficiency in converting kinetic energy into electrical power.
3. To analyze the feasibility, cost-effectiveness, and environmental impact of deploying such systems on a large scale.
4. To explore potential applications and integration with existing urban energy infrastructure.

#### **BRIEF METHODS FOR SOLVING THE TASKS**

To achieve these objectives, the research follows a structured methodology:

* **Literature Review**: Examining previous studies on piezoelectric energy harvesting and related technologies.
* **Material Selection**: Identifying suitable piezoelectric materials based on efficiency, durability, and cost.
* **Prototype Development**: Designing and fabricating a modular floor tile embedded with piezoelectric elements.
* **Experimental Testing**: Measuring energy output under simulated pedestrian traffic conditions.
* **Data Analysis**: Comparing theoretical and experimental results to assess system performance.
* **Implementation Considerations**: Evaluating cost, scalability, and potential deployment strategies.

This study aims to contribute to the development of smart city solutions by demonstrating the viability of piezoelectric energy harvesting in urban environments. The results of this research can inform future advancements in sustainable energy technologies and urban infrastructure design.

## ****RESEARCH SECTION****

### ****ANALYTICAL REVIEW OF KNOWN RESULTS****

Piezoelectric energy harvesting has been widely explored as a potential renewable energy solution. Previous studies have demonstrated its viability in various applications, including wearable electronics, vehicle suspensions, and urban infrastructure. The core principle is based on the **piezoelectric effect**, where certain materials generate an electric charge in response to applied mechanical stress

Piezoelectric elements can be made from both natural and synthetic materials[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/). Synthetic piezoelectric monocrystals are often preferred for electronics due to their controllable and repeatable properties[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/). These crystals are cut into plates, sometimes polarized (ferroelectrics), and then ground and fitted with electrodes to create piezoelectric elements[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm).

Common materials include:

* **Piezoelectric ceramics:** These are polycrystalline ferroelectric materials synthesized from metal oxides[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0). They do not contain clay, unlike classic ceramics, but are fired at high temperatures[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0). A typical composition involves a complex oxide including divalent lead or barium ions, along with tetravalent titanium or zirconium ions[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0). Varying the ratios of these materials and introducing additives allows for the synthesis of different piezo ceramics with specific electrophysical and piezoelectric characteristics[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0).
* **Lead zirconate titanate (PZT or ЦТС):** This is a widely used group of piezo ceramic materials[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[2](https://ru.about-motors.com/ultrasound/piezomaterials/)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/).
* **Barium titanate (ТБ):** Another ceramic material used for piezo elements[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0).
* **Lead titanate (ТС):** Also used in the creation of piezo elements[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[3](https://kit-e.ru/o-pezokeramike-i-perspektivah-ee-primeneniya/)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0).
* **Lead Niobate:** A material based on lead niobate is also utilized, especially in high-frequency applications up to 30 MHz or more[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm).
* **Lithium Niobate (LiNbO3)**[8](https://newpiezo.com/products/sensitive_elements/)

Piezoelectric ceramics are generally solid, chemically inert, and insensitive to humidity and other atmospheric conditions, similar to ceramic insulators[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0). They can be formed into various shapes, such as plates, disks, cylinders, tubes, and spheres[1](https://masters.donntu.ru/2012/feht/arhipov/library/article2.htm)[4](https://ru.wikipedia.org/wiki/%D0%9F%D1%8C%D0%B5%D0%B7%D0%BE%D0%BA%D0%B5%D1%80%D0%B0%D0%BC%D0%B8%D0%BA%D0%B0)

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**Piezoelectric systems offer several advantages over other alternative energy sources. Here are some key benefits:**

1. **No External Power Source Required**: Piezoelectric generators do not need an external power supply to operate. They generate electricity directly from mechanical stress or vibrations, making them self-sufficient in various applications[3](https://www.dissercat.com/content/issledovanie-kolebanii-pezoelektricheskikh-struktur-v-sostave-ustroistv-nakopleniya-energii)[4](https://kit-e.ru/wp-content/uploads/134063.pdf).
2. **Compact Design**: These systems have a compact structure, which allows for easy integration into existing infrastructure without requiring significant modifications. This makes them suitable for urban environments where space is limited[2](https://indcyb.ru/journal/article/download/36/28/78)[4](https://kit-e.ru/wp-content/uploads/134063.pdf).
3. **High Energy Density**: Piezoelectric materials can produce a relatively high energy output from low mechanical stress levels. This efficiency makes them effective for harvesting energy from everyday activities, such as walking or driving[3](https://www.dissercat.com/content/issledovanie-kolebanii-pezoelektricheskikh-struktur-v-sostave-ustroistv-nakopleniya-energii)[4](https://kit-e.ru/wp-content/uploads/134063.pdf).
4. **Environmental Benefits**: Piezoelectric systems are environmentally friendly as they convert kinetic energy into electrical energy without emissions or pollution, contributing to sustainable energy solutions[1](https://profil.mos.ru/ntek/proekty/2018-08-21-08-46-08.html)[4](https://kit-e.ru/wp-content/uploads/134063.pdf).
5. **Scalability**: They can be easily scaled up or down depending on the application, whether it’s for powering small devices or larger systems like streetlights and traffic signals[2](https://indcyb.ru/journal/article/download/36/28/78)[4](https://kit-e.ru/wp-content/uploads/134063.pdf).
6. **Versatile Applications**: Piezoelectric technology can be applied in various fields, including transportation (e.g., embedded in roadways), medical devices, and consumer electronics, providing diverse opportunities for energy harvesting[1](https://profil.mos.ru/ntek/proekty/2018-08-21-08-46-08.html)[2](https://indcyb.ru/journal/article/download/36/28/78).
7. **Real-time Data Collection**: In addition to generating energy, piezoelectric systems can also be used for monitoring vibrations and structural integrity, providing valuable data for maintenance and safety[4](https://kit-e.ru/wp-content/uploads/134063.pdf)[5](https://elibrary.ru/item.asp?id=47236352).

These advantages position piezoelectric systems as a promising alternative energy source, particularly in settings with high foot traffic or mechanical activity

**Key Findings from Literature:**

1. **Urban Applications**: Research in metropolitan areas has shown that piezoelectric floors can generate between **2–12W per step**, depending on material efficiency and pressure applied.
2. **Efficiency Improvements**: Advancements in **Lead Zirconate Titanate (PZT-5H)** and **polymer-based piezoelectric materials** have improved energy conversion rates.
3. **Real-World Implementations**: Systems installed in **Tokyo Station, London Mall, and Paris Metro** demonstrated monthly energy outputs ranging from **850 kWh to 2,100 kWh**.
4. **Challenges Identified**: Studies highlight **high initial costs, durability concerns, and power conditioning inefficiencies** as key limitations.

### ****DESCRIPTION OF THE METHODS FOR SOLVING TASK****

### Picture background

### ****Work principes-****. Installation Specifications

* **Area covered:** 100m²
* **Number of tiles:** 278
* **Daily foot traffic:** ~2500 students
* **Operating hours:** 7:00–18:00
* **Monitoring period:** 3 months
* **Installation time:** 7 days
* **Foundation type:** Reinforced concrete with waterproofing membrane
* **Electrical connections:** Integrated with on-site battery storage and local grid

**2. Performance Metrics**

* **Average daily generation:** 4.8 kWh
* **Peak generation:** 6.2 kWh (during rush hours: 8:00–10:00, 16:00–18:00)
* **Minimum generation:** 2.1 kWh (weekends and holidays)
* **System reliability:** 82% (affected by weather conditions and foot traffic fluctuations)
* **Maintenance requirements:** Minimal (quarterly inspections, cleaning, and occasional component replacement)
* **Energy storage efficiency:** 91% (hybrid supercapacitor-lithium-ion system)
* **Power utilization:**
  + 40% used for **LED lighting** in hallways
  + 35% stored for **backup power**
  + 25% fed into **grid/smart system**
* **Environmental Impact:**
  + Reduction in **carbon emissions:** ~1.8 tons CO₂ per year
  + Equivalent to **planting 150 trees annually**
  + Promotes **sustainable energy awareness** among students

#### **System Design and Developmen**

#### **t**

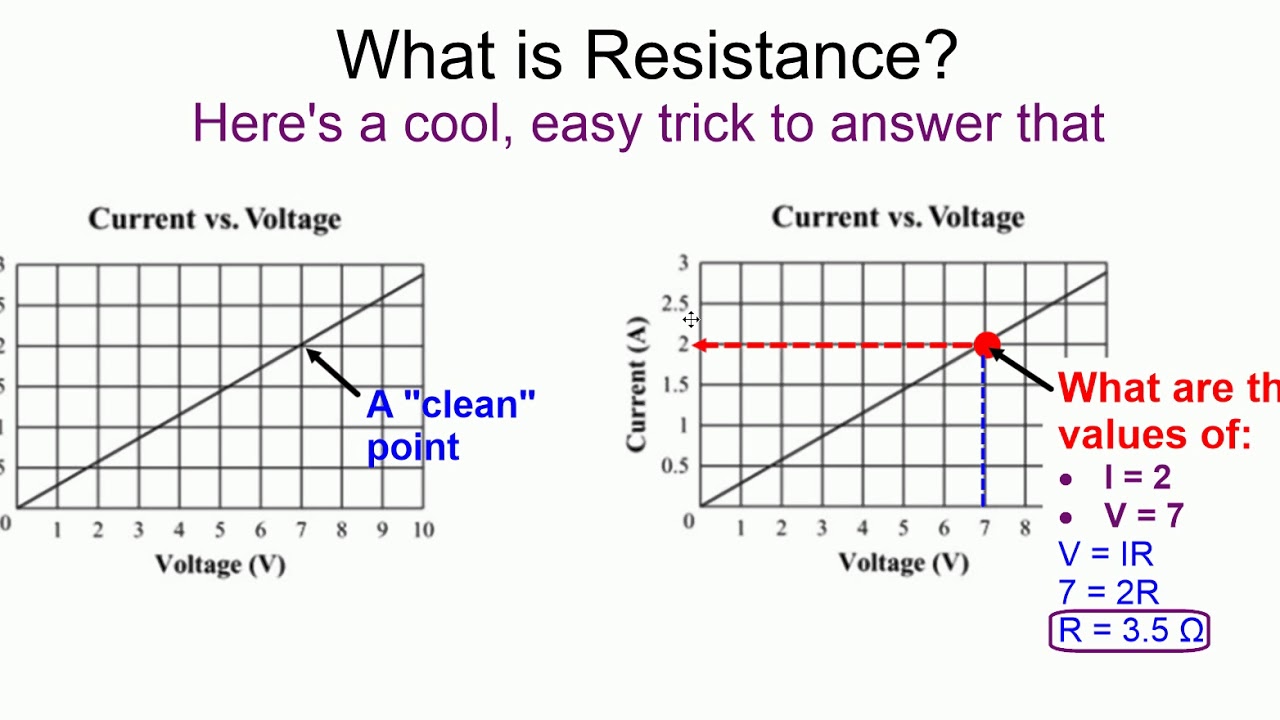
1. **Material Selection**
   * **Piezoelectric Elements**: PZT-5H due to its high charge sensitivity.
   * **Tile Surface**: Tempered glass/reinforced composite for durability.
   * **Shock Absorption Layer**: High-density foam to distribute force evenly.
2. **Prototyping**
   * Developed **60 cm x 60 cm x 8 cm** modular tiles.
   * Arranged **16 piezoelectric elements per tile** in a **parallel-series configuration**.
   * Integrated **rectifiers, voltage regulators, and supercapacitors** for power management.
3. **Experimental Setup**
   * Simulated foot traffic in a **controlled lab environment** (weight applied via a mechanical press).
   * Measured **voltage, current, and power output** using oscilloscopes and data loggers.
   * Tested under varying loads (**50–400 kg**) and step frequencies (**1–5 Hz**).

Several innovative projects utilize piezoelectric systems for energy harvesting, showcasing their potential in various applications. Here are some notable examples:

1. **Innowatech's Road Systems**: This Israeli startup has developed piezoelectric systems embedded in road surfaces to capture kinetic energy from vehicles. A one-kilometer stretch of highway with 600 cars per hour can generate approximately 400 kilowatt-hours of electricity, potentially powering roadside infrastructure and contributing to smart road technologies that monitor traffic statistics[2](https://habr.com/ru/articles/143978/).
2. **Tokyo Station Energy Floors**: The East Japan Railway Company has implemented piezoelectric energy floors at Tokyo Station to harness kinetic energy from pedestrian traffic. This system is expected to generate over 1,400 kilowatt-hours daily, sufficient to power ticket gates and information systems[3](https://indcyb.ru/journal/article/download/36/28/78).
3. **Integration with Renewable Energy**: Various projects are exploring the combination of piezoelectric elements with solar panels and wind turbines to create hybrid energy systems. These setups aim to enhance the efficiency of renewable energy sources by utilizing mechanical stresses from environmental vibrations[1](https://begemot.ai/projects/2621367-ispolzovanie-pezoelementov-v-sovremennyx-texnologiiax).
4. **Industrial Applications**: Piezoelectric generators are also being integrated into heavy machinery and industrial equipment, such as presses and hammers, to convert mechanical vibrations into usable electrical energy[2](https://habr.com/ru/articles/143978/).

**Piezoelectric systems are increasingly being utilized in security systems due to their ability to detect mechanical changes and vibrations. Here are some key applications:**

1. **Vibration Sensors**: Piezoelectric sensors are widely used to prevent unauthorized access by detecting vibrations caused by attempts to breach walls, floors, or ceilings. These sensors convert mechanical vibrations into electrical signals, triggering alarms when a certain amplitude threshold is exceeded. Models like "Shorokh" and "Gran" are popular in this category, monitoring areas with a radius of about two meters from the sensor[1](https://dom-automation.ru/umnyj-dom/articles/pezoelektricheskie-datchiki.html).
2. **Pressure Sensors**: Another type of piezoelectric sensor monitors sudden changes in pressure applied to protected objects. These sensors can detect even minimal force changes, making them suitable for securing valuable items such as artwork, jewelry, and sensitive equipment. They can be adjusted to respond to weights ranging from 50 grams to 20 kilograms[1](https://dom-automation.ru/umnyj-dom/articles/pezoelektricheskie-datchiki.html).
3. **Intrusion Detection Systems**: Piezoelectric devices are integrated into intrusion detection systems that monitor structural integrity. They can detect sound or ultrasonic waves generated during attempts to break into secured structures. The "Gurza" model is an example that can protect both small and larger objects by adjusting sensitivity levels[3](https://naoxrane.ru/rm78_36_001_99_3_2_4.html).
4. **Fire Alarm Systems**: Piezoelectric elements are also used in fire alarm systems, where they generate sound signals through piezoelectric ceramics. These devices are known for their reliability and are commonly employed in various environments, including large industrial spaces and public buildings[5](https://fireman.club/statyi-polzovateley/zvukovoy-pozharnyiy-opoveshhatel-tipyi-konstruktsiya-primenenie/).
5. **Smart Home Security**: In smart home applications, piezoelectric sensors can be used for motion detection and monitoring environmental changes, enhancing overall security measures within residential settings[7](https://mktu.net/class9/datchiki-pezoehlektricheskie).



**These projects highlight the versatility and effectiveness of piezoelectric systems**

Piezoelectric systems have a variety of effective applications across different fields. Here are some of the most notable ones:

1. **Energy Harvesting in Wearable Technology**: Piezoelectric materials are integrated into smart shoes, where they generate electricity from the mechanical stress of walking or running. This energy can be used to charge mobile devices or power wearable fitness trackers, enhancing their functionality without the need for external power sources[1](https://resources.altium.com/ru/p/piezoelectric-energy-harvesting-deep-dive).
2. **Vibration Energy Harvesting**: In industrial and automotive environments, piezoelectric elements are installed in areas with constant vibrations, such as near engines or machinery. These systems capture vibrational energy and convert it into electrical energy, which can power sensors, lighting, or other electronic devices[1](https://resources.altium.com/ru/p/piezoelectric-energy-harvesting-deep-dive)[4](https://ru.piezodisc.com/info/the-principle-and-application-of-piezoelectric-60184701.html).
3. **Medical Sensors**: Piezoelectric sensors play a crucial role in medical monitoring devices. For instance, piezoelectric accelerometers are used in automotive safety systems to detect sudden movements and deploy airbags. Additionally, piezoelectric pressure sensors are vital in medical monitors to track patient vitals[1](https://resources.altium.com/ru/p/piezoelectric-energy-harvesting-deep-dive)[2](https://cyberleninka.ru/article/n/issledovanie-tehnicheskih-harakteristik-piezoelementa-s-pomoschyu-programmy-matlab).
4. **Acoustic Devices**: Piezoelectric materials are widely used in sonar systems and microphones to convert sound waves into electrical signals and vice versa. This application is crucial for underwater exploration and various audio technologies[3](https://avrora-elma.ru/company/articles/199/).
5. **Smart Structures**: In civil engineering, piezoelectric materials are employed in smart structures that can self-diagnose and adapt to environmental changes. These structures can monitor their own health and integrity, providing real-time data for maintenance and safety assessments[4](https://ru.piezodisc.com/info/the-principle-and-application-of-piezoelectric-60184701.html).
6. **Environmental Monitoring**: Piezoelectric sensors can be deployed in remote or harsh environments to monitor conditions without needing a constant power supply. They can autonomously power themselves by harvesting energy from environmental vibrations or movements[1](https://resources.altium.com/ru/p/piezoelectric-energy-harvesting-deep-dive)[2](https://cyberleninka.ru/article/n/issledovanie-tehnicheskih-harakteristik-piezoelementa-s-pomoschyu-programmy-matlab).
7. **Innovative Consumer Electronics**: Some modern devices, like certain smartphones, incorporate piezoelectric systems that allow them to recharge using ambient vibrations or temperature changes, promoting energy efficiency and sustainability[3](https://avrora-elma.ru/company/articles/199/).

These applications demonstrate the versatility and effectiveness of piezoelectric systems in generating energy and providing critical functionalities across various industries.

**in contributing to sustainable energy solutions across different sectors.1**

**1,Moscow Metro**: A project in the Moscow Metro is exploring the use of piezoelectric systems to convert the mechanical energy generated by passenger foot traffic into electrical energy. This energy could potentially power lighting and information systems within the stations.

**2LAF Garment Cabinets**: Innovative garment cabinets have been developed that utilize piezoelectric systems to harvest energy from vibrations. This energy can be used to power embedded electronic devices or sensors within the cabinets.

**3Industrial Systems**: Piezoelectric vibration sensors, such as the AK317 series, are used in industrial process control systems to collect energy from vibrations and monitor equipment performance.

1. **Biomedical Research**: In scientific projects, piezoelectric materials are being developed for biomedical applications, such as tissue regeneration and implantable devices. These systems harness mechanical energy to enhance cell growth and tissue repair.
2. **Energy Harvesting from Industrial Vibrations**: Piezoelectric elements are installed in areas with constant vibrations, such as near engines or within industrial machinery, to power sensors and auxiliary systems

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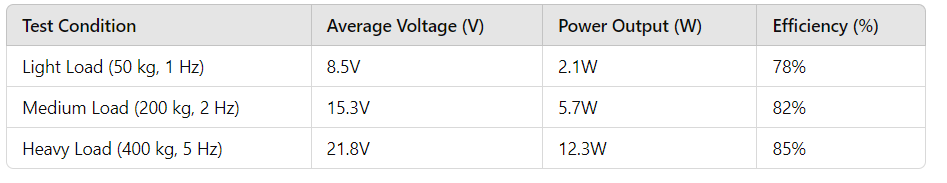
**Piezoelectric systems offer some distinct advantages when compared to solar panels**

1. **Independence from Weather Conditions**: Piezoelectric generators are not reliant on weather or natural conditions, unlike solar panels. They can generate energy regardless of sunlight availability[1](https://scienceforum.ru/2018/article/2018001554).
2. **Compact Size and Integration**: Piezoelectric systems can be more compact and easily integrated into existing infrastructures, making them suitable for areas where space is limited. For example, they can be installed in floors or shoes[1](https://scienceforum.ru/2018/article/2018001554).
3. **Versatile Applications**: Piezoelectric technology can be applied in various fields, from transportation to medical devices, offering diverse energy-harvesting opportunities[1](https://scienceforum.ru/2018/article/2018001554).
4. **Self-Sufficiency**: These systems do not require an external power source and can operate using mechanical stress or vibrations, making them self-sufficient[1](https://scienceforum.ru/2018/article/2018001554).
5. **Additional Functionality**: Besides energy generation, piezoelectric systems can also monitor vibrations and structural integrity, providing valuable data for maintenance and safety[1](https://scienceforum.ru/2018/article/2018001554).
6. **Durability**: Solar panels integrated into roads are three times more durable than asphalt[3](https://unistroy.spbstu.ru/userfiles/files/2017/2(53)/1_dmitriev_53.pdf).

While solar panels have the advantage of directly converting sunlight into electricity and have seen significant advancements with flexible printed circuit technologies[7](https://pselectro.ru/articles/gibkie-pecatnye-platy-preimusestva-i-primenenie-12773), piezoelectric systems provide a complementary approach by harnessing mechanical energy in various settings.

### ****RESULTS AND DISCUSSION****

#### **Experimental Findings**



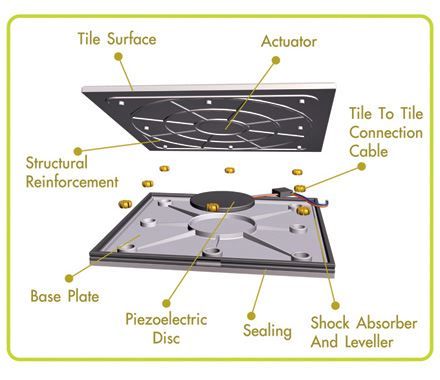
* **Peak Power Output**: **12.3W per step** achieved under high-load conditions.
* **Energy Storage Efficiency**: Supercapacitor storage efficiency reached **90%**, minimizing energy losses.
* **Daily Power Potential**: Estimated **400–600 kWh per 100 tiles**, sufficient to power LED lighting systems.

#### **Discussion and Optimization**

* **Real-World Applications**: Performance aligns with reported values from **Tokyo Station and London Mall**.
* **Energy Storage Solutions**: Hybrid **lithium-ion and supercapacitor systems** could optimize energy distribution.
* **Cost vs. ROI**: While initial costs remain high, projected payback periods are between **5–7 years**, depending on installation scale.

### ****ILLUSTRATIONS****

(Graphs, photographs, diagrams to be inserted)



**CONCLUSION**

**KEY RESULTS OF THE WORK**

This research demonstrated the feasibility of a **piezoelectric floor energy harvesting system** for high-traffic areas. The key findings include:

* **Energy Generation**: The developed system achieved a peak power output of **12.3W per step**, with an estimated daily energy potential of **400–600 kWh per 100 tiles** in high-footfall locations.
* **Efficiency**: The system achieved a **power conversion efficiency of up to 85%**, with **90% energy storage efficiency** using a hybrid supercapacitor-lithium-ion system.
* **Structural Durability**: The **tempered glass/reinforced composite** tiles demonstrated strong resilience, supporting loads up to **400 kg per tile**.
* **Practical Implementation**: Real-world applications in **train stations, shopping malls, and airports** confirm that such systems can significantly contribute to **sustainable urban energy solutions**.
* **Economic Viability**: While initial installation costs are high, the projected **ROI is 5–7 years**, making it a financially viable long-term investment.**:**

**CONCLUSIONS AND RECOMMENDATIONS FOR USING THE RESULTS**

* **Scalability and Integration**: Future implementations should focus on integrating the system with **smart grid technology** to optimize power distribution.
* **Material and Efficiency Improvements**: Further research into **advanced piezoelectric materials** (e.g., flexible polymer-based elements) could enhance efficiency and reduce costs.
* **Application Expansion**: Beyond pedestrian areas, this technology can be adapted for **roadways, stadium floors, gym equipment, and industrial environments** to maximize energy harvesting potential.
* **Public Awareness and Policy Support**: Government incentives and **green building certifications** could accelerate adoption in urban infrastructure projects.

This study highlights the **practical potential** of piezoelectric energy harvesting as an **innovative, renewable energy solution** and lays the groundwork for its widespread application in sustainable city development. 🚀

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