

Energy-Harvesting Pavement Materials: A Review of Technologies for Sustainable Infrastructure

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Abstract

Energy-harvesting pavement materials represent an innovative frontier in sustainable infrastructure, leveraging ambient kinetic, thermal, and solar energy inherent in roadways to power sensor networks, lighting, and low-power devices. This review comprehensively examines the state-of-the-art technologies piezoelectric transducers embedded within asphalt, thermoelectric generators (TEGs) exploiting pavement temperature gradients, and photovoltaic/solar-thermal systems integrated into surfaces such as solar roads or bike paths. Recent advances include improved piezoelectric materials (e.g., PZT, PVDF, lead-free ceramics), cantilevered beam configurations, and optimized embedment strategies that maximize power output under vehicular loading. Thermoelectric systems have been explored using asphalt solar collectors and pipe-based systems to reduce surface temperature while harvesting heat. Solar-integrated pavements, such as the Netherlands' SolaRoad and France's Wattway pilot projects, demonstrate technological potential, though challenges in durability, cost, and efficiency persist. The review critically assesses field deployments and laboratory prototypes, evaluating power density, installation complexity, life-cycle cost, and resilience under traffic. Piezoelectric systems show instantaneous power in the milliwatt to watt range sufficient for distributed IoT sensors and weigh-in-motion systems. Thermoelectric harvesters can mitigate urban heat islands while powering remote monitoring. Solar pavements promise distributed generation but face structural limitations and economic constraints. Emerging nanogenerators and triboelectric systems offer high conversion efficiency yet remain unproven at scale. The review includes a comparative table summarizing performance across key metrics and discusses methodological considerations for evaluating these systems LCA, durability testing, embedment design, and hybridization of multiple harvesting modalities. Future research priorities include developing standards for durability and integration, combining modalities (e.g. piezo + thermoelectric + solar), leveraging AI for design optimization, and ensuring materials and designs are climate-resilient and cost-effective. This review aims to guide researchers, engineers, and policymakers in identifying viable pathways toward integrating energy-harvesting pavements into sustainable infrastructure ecosystems.

Keywords: Energy-harvesting pavements, piezoelectric materials, thermoelectric generation, photovoltaic pavements, smart infrastructure.

1. Introduction

The global energy demand has been on a relentless rise, driven by population growth, urban expansion, and the proliferation of energy-dependent technologies. Traditional energy sources, primarily fossil fuels, continue to dominate the supply chain, leading to significant environmental concerns including greenhouse gas emissions, pollution, and ecological degradation. These challenges underscore the urgent need to diversify energy sources, particularly by integrating renewable and sustainable alternatives into everyday infrastructure.

Civil infrastructure, such as roads and pavements, occupies vast surface areas and endures constant mechanical and thermal stress due to human and vehicular traffic [7]. Traditionally, these surfaces have been viewed solely as structural components. However, recent innovations have explored how such ubiquitous structures can be transformed into energy-generating platforms, giving rise to the concept of energy-harvesting pavements.

Energy-harvesting pavements are specially engineered materials that generate electricity from mechanical pressure, heat gradients, or solar radiation. These technologies are designed to work passively, requiring no external power input for activation. Instead, they exploit natural phenomena such as the compression of footfalls, the vibration from traffic, or the sun's irradiance. The harvested energy can be stored in batteries or used immediately to power streetlights, sensors, or public infrastructure [7].

The core mechanisms behind energy-harvesting pavements include piezoelectric, thermoelectric, and photovoltaic technologies. Piezoelectric materials generate electric charge when subjected to mechanical stress, making them ideal for areas with high pedestrian or vehicular activity. Thermoelectric systems exploit temperature differences between the pavement surface and subgrade to generate voltage, while photovoltaic pavements integrate solar panels into the surface to harness solar energy.

The use of energy-harvesting pavement materials aligns with the principles of smart cities and sustainable development. In addition to producing clean energy, these systems can support smart monitoring functions, including traffic density sensing and real-time infrastructure health monitoring. This dual-purpose functionality significantly enhances the value proposition of integrating energy-harvesting materials into civil infrastructure.

Despite their promise, energy-harvesting pavements face several challenges. These include high material costs, limited energy conversion efficiencies, mechanical durability, and integration with existing urban systems. Furthermore, different geographical regions with varying climates and traffic densities demand context-specific solutions. Research is ongoing to address these limitations by developing more efficient materials, optimizing design configurations, and testing full-scale implementations [3].

Real-world pilot projects in countries like the Netherlands, China, and the United States have demonstrated the feasibility of these systems, albeit on a limited scale. These projects have provided valuable insights into operational challenges, user acceptance, and long-term sustainability. However, widespread deployment will require comprehensive testing under diverse environmental and loading conditions, as well as cost-benefit analyses and policy support [4].

Energy-harvesting pavements also offer educational and social benefits by raising public awareness about renewable energy and promoting community engagement in sustainability initiatives. As cities aim to reduce their carbon footprints and adopt smarter technologies, integrating energy-harvesting capabilities into existing infrastructure may become an essential strategy.

The advancement of material science, nanotechnology, and sensor integration plays a pivotal role in enhancing the performance and applicability of these pavements. Researchers are actively exploring

hybrid systems that combine multiple energy-harvesting mechanisms to maximize output and reliability. Such interdisciplinary innovations are central to pushing the boundaries of what civil infrastructure can achieve.

This paper presents a comprehensive review of energy-harvesting pavement technologies, focusing on their principles, material compositions, and real-world applications. The subsequent sections provide a critical evaluation of the existing literature, followed by a structured methodology for evaluating and deploying these systems. The global energy demand has been on a relentless rise, driven by population growth, urban expansion, and the proliferation of energy-dependent technologies. Traditional energy sources, primarily fossil fuels, continue to dominate the supply chain, leading to significant environmental concerns including greenhouse gas emissions, pollution, and ecological degradation. These challenges underscore the urgent need to diversify energy sources, particularly by integrating renewable and sustainable alternatives into everyday infrastructure.

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2. Literature Review

The emergence of energy-harvesting pavements has attracted considerable academic and industrial interest over the past decade. Multiple studies have explored various mechanisms, materials, and deployment strategies, contributing to a growing body of knowledge in this interdisciplinary domain. This section critically reviews six to seven pivotal studies that have laid the groundwork for understanding the feasibility and effectiveness of energy-harvesting pavement systems.

Presented an early and comprehensive study on piezoelectric energy harvesting from road traffic. Their research focused on integrating piezoelectric ceramic patches beneath asphalt surfaces to generate electricity from vehicular vibrations [1]. The findings demonstrated that energy harvesting is viable under controlled laboratory conditions, with significant electrical output depending on the load and material type. However, they noted challenges in long-term durability and energy storage, indicating the need for material improvements and optimized configurations.

Study explored the practical aspects of installing piezoelectric modules in real-road environments. They embedded piezoelectric transducers in a section of road subjected to heavy traffic in South Korea [7]. Their results showed consistent energy generation, but environmental factors such as temperature fluctuations and moisture ingress led to performance variability. The study highlighted the importance of protective encapsulation and advanced materials that can endure harsh outdoor conditions.

Authors introduced a hybrid pavement system combining thermoelectric and piezoelectric mechanisms [3]. Their model aimed to simultaneously exploit mechanical stress and temperature gradients, thereby maximizing energy output. This approach showed improved power generation efficiency over single-mechanism systems, with energy output increasing by approximately 25%. Their research demonstrated the advantages of hybrid systems in overcoming the limitations of individual technologies and offered a roadmap for system integration.

In terms of photovoltaic pavements, the Wattway project in France, reported by [2], remains one of the most well-known field experiments. The solar road consisted of photovoltaic cells embedded in a resin-based surface coating. Despite initial optimism, the project faced criticism due to low energy output compared to conventional solar panels, high installation costs, and structural degradation over time. This case underscored the trade-offs between visibility, cost, and performance in public energy-harvesting infrastructure.

The author took a materials-engineering approach by investigating flexible piezoelectric composites suitable for pavement integration [6]. They experimented with polymer-based piezoelectric materials such as PVDF (polyvinylidene fluoride) reinforced with nanoparticles to enhance energy conversion

efficiency. Their results indicated improved flexibility, mechanical endurance, and energy yield, making these materials suitable for high-frequency pedestrian pathways. The research emphasized the importance of selecting materials that align with specific use-case scenarios, whether high traffic loads or frequent footfalls.

A review provided a systematic analysis of various energy-harvesting pavement techniques [9]. Their meta-analysis included over 100 peer-reviewed studies and concluded that piezoelectric systems offer the highest energy potential per unit area in dynamic load conditions, while photovoltaic systems are more suitable for stable, sun-exposed locations. Thermoelectric systems, although less efficient, were recommended for integration in extreme climates with large temperature gradients. The study also highlighted critical gaps in scalability, cost analysis, and environmental durability that need to be addressed before widespread adoption.

Most recently, conducted a pilot implementation of an intelligent pavement embedded with energy-harvesting sensors and wireless data transmission capabilities [4]. This smart pavement prototype not only harvested energy through piezoelectric tiles but also powered embedded sensors used for traffic monitoring and structural health assessment. The study demonstrated the multifunctionality of energy-harvesting pavements beyond power generation, showing potential applications in smart transportation systems.

From the reviewed studies, several key insights emerge. First, the energy conversion efficiency of current systems remains relatively low, necessitating advancements in material science and device architecture. Second, environmental durability is a major concern, with temperature, moisture, and mechanical wear significantly affecting system longevity. Third, while laboratory tests often yield promising results, real-world deployments highlight logistical and operational challenges that must be resolved through interdisciplinary collaboration and system-level optimization.

Moreover, economic viability remains a critical barrier. Several studies have reported high initial installation and maintenance costs, which limit commercial interest and public investment. Life cycle cost analysis and performance-based incentive models are needed to make these systems more attractive to municipalities and developers. Additionally, social acceptance and public perception, though less frequently studied, play a role in the adoption of such visible and novel infrastructure systems.

In summary, the literature suggests a promising but still-developing field. Piezoelectric, thermoelectric, and photovoltaic technologies each have unique strengths and challenges. Hybrid systems appear to offer enhanced performance, while smart integration with sensors and data infrastructure could unlock new functionalities. Future research must focus on improving material durability, optimizing energy efficiency, and evaluating long-term economic and environmental impacts.

3. Methodology

The methodology of this review focuses on synthesizing existing research, analyzing technical performance, and comparing implementation strategies of different energy-harvesting pavement systems. A systematic approach was adopted to categorize technologies, assess performance metrics, and present comparative data through structured analysis. The methodology consists of four key components: classification of technologies, evaluation criteria, comparative analysis, and case study synthesis.

3.1. Classification of Energy-Harvesting Pavement Technologies

To understand the diversity and potential of energy-harvesting pavements, the materials and systems were classified into three major categories [3]:

- **Piezoelectric Pavements:** Utilize mechanical stress from vehicular or pedestrian traffic to

- **Thermoelectric Pavements:** Exploit temperature gradients between the pavement surface and subgrade to produce power.
- **Photovoltaic Pavements:** Integrate solar cells into the pavement surface to convert sunlight into electricity.

Hybrid systems that combine two or more of the above technologies were also included for analysis [7].

3.2. Evaluation Criteria

To compare and assess various energy-harvesting pavement systems, specific criteria were defined based on previous literature and practical implementations [8]:

- Energy Conversion Efficiency (%)
- Power Output (mW/cm² or W/m²)
- Material Durability (Years)
- Installation Complexity
- Cost per Square Meter (USD)
- Suitability for Environment (Urban, Rural, High Traffic)
- Maintenance Frequency (per year)

Each technology was evaluated using these parameters to derive a comparative understanding of performance and viability.

3.3. Data Collection and Analysis

Data were extracted from peer-reviewed journal articles, industry reports, field implementations, and experimental studies between 2010 and 2024. Only studies with quantifiable outputs and detailed technical information were selected. The datasets were normalized for consistency and presented in comparative tables.

3.4. Comparative Performance Table

Below is a summary table comparing the major energy-harvesting pavement technologies based on average reported values from selected studies:

Table 1: Comparative Analysis of Energy-Harvesting Pavement Technologies

Criteria	Piezoelectric Pavement	Thermoelectric Pavement	Photovoltaic Pavement
Energy Conversion Efficiency (%)	5–10	2–5	10–18
Average Power Output	1–3 mW/cm ²	0.5–1.5 mW/cm ²	20–30 W/m ²
Material Durability	5–10 years	8–15 years	10–12 years
Installation Complexity	High	Moderate	High
Cost per m ² (USD)	300–500	200–350	400–700
Ideal Environment	Urban intersections	Climate extremes	Sunny pedestrian zones
Maintenance Frequency	2–4 times/year	1–2 times/year	1–3 times/year

Table 1 illustrates that while photovoltaic pavements offer the highest output, piezoelectric systems are more effective in dynamic environments, and thermoelectric systems work best in regions with large diurnal temperature variations.

3.5. Performance Evaluation Framework

To assess the viability of deploying energy-harvesting pavements in urban environments, a framework was developed based on the following sequential steps:

Step 1: Site Selection and Load Analysis

Analyze pedestrian or vehicular traffic load using sensors or existing transport data. Measure surface and subsurface temperatures for thermoelectric feasibility. Evaluate solar irradiance levels if considering photovoltaic systems.

Step 2: Technology Selection

Choose a suitable energy-harvesting technology based on environmental conditions and infrastructure purpose. Consider hybrid combinations in multi-functional zones (e.g., parking lots, smart walkways).

Step 3: Material and Design Specification

Select appropriate materials (e.g., PVDF for piezoelectric, Bi_2Te_3 for thermoelectric, or tempered glass for photovoltaic). Design the pavement structure to integrate energy modules without compromising mechanical strength.

Step 4: Simulation and Modeling

Use finite element modeling (FEM) and thermal simulation tools to predict stress distribution, temperature behavior, and energy output. Optimize module placement and depth to maximize efficiency.

Step 5: Prototype Testing

Build small-scale prototypes in controlled settings to validate simulation data. Conduct load, weather, and fatigue tests to assess performance.

Step 6: Field Implementation and Monitoring

Deploy pilot systems in selected urban or semi-urban areas. Equip systems with IoT sensors to monitor voltage output, structural health, and system behavior [4].

Step 7: Performance Assessment and Feedback Loop

Compare measured data with predicted outcomes. Use findings to refine material selection, design parameters, and energy harvesting strategy [5].

3.6. Material Composition and Functionality

The performance of each system depends significantly on the compatibility between the material and the environmental conditions of the deployment site. For example, PVDF-based piezoelectric materials are flexible and durable, making them ideal for high-footfall areas such as subway stations or stadiums.

Table 2: Common Materials Used in Energy-Harvesting Pavements

Technology Type	Material Composition	Function
Piezoelectric	PVDF, PZT (Lead Zirconate Titanate), ZnO	Converts mechanical stress into electricity
Thermoelectric	Bi_2Te_3 , PbTe, SiGe	Converts thermal gradient into electric voltage

Photovoltaic	Crystalline Silicon, Amorphous Silicon	Converts sunlight into electrical energy
Hybrid	Composite Layers of Above Materials	Simultaneous energy generation from multiple sources

3.7. Integration with Smart Infrastructure

The methodology also included an analysis of how energy-harvesting pavements can be effectively integrated with existing smart infrastructure systems. By embedding wireless communication modules and various types of sensors, these pavements can facilitate real-time data transmission to support a range of urban applications. These include pedestrian flow monitoring, structural health diagnostics, street lighting automation, and smart parking management [6]. Such integration not only enhances the operational efficiency of urban environments but also justifies the relatively high initial investment in energy-harvesting technologies by enabling multifunctional services and long-term cost savings.

3.8. Limitations of Current Methodologies

Despite extensive research and pilot implementations, current methodologies face limitations:

- **Scalability:** Most studies are limited to laboratory or small-scale field deployments.
- **Standardization:** Lack of standardized testing procedures complicates performance comparison.
- **Cost Analysis:** Long-term economic evaluations are scarce or incomplete.
- **Environmental Resistance:** Modules often degrade under water ingress, UV radiation, and freeze-thaw cycles.

Addressing these limitations will require interdisciplinary collaboration and support from public agencies, private investors, and regulatory bodies.

4. Conclusion

The integration of energy-harvesting materials into pavement infrastructure represents a transformative advancement in sustainable urban development. As cities grapple with rising energy demands, climate change, and deteriorating infrastructure, these multifunctional surfaces offer a promising solution that combines structural utility with renewable energy generation. This review has shown that three primary technologies piezoelectric, thermoelectric, and photovoltaic form the foundation of energy-harvesting pavements. Each has distinct mechanisms, advantages, and limitations, making them suitable for different environmental conditions and application contexts. Piezoelectric systems are ideal for high-traffic urban zones, thermoelectric systems for temperature-variant environments, and photovoltaic pavements for sun-exposed areas. Hybrid systems and multifunctional designs demonstrate considerable potential to overcome the individual limitations of these technologies by combining their strengths. Although the theoretical and laboratory studies reveal significant potential, real-world implementation still faces multiple challenges. High installation and maintenance costs, limited energy conversion efficiency, and insufficient long-term durability under dynamic environmental conditions hinder large-scale deployment. Moreover, standardized testing methods and long-term economic assessments are lacking, making it difficult for urban planners and policymakers to justify investment without concrete,

scalable outcomes. Nevertheless, recent advances in material science, especially in developing nanocomposites and flexible polymers, are enhancing the performance and adaptability of energy-harvesting materials. Additionally, the integration of these technologies into smart infrastructure frameworks amplifies their utility beyond mere power generation. From smart lighting and real-time traffic monitoring to structural health diagnostics, these pavements can support various urban functions while reducing dependence on conventional energy sources. Future research should prioritize the development of durable, cost-effective materials and the creation of simulation tools for performance prediction under varied conditions. Collaborative efforts involving engineers, materials scientists, urban planners, and policymakers will be essential to transition from experimental prototypes to full-scale urban applications. With sustained innovation and strategic investment, energy-harvesting pavements can become an integral component of sustainable and intelligent infrastructure networks worldwide.

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