Harvesting Invisible Energy in Smart Cities and Net-Zero Urban Development:

Piezoelectric Energy for IoT-Enabled Urban Infrastructure

Executive Summary:

Smart cities and net-zero buildings are redefining how energy is generated, managed, and consumed within the built environment. As urban areas increasingly integrate digital technologies and Internet of Things (IoT) systems, the demand for decentralized, low-carbon energy solutions continues to grow, as highlighted by the International Energy Agency's Buildings Global Status Report. While mainstream renewables such as solar photovoltaics and wind energy remain central to decarbonization strategies, energy harvesting technologies offer complementary opportunities to capture ambient energy embedded within everyday urban activity.

Piezoelectric energy harvesting converts mechanical stress from footfall, vehicular movement, and structural vibration into electrical energy. Although not intended for large-scale power generation, piezoelectric systems can play a strategic role in sustainable urban infrastructure by supporting self-powered sensors, reducing battery dependence, and improving the resilience of IoT-enabled systems. This article explores the applicability of piezoelectric energy harvesting in buildings, campuses, and mobility infrastructure, drawing on global case studies to evaluate performance, sustainability implications, and practical limitations.

Smart Cities, Net-Zero Buildings, and the Role of Decentralized Energy

Smart cities are increasingly defined by their ability to integrate sustainable urban infrastructure with digital intelligence. Buildings and transport systems account for a significant share of global energy consumption, positioning net-zero buildings as a cornerstone of climate action strategies, according to analysis by the International Energy Agency. At the same time, IoT deployment in the built environment is accelerating, with sensors, monitoring systems, and connected assets becoming standard features of modern developments.

This convergence of sustainability and digitalization has intensified the need for decentralized energy solutions capable of powering low-energy devices reliably and with minimal maintenance. Conventional centralized power systems and battery-dependent sensors can introduce operational and environmental burdens at scale. Piezoelectric energy harvesting offers a complementary approach by converting mechanical energy already present in urban environments into usable electrical power, enabling localized and resilient smart infrastructure.

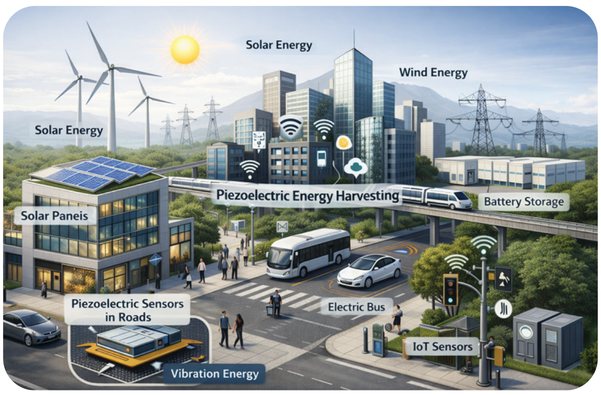
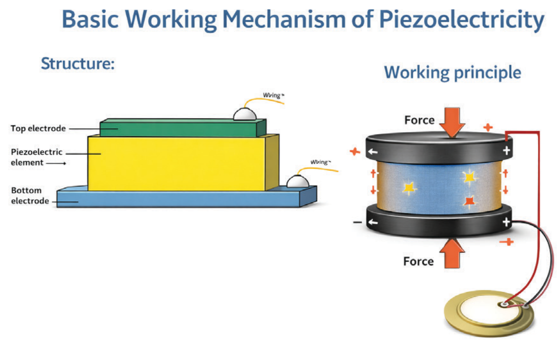


Figure 1: Smart city energy ecosystem showing decentralized renewables, IoT sensors, and data flows

Piezoelectric Energy Harvesting Technology in the Built Environment

Piezoelectric materials generate an electrical charge when subjected to mechanical stress such as compression, bending, or vibration, a phenomenon extensively described in the smart materials literature by Anton and Sodano. This principle has long been applied in sensors and actuators, while energy harvesting applications focus on capturing small amounts of power from repetitive mechanical events.

Within buildings and infrastructure, these events include pedestrian movement, vehicular loads, and vibrations from mechanical systems. The generated electricity is typically conditioned, stored in capacitors or small batteries, and used to power low-energy devices such as wireless sensors and communication nodes. Research summarized by Stanford University indicates that piezoelectric harvesting is best suited to environments where vibration or loading is frequent, predictable, and aligned with low-power demand.



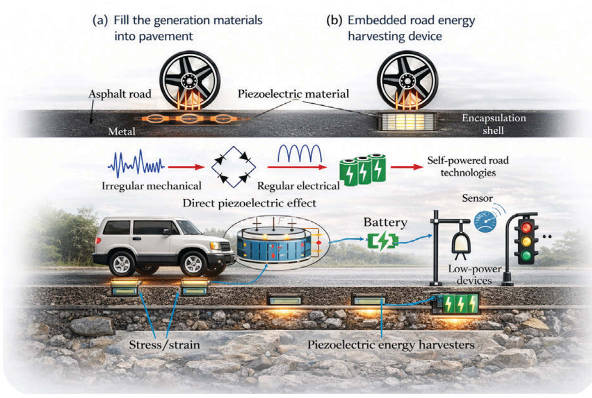
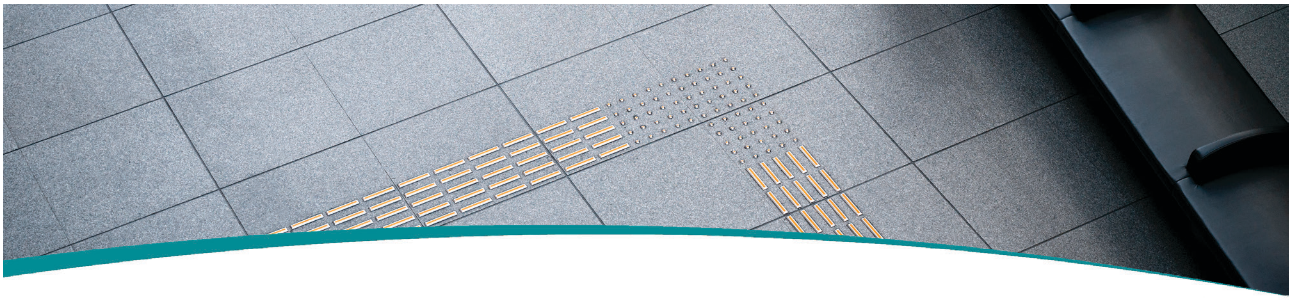


Figure 2. Schematic of piezoelectric energy conversion from mechanical stress to electrical output



Materials and System Design for Sustainable Urban Infrastructure

Material selection plays a critical role in determining the efficiency and sustainability of piezoelectric systems. Lead zirconate titanate (PZT) ceramics provide high energy conversion efficiency but raise concerns regarding toxicity and end-of-life management, as discussed in Priya and Inman's work on energy harvesting technologies. Polymer-based materials such as polyvinylidene fluoride (PVDF) enable flexible integration into floors and building elements but offer lower energy density.

Emerging lead-free ceramics seek to balance performance with environmental responsibility, aligning more closely with ESG objectives. Beyond materials, system design must address durability under repetitive loading, electrical conditioning, integration with energy storage, and seamless connectivity with IoT platforms. Long-term reliability is particularly critical for installations embedded in floors, pavements, or road infrastructure.

Smart Buildings and Campuses: Practical Applications

Smart buildings and campuses represent the most viable environments for piezoelectric energy harvesting due to predictable footfall patterns and controlled operating conditions. High-traffic areas such as entrances, corridors, transit interfaces, and university campuses can generate sufficient mechanical energy to support localized applications.

Typical use cases include self-powered occupancy sensors, environmental monitoring devices, wayfinding systems, interactive displays, and data collection nodes. In net-zero developments, piezoelectric systems complement broader energy strategies by enhancing operational efficiency and reducing reliance on batteries and wired connections rather than contributing meaningfully to bulk energy supply.

Figure 3. Applications of piezoelectric harvesting across smart buildings and campuses.

Smart Mobility Infrastructure and Energy Harvesting

Urban mobility infrastructure—such as roads, parking facilities, and logistics hubs—has also been explored for piezoelectric energy harvesting. Vehicular load applications involve higher mechanical forces than pedestrian systems, offering theoretical potential for greater energy capture.

Pilot projects reported by the California Energy Commission demonstrate that embedding piezoelectric generators beneath road surfaces demonstrate technical feasibility for powering localized infrastructure such as traffic sensors and low-power lighting. However, installation complexity, durability challenges under heavy vehicles, and limited energy yield have constrained large-scale deployment. As a result, mobility-based applications are best suited to targeted or demonstrative roles within smart city programs.

Global Case Studies in Sustainable Urban Infrastructure

Real-world deployments provide valuable insight into the performance, scalability, and limitations of piezoelectric energy harvesting. While most projects remain at pilot or demonstrator scale, they offer important lessons for smart cities and net-zero developments.

United Kingdom – Pavegen (Public Realm, Transport Hubs, and Campuses)

In the United Kingdom, piezoelectric energy harvesting has been most visibly deployed through Pavegen's kinetic flooring systems installed in airports, retail environments, transport hubs, and educational campuses. According to Pavegen Technology and Case Studies, these systems are typically located in high-footfall areas where pedestrian movement provides a consistent mechanical energy source.

The harvested energy is used to power LED lighting, digital displays, and interactive installations, often combined with analytics platforms that visualize pedestrian movement. While absolute energy output is modest, these projects demonstrate strong feasibility for localized, low-power applications and deliver significant value in public engagement and sustainability visibility.

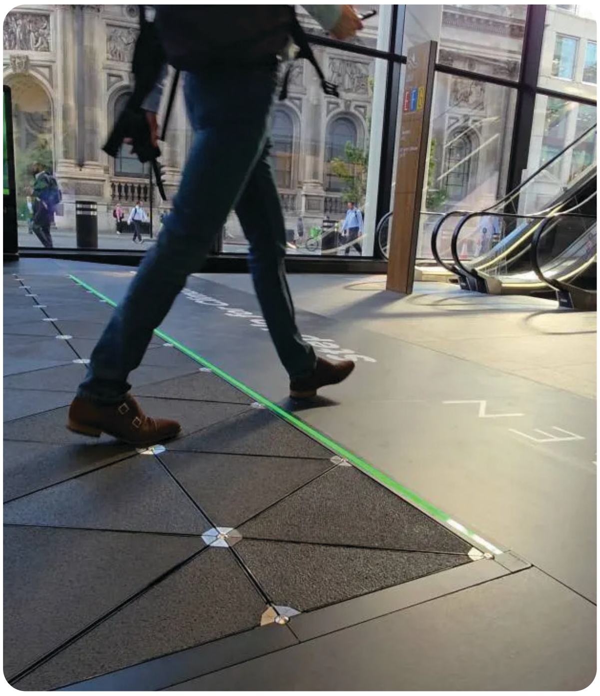


Figure 4. Pavegen kinetic flooring in a public transport environment

Japan – Tokyo Railway Stations (Shibuya Station)

Japan has explored piezoelectric energy harvesting within one of the world's busiest urban transport environments. A widely reported demonstration at Shibuya Station in Tokyo involved piezoelectric tiles installed to capture energy from commuter footfall, as documented by Parametric Architecture, Technrok, and OHEPIC.

The system converts mechanical pressure from footsteps into electrical energy, which was stored and used to power localized applications such as LED displays and experimental lighting. Reports indicate that individual footsteps generate very small amounts of electricity, but the exceptionally high pedestrian volumes at Shibuya enable meaningful cumulative output for low-power uses.

Publicly available long-term performance data and detailed economic metrics remain limited. The project is nevertheless instructive, illustrating both the potential and the constraints of footfall-based energy harvesting in dense urban environments, and reinforcing the importance of realistic expectations regarding energy contribution.

Figure 5. Conceptual illustration of piezoelectric tiles at Shibuya Station

United States – California Highway Pilot Projects

In the United States, pilot projects—particularly in California—have investigated piezoelectric generators embedded beneath road surfaces to harvest energy from vehicular loads. Findings published through state energy research programs show that electricity can be generated from traffic-induced stress but also reveal significant durability and cost challenges.

Energy yields have generally been insufficient to justify widespread deployment, especially under heavy truck traffic. These findings reinforce the view that road-based piezoelectric systems are better suited to powering localized sensors or monitoring equipment rather than contributing meaningfully to grid-scale energy supply.

Figure 6. Road-embedded piezoelectric energy harvesting concept.

Israel – Highway Infrastructure (Innowattech)

Israel-based company Innowattech has conducted some of the most extensively documented trials of piezoelectric energy harvesting in highway environments. Innowattech reports describe systems embed piezoelectric sensors within roadways to capture energy from passing vehicles, directing output toward street lighting, traffic monitoring sensors, and communication systems.

These projects demonstrate a multi-functional approach, combining energy harvesting with sensing and data collection. While scalability has been demonstrated conceptually, long-term deployment depends on sustained investment, supportive policy frameworks, and continued performance monitoring.

Figure 7. Innowattech piezoelectric highway system schematic.

Europe – Hybrid Smart Road Initiatives (Italy, Netherlands, Germany)

Several European pilot projects, particularly in Italy and the Netherlands, have explored hybrid smart road concepts that combine piezoelectric elements with solar photovoltaics, as documented through research and project reporting published by the European Commission's CORDIS platform. In these systems, piezoelectric components typically support auxiliary functions such as sensors or signage, while solar panels provide the primary energy input.

This hybrid approach improves overall system viability and underscores a key lesson for sustainable urban infrastructure: piezoelectric energy harvesting is most effective when integrated within broader, multi-technology energy strategies.

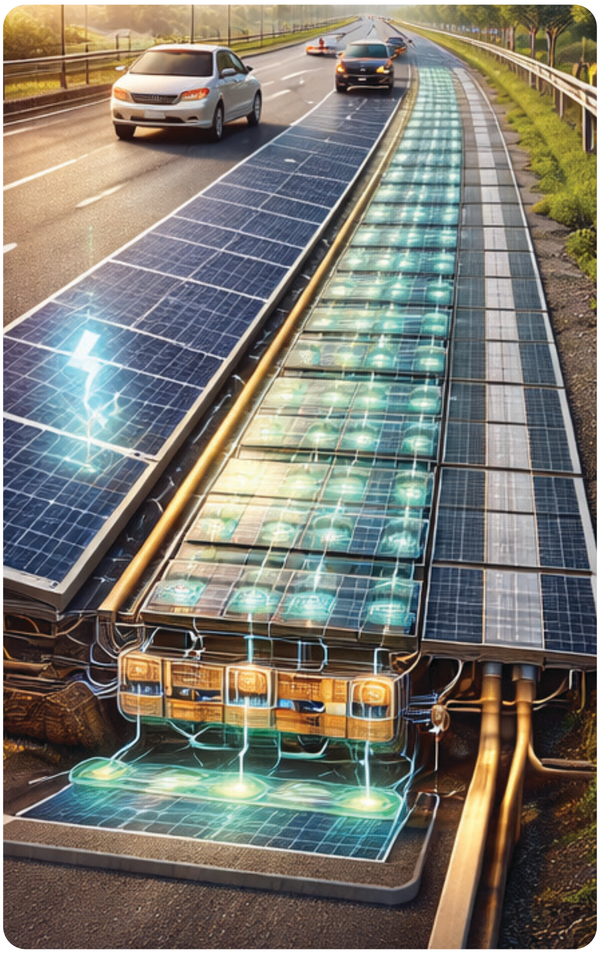


Figure 8. Hybrid smart road integrating solar PV and piezoelectric elements.

Summary Insights from Case Studies

Across regions and applications, several consistent insights emerge:

- Piezoelectric energy harvesting is technically viable but energy-limited.
- The strongest use cases are localized, low-power applications.
- Value extends beyond energy generation to include data, visibility, and public engagement.
- Large-scale deployment depends on durability, cost reduction, and hybrid integration.

These findings position piezoelectricity as a complementary technology within smart cities and net-zero developments rather than a standalone energy solution.

LOCATION	APPLICATION	OUTPUT / USE	REMARKS
London (Pavegen)	Floor tiles in airports/ stores	Power for LEDs & digital displays	Feasible at small scale
Tokyo, Japan	Shibuya Station flooring	Captured commuter footfall	Large-scale pilot, modest yields
California, USA	Highway test by Energy Commission	Vehicular load	Durability challenges under trucks
Israel (Innowattech)	Highways	Streetlights, sensors	Scalable concept, needs investment
Europe	Smart roads	Lighting, signage	Integrated with solar for hybrid effect

Net-Zero Buildings, ESG, and Smart City Sustainability

From an ESG perspective, piezoelectric energy harvesting contributes primarily by supporting decentralized digital infrastructure rather than bulk energy generation. Its strengths lie in resilience, innovation signaling, and alignment with smart city narratives centered on climate action and technological leadership.

Lifecycle considerations—including embodied carbon, material toxicity, durability, and end-of-life management—are essential to ensure genuine sustainability outcomes and avoid overstating environmental benefits.

Limitations and Realistic Expectations

Despite growing interest, piezoelectric energy harvesting faces clear limitations. Energy output remains low, economic returns are uncertain, and standardized design guidance is limited. Transparent communication of these constraints is essential to maintaining credibility in net-zero and smart city strategies.

Future Directions and Research Needs

Future research and innovation can strengthen the role of piezoelectricity in sustainable infrastructure through:

- Development of lead-free, durable materials.
- Hybrid systems integrating piezoelectric, solar, and thermal technologies.
- Deeper integration with IoT platforms for self-powered sensing.
- Comprehensive life-cycle assessments (LCA).
- Policy frameworks supporting pilot-to-market transition.

By aligning piezoelectric innovation with global sustainability goals, the built environment can diversify its renewable energy portfolio and unlock new pathways for decarbonization.

Conclusion: Complementary Technology for Smart, Net-Zero Cities

Piezoelectricity represents a promising frontier for sustainable construction and infrastructure. While unlikely to replace mainstream renewables, its niche applications in high-footfall and high-traffic environments offer tangible opportunities for localized energy harvesting. When deployed strategically and transparently, piezoelectric systems can support self-powered IoT infrastructure and enhance the resilience of smart, net-zero developments.

How AESG can help

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Dheeraj is a Senior Sustainability Consultant at AESG, with over 13 years of experience as a Building Science Engineer, specializing in sustainable design and climate action. He is a USGBC faculty, LEED SME and holds key sustainability credentials, including LEED AP, WELL AP, Envision SP, Parksmart Advisor, Activescore+Modescore AP, ISO 14064 GHG Lead Verifier/Validator and ISO 14001 Lead Auditor.
His expertise spans sustainable engineering, energy conservation, and integrated building design.

He leverages a cross-functional background and a holistic approach to develop effective sustainability strategies for the built environment and guides clients in achieving their Sustainability goals and certifications.

For further information relating to specialist consultancy engineering services, feel free to contact us directly via info@aesg.com

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