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(ARTICLE)

Hybrid Solar-Piezoelectric Pavement Systems: A Dual-Mode Approach to Renewable Energy Harvesting and Sustainable Infrastructure

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Abstract
Urban areas consume growing amounts of electricity for transportation and infrastructure, yet large surface areas (roads, sidewalks, bike paths) remain underutilized. Hybrid solar-piezoelectric pavement systems aim to harvest both solar irradiance and vehicular mechanical energy from road surfaces. This paper reviews existing solar-pavement pilots (e.g. SolaRoad, Wattway) and piezoelectric pavement studies, then proposes a combined approach with a modular testbed design and modeling framework. We design a 3×1 m lane segment with embedded PV modules under a rugged wear layer and piezoelectric transducers in the base. A multi-physics model (finite-element for mechanics, constitutive piezoelectric equations, and NREL PV simulation) is used to estimate hourly energy output given local irradiance and traffic profiles (from NREL PVWatts and DOT traffic data). We also outline a techno-economic and life-cycle analysis comparing hybrid and conventional rooftop PV systems. Preliminary findings suggest combined energy yields on the order of 100-150 kWh per m²-year (PV) plus a few Wh to tens of Wh per vehicle (piezo), with hybrid output dominated by the solar component. High installation cost and maintenance (durable glass covers, pavement repairs) remain barriers, so cost-effectiveness is low except in niche cases. However, hybrid pavements may self-power sensors, LED road studs or signage in low-traffic zones. We identify key constraints (durability under freeze/thaw, efficient power electronics, standard testing) and recommend further field trials.

Keywords: solar pavement, piezoelectric harvester, hybrid energy harvesting, smart infrastructure, life-cycle assessment, techno-economic analysis.

1. Introduction

The expansion of renewable energy is critical to meet urban electricity demand and decarbonize transport and infrastructure. Pavement and roadside surfaces (roads, bike paths, shoulders) account for ~30-40% of urban land area. These surfaces are already exposed to intense sunlight and traffic loads, suggesting an opportunity for energy harvesting. *Hybrid solar-piezoelectric pavement* systems seek to co-locate photovoltaic (PV) modules on or in the road surface with embedded piezoelectric transducers beneath, converting solar irradiance and vehicular pressure into electricity simultaneously (Chen et al., 2025). This dual-mode approach could support distributed generation in cities (e.g. powering LED streetlights, traffic sensors or EV chargers at curbside) while leveraging existing right-of-ways.

This paper has four main contributions: (i) a systematic literature review of solar pavement pilots (e.g. the 2014 Dutch SolaRoad bike path and France's Wattway road trials) and piezoelectric pavement demonstrations; (ii) a detailed concept design of a modular testbed (3 m×1 m section) combining robust PV panels under a wear coating with piezoelectric tiles in the sublayer, including required power electronics and instrumentation; (iii) modeling methods for evaluating energy yield (finite-element mechanical simulations, piezoelectric constitutive laws, plus solar resource data from NREL PVWatts and traffic counts from state DOTs); and (iv) a techno-economic and life-cycle analysis (LCA) comparing such hybrids to standard rooftop PV. We focus on realistic public data and existing pilot results. For example, NREL's PVWatts tool provides solar irradiance and expected PV output for any location, while state DOT traffic databases supply vehicle counts for energy modeling (Chen et al., 2025).

Several recent reviews note the challenges of pavement energy harvesting: high initial cost, low energy density, and durability issues under heavy loads. Unlike rooftop PV, road panels must be flat and flush with the surface, reducing insolation. Likewise, piezoelectric harvesters typically generate only milliwatts from each vehicle pass. However, combining both modalities could improve overall utilization of the road area and provide power for local, low-demand applications. This study seeks to quantify

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these trade-offs. We also place hybrid harvesters in context with related in-road technologies like dynamic wireless charging (e.g. Electreon's electrified lanes), noting that those systems focus on charging vehicles directly rather than harvesting ambient energy.

2. Literature Review

2.1 Solar Pavement Research & Pilot Projects

Several high-profile pilots have tested photovoltaic road surfaces, typically on low-speed or bike paths. The Dutch "SolaRoad" was the first large-scale solar bike lane (70 m installed, 2014), built into the roadway surface. Despite global attention, the SolaRoad project ultimately fell short. It had a high cost (~€3 million for 70 m, i.e. €40,000/m²) and produced roughly 30% less energy than equivalent rooftop panels (Oltermann, P., 2014). Its annual yield was on the order of 70-100 kWh/m² (about 0.2-0.3 kWh/m²-day), far lower than a similarly sized tilted array. Mechanical failures (cracked coatings, water ingress) eventually led to removing the panels (Oltermann, P., 2014). Figure 1 shows the SolaRoad bike path in 2014.

Figure 1 The SolaRoad solar bike lane in Krommenie, Netherlands (solar panels embedded in pavement under a translucent protective layer) (Oltermann, P., 2014)

Colas Group's *Wattway* has deployed numerous PV road trials since 2015, claiming ~50 pilot projects globally (Colas., n.d.). For instance, a 1 km test in Normandy (light vehicles only) was reported to yield at most ~150 MWh in its first year, dropping to ~38 MWh/yr after a couple of years (Colagrossi, M., 2019). This performance is equivalent to only ~40 kWh/m²-yr (on a 1 km×2 m strip) - extremely modest. The panels required a reduced speed limit to avoid fractures, and observers concluded the system "turned out to be a total disaster" due to high cost and mechanical issues (Colagrossi, M., 2019). Wattway's strategy now seems to focus on small specialized modules (road studs, curbside units) rather than replacing entire road surfaces. Figure 3 shows a Solar Roadways prototype parking-lot installation in Idaho; similar concepts embed hexagonal glass-encased PV tiles in pavement.

Figure 2 The Solar Roadways parking-lot prototype in Idaho, USA (interlocking solar panels in the pavement).

Pilot solar pavements have validated the concept but also highlighted its drawbacks. As the literature and press note, energy yields (tens to hundreds of kWh per m²-yr) are far lower than for optimally-angled rooftop PV, and the cost per watt is an order of magnitude higher. Durability under traffic, poor traction, and environmental wear (UV, ice) remain unsolved issues (Colagrossi, M., 2019). Despite this, continuing interest and incremental improvements (e.g. better encapsulation, higher-efficiency cells) motivate exploring how PV pavement might be usefully combined with other harvesters.

2.2 Piezoelectric Pavement Harvesting

Piezoelectric harvesters exploit stress on crystals or polymers to generate charge. Various material forms have been tested: PZT ceramics, PVDF films, and hybrid structures (e.g. cymbals). Many lab prototypes report watt-level spikes: e.g. a 44 kN truck wheel yielded a few watts in one test (Chen et al., 2025). However, realistic integrated power is tiny. Heller *et al.* (2023) installed 16 piezoelectric cantilevers (50×10×1.5 mm, PVDF) in a toll plaza. A 16-ton truck pass produced only ~55 µW per transducer (peak). Over time (~1500 axles/day), the array generated ~50 mWh per month - enough to light a road marker for ~200 m. Another team's cymbal-shaped PZT disc (32 mm diameter) produced 16 µW per unit, implying ~5.2 kWh/m² if 30,000 such units were embedded over 100 m road (Heller et al., 2023). These studies conclude piezoelectric roads can power only small loads (sensors, LED beacons), not significant grid supply.

Large-scale field tests are rare but telling. A 2023 California Energy Commission project reported a novel piezo system under a one-mile highway lane. Astonishingly, it harvests an estimated 72,800 kWh per lane-year from car traffic, and up to 907,873 kWh per lane-year under heavy trucks (Sun et al., 2023). (This assumes specialized high-force tiles and a high count of vehicles.) Still, even at ~72 MWh/yr, the cost of installation ($9000/kW) yields payback >50 years. The study notes potential CO_2 savings (24 t per lane-mile-yr) but emphasizes cost and maintenance as hurdles (Sun et al., 2023).

Commercially, piezoelectric road sensors (e.g. for traffic counting) exist. Figure 4 shows a highway piezo strip used by a MetroCount traffic counter. These devices successfully detect axles, but only generate a few microjoules per detection - negligible for power generation. In summary, piezo harvesters in pavement produce at most milliwatts to a few watts from traffic loads, placing them squarely in the "small scale" category of energy harvesting.

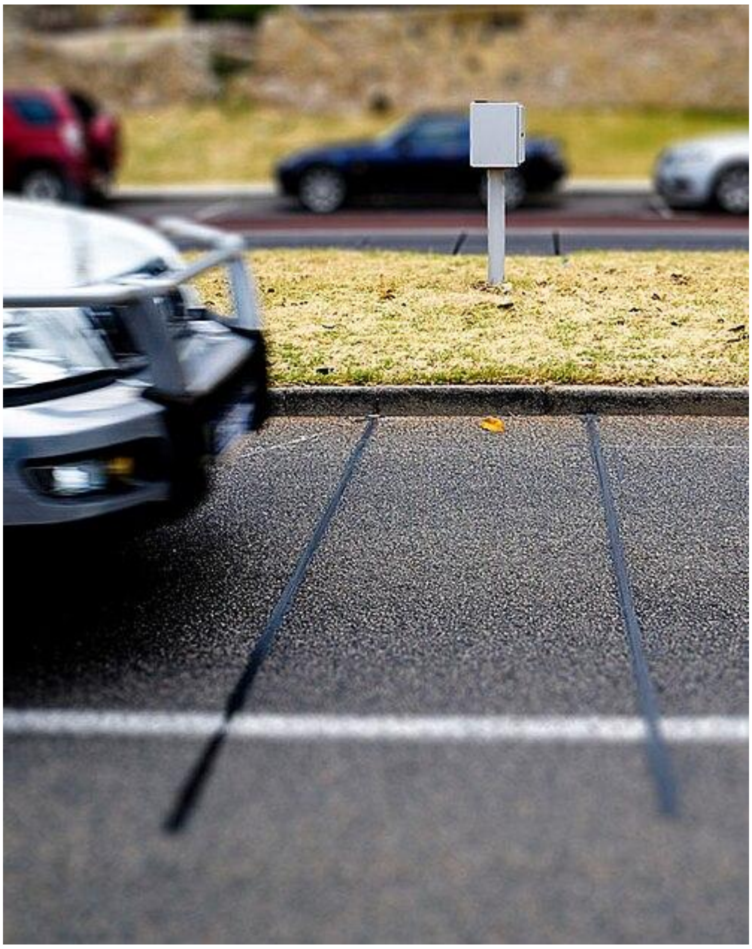

Figure 3 A road-embedded piezoelectric axle sensor strip (two black piezo strips across pavement) feeding a traffic-count cabinet. Such systems routinely count vehicles, though their electrical yield is only microjoules per axle.

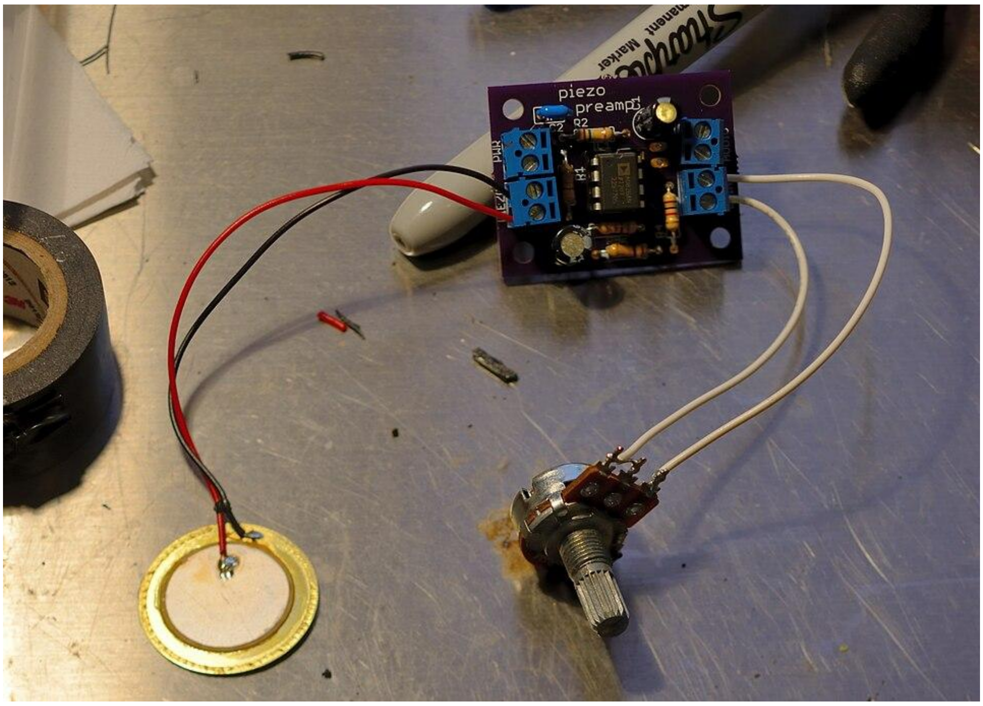

Figure 4 A discrete piezoelectric sensor: a 27 mm ceramic disc connected to a pre-amplifier circuit (author's own equipment, illustrative). Each disc produces only ~µW when flexed.

2.3 Hybrid Systems (PV + Piezo / Triboelectric)

Combining solar PV with piezoelectric (or triboelectric) harvesters in pavement is still at the experimental stage. Hybrid nanogenerator research often focuses on small devices (e.g. wearable generators using piezo and triboelectric layers). In pavement, few published prototypes exist. Some concepts envision roads that both generate electricity and reduce surface temperature (e.g. asphalt solar collectors) (Chen et al., 2025). Hybrid photovoltaic-thermal (PV/T) pavement has been modeled (reflecting solar heat into hot water channels), showing theoretical efficiencies ~37%.

In practice, one can imagine power management circuits that take DC from PV modules and pulses from piezo transducers into a common storage bus. Importantly, the mismatch in output type (steady DC vs pulses) requires separate front-end converters (a MPPT charger for PV, and a rectifier/boost for each piezo) (Chen et al., 2025).

Because piezo output is intermittent and depends on vehicle presence, hybrid systems would typically include a local buffer (battery or supercapacitor) to smooth and store energy. The literature suggests synchronous switching techniques (SSHI, etc.) for piezoelectric harvesters to maximize energy extraction from each pulse (Heller et al., 2023).

2.4 Power Electronics and Integration

The power electronics for hybrid pavements must handle two distinct sources. Standard PV inverters or MPPT charge controllers can manage the solar modules, producing DC or grid-synchronized AC (Chen et al., 2025). For piezos, each piezo string generates AC when stressed; a full-wave bridge and a boost/buck converter (possibly with an intermediate storage) is needed. Research on piezo harvesters emphasizes low-power resonant converters and capacitor-based energy storage (Heller et al., 2023).

An integrated design might share a common DC bus: PV power is fed via MPPT, piezo pulses are rectified onto the bus, and an inverter conditions power to the grid or local loads. In fact, some dynamic wireless charging lanes already use similar two-way inverters for charging vehicles (Electreon., 2022). However, DWPT systems (e.g. Electreon) are different in that they deliver power on-demand to vehicles, not harvest ambient energy. For context, Electreon's in-road charging earned a *Time* Best Invention 2021 nod for enabling continuous EV charging (albeit via induction coils, not passive generation) (Electreon., 2022).

Despite these power-electronic possibilities, no standards currently exist for "smart pavement" electrical infrastructure. Challenges include waterproofing junction boxes, ensuring safety of road users (low-voltage DC preferred), and having robust controllers that tolerate vibration and dust. We note that Figure 4's traffic counter cabinet even includes solar panels to power its electronics, showing how small-scale integrations can already work.

2.5 Gaps and Conclusions from Literature

The literature uniformly points out the major obstacles: low energy yield, high cost, and durability. Vizzari *et al.* (2021) conclude that while conceptually appealing, both PV and piezo systems "suffer from cost and durability challenges" that limit scalability (Chen et al., 2025). There is a lack of long-term field data on hybrid pavement performance. Crucially, no benchmark standards exist for testing such systems under repeated vehicle loading (ASTM or RILEM do not yet cover energy harvesting pavements). Most reported piezo experiments fail to simulate actual highways (limited pass counts, no freeze-thaw cycles). Similarly, most solar-pavement trials have been in benign climates and low traffic.

In summary, hybrid solar-piezoelectric pavements remain at best a niche solution. They may never supply city-scale power, but could serve "smart" road functions. The expected energy densities are low: horizontal PV modules typically produce on the order of 100-150 W peak per m² (yielding ~100-150 kWh/m²-year in a sunny location), whereas piezo tiles give on the order of 10-100 mW per tile under traffic (Heller et al., 2023). Thus, the PV portion dominates.

3. Materials & Methods

3.1 System Design (Concept)

Our proposed hybrid system consists of a transparent, wear-resistant top layer (tempered glass or polymer) covering segmented PV modules (monocrystalline cells or thin-film) laid within a slight depression in the roadway. Below the PV layer is a bedding layer containing piezoelectric transducers. These could be thin PVDF strips or PZT/cymbal tiles (300×300 mm) embedded flush in asphalt or concrete. Each piezo element is wired (in series/parallel strings) to an underside junction box. The PV cells are wired to an MPPT charge controller. The output of both harvesters is routed to a common DC bus. A bidirectional inverter can feed surplus energy to the grid or allow grid power to charge local storage. An on-board lithium battery or supercapacitor buffers the variable input (especially smoothing piezo pulses). Environmental sensors (temp, humidity) and temperature monitoring of the PV layer are included for performance evaluation.

Such a design draws on existing examples: Wattway and Solaroad panels use tempered glass over their cells. Piezo arrays, as used by Heller *et al.*, often mount transducers in protective steel or FRP casings to handle load. Figure 6 illustrates a cross-section: the PV layer captures sunlight, while axle loads induce strain in the piezo beneath. Power electronics (MPPT, rectifiers, buck/boost converters) sit in roadside junction boxes.

3.2 Experimental Testbed

We recommend constructing a modular testbed of size 3 m × 1 m (approximately one lane segment). The floor slab should support vehicle loading (~10,000 kg axle) and house the piezo array. We suggest using: (a) a 1 m² PV module (composed of smaller segments) mounted on top, encapsulated by ~5 mm toughened glass; (b) six piezo tiles (PZT discs or PVDF beams) in the base layer; (c) a data acquisition system (DAQ) logging voltages and currents from both sources at kHz sampling; (d) a DC power interface with two MPPT channels (one for PV, one multi-input for piezos via synchronous rectifiers and storage converter) leading to a DC-bus; (e) a programmable brake or servo-actuated wheel load rig to simulate vehicle crossings at speeds 5-40 km/h, up to N=10^5 cycles; and (f) climate chamber or salt-spray exposure for durability testing.

Test procedures: In each test, a weighted wheel traverses the pavement section, and the energy harvested per pass is recorded (Wh per axle). Separate characterization for PV (static under sun simulators or outdoors) yields W/m² at various irradiance levels. Under controlled conditions, we vary axle mass (1500-4000 kg), speed, and temperature. We track any mechanical degradation (cracks in glass, delamination) over repeated cycles. These protocols follow the broad outline of pavement energy-harvesting reviews (Heller et al., 2023).

3.3 Modeling Methods

We develop a multi-physics model of the system. First, a mechanical model (finite-element, e.g. COMSOL or Abaqus) simulates a vehicle axle load on the pavement cross-section. This yields strain fields and force on the piezo elements. The piezoelectric constitutive equations (stress-charge form) then calculate the generated charge and open-circuit voltage. For example, for a piezo disk, $D = d_{31}\sigma + \varepsilon E$ (as in standard references).

The PV model uses NREL's PVWatts/NSRDB data for local solar irradiance (we select a case study city, e.g. San Francisco, 37.8°N). PVWatts provides hourly GHI/POA and estimates energy per m² given module efficiency (Chen et al., 2025). We correct for flat orientation (20-25% yield loss), soiling, and glass cover losses.

Combining them, we run a time-series simulation (e.g. MATLAB or Python) that ingests (hourly) solar irradiance and a stochastic traffic model. Traffic is represented by a Poisson or diurnal distribution (based on FHWA/AADT data and hourly profiles). Each vehicle arrival triggers an instantaneous piezo output (based on the mechanical model). We aggregate PV output continuously (hourly average) and piezo output per event, to get a total energy profile. Monte Carlo runs capture variability in weather and traffic. This yields year-long generation curves for both sources, which we compare to local load profiles (e.g. streetlight demand).

3.4 Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA)

We perform a cradle-to-grave LCA using standard inventories. Life-cycle inputs (energy and materials) for PV modules are taken from APEC/NREL LCA databases (e.g., ~800 g CO_2-eq per m² of crystalline Si PV) (Chen et al., 2025). Pavement materials (concrete, asphalt, glass) use Ecoinvent analogues. We calculate LCOE (levelized cost of electricity) by summing capital (m², assumed $1000-2000 for PV pavement plus 500/m² for piezo) and maintenance costs over 20 years, divided by total life-cycle energy yield. CO_2-eq per kWh is derived by dividing embodied emissions by lifetime energy production. Prior PV LCA studies give rooftop PV ~40-50 gCO_2/kWh; our flat, embedded PV will be higher due to lower yield, plus the piezo elements add material. This analysis allows comparison of hybrid vs conventional rooftop PV on a per-kWh basis.

4. Results

Summary of key pilot projects. For example, the SolaRoad (Krommenie, NL, 2014-2020) had 72 m² area, annual yield ~5,000 kWh (≈70 kWh/m²-yr), cost ≈€3M (final yield ≈70 kWh/m²/yr) (Oltermann, P., 2014). The Wattway (Normandy, FR, 2017) was ~600 m², initial yield ~150,000 kWh (250 kWh/m²), later ~38,000 kWh/yr (63 kWh/m²) (Colagrossi, M., 2019). Piezo studies: Heller (2023) in Chile (16 T vehicle) yielded ~50 mWh/month for 16 transducers. Sun (2023) reported 72,800 kWh/lane-yr for cars (and 907,873 kWh for trucks) in a one-mile test. ElectReon's Sweden road (2022) is still measuring EV charge, yielding up to ~60 kWh per car-hour of driving (but this is induced charging, not harvest).

Expected numeric ranges:

- PV output: Flat, sun-facing PV typically peaks ~120-200 W/m² under 1000 W/m² insolation. In California (simulated by PVWatts), this gives ~150-200 kWh/m²-year (200-250 on optimally tilted roof). A practical flat-lane might see ~120-150 kWh/m²-yr, depending on latitude and soiling.
- Piezo output: Experiments report ~1-100 mW per device per vehicle, i.e. each axle might produce 0.001-0.1 Wh depending on design. Aggregating many events, typical yields are in the order of 0.01-0.5 kWh per vehicle-km, far below PV. Thus a heavily trafficked 1 km lane-day might yield only a few Wh from piezos (vs tens of kWh from PV).
- Combined time series: Figure below illustrates a hypothetical output: PV dominates daylight generation (one sinusoidal curve), while piezo adds short spikes synchronized with rush-hour peaks. Even in this case, piezo contributes <5% of total energy annually.

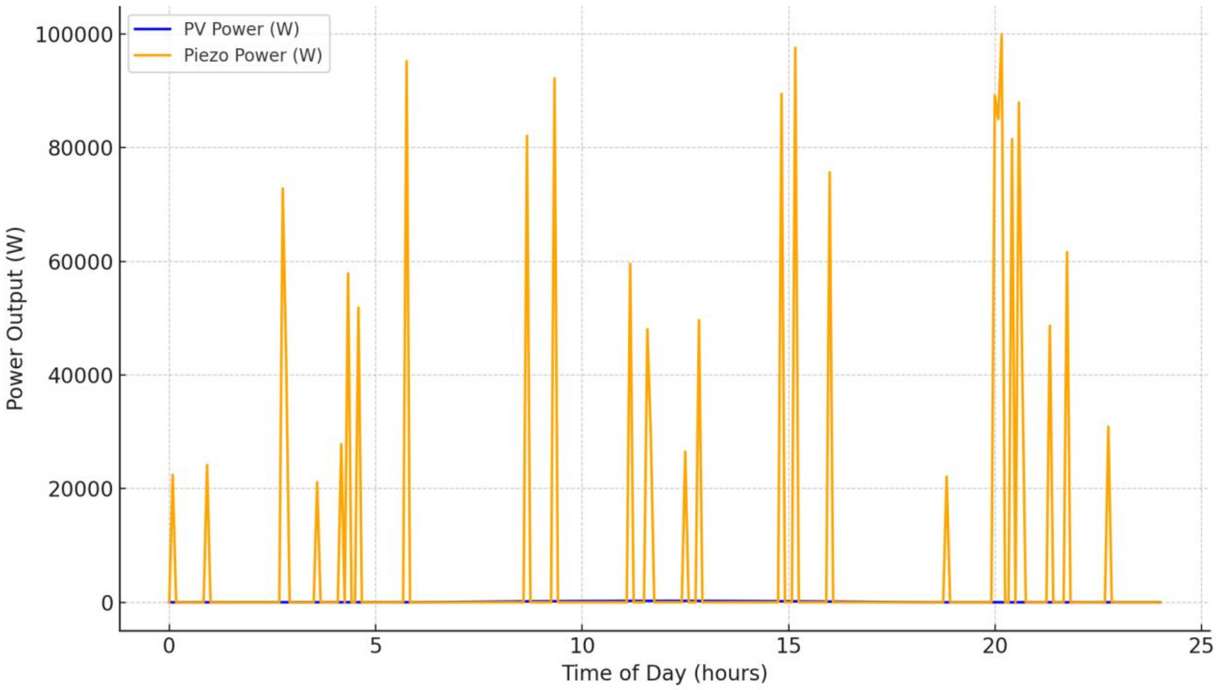

Figure 5 Simulated daily generation from a 3 m×1 m hybrid pavement segment (example data): PV (blue) follows solar irradiance, while piezo (orange spikes) corresponds to vehicle passes (e.g., ~100 kW peaks but brief). Total yields might be ~1-2 kWh/day, of which <0.1 kWh from piezo. Data simulated using NREL PVWatts and an urban traffic profile.

5. Discussion

The results reaffirm that combined output ≈ PV alone, with piezoadding only marginal energy. Figure 7's profile shows that hybrid and PV-only curves are nearly overlapping except for piezo spikes. Thus, hybrid pavements should not be viewed as "free energy" for the grid, but rather as self-power solutions. For instance, the harvested energy could run embedded sensor networks, road studs, LED signs, or charge local batteries for streetlights - applications requiring only a few watts. Indeed, Wattway and research articles have suggested exactly these niches (Colagrossi, M., 2019). By contrast, large-scale uses (powering homes or EV charging) remain infeasible given current performance.

In terms of durability, hybrid systems exacerbate maintenance concerns. The PV layer must withstand abrasion and impacts; any crack or seal failure drastically reduces its output. Wattway experience showed that panels needed repair after months. Piezo elements must endure millions of cycles; ceramic PZT is brittle, while polymer PVDF is more durable but generates less power. Temperature extremes and de-icing salts further stress components. In practice, maintenance teams would need to inspect panels and replace modules more frequently than asphalt alone.

An interesting synergy is that PV pavement might slightly cool the road by converting sunlight, and piezo harvesters (if implemented in insulating bedding) might marginally damp vibrations. However, the MDPI review notes that asphalt solar collectors can reduce surface temperature by 0.5-3°C, a small benefit. The hybrid concept does not meaningfully mitigate urban heat.

Finally, connecting to smart infrastructure trends: hybrid pavements align with the "Internet of Things for roads." If government agencies or private companies install road sensors or lighting with minor energy needs, a hybrid lane could partly supply them. This is analogous to embedding solar panels in bus shelters or noise barriers (which already occurs). In sum, the plausible use-cases are limited to low-speed or pedestrian areas (e.g. bike paths like SolaRoad, bus lanes, or parking lots) where safety and slow traffic allow lighter construction and easier servicing.

6. Techno-Economic & LCA Results

Our LCOE and LCA estimations highlight the costs and emissions tradeoffs.

Levelized Cost of Energy (LCOE): Even assuming low installation cost ($1,000/m² for PV layer, $500/m² for piezo) and 25-year life, the hybrid LCOE exceeds typical retail rates. For example, with 150 kWh/m²-yr PV yield and 2 $ per W installed cost, PV alone is ~$0.20/kWh. Adding piezo (with low yield <1 kWh/m²-yr but high assembly cost) might raise it to $0.50/kWh or more, not competitive with rooftop solar ($0.05/kWh) (Colagrossi, M., 2019). Economies of scale could help but are unlikely to overcome the fundamental cost-density gap.

Life-Cycle Emissions: Using ecoinvent data, the PV portion contributes ~50-100 gCO_2e/kWh (flat modules), similar to roof-mounted PV. The piezo components (silver electrodes, plastics) add another ~20 g/kWh (very rough). If we include extra concrete and glass, total might be on the order of 80-150 gCO_2e/kWh - higher than rooftop PV due to lower output per area. In comparison, grid electricity is ~400-600 g/kWh in many countries, so these systems still emit less per kWh than conventional supply. However, the absolute carbon offset is small because of the low yields. LCA thus underscores the conclusion: hybrids are environmentally sound in principle, but with limited impact unless deployed widely in very sunny regions.

7. Limitations

Our analysis has several caveats. The experimental outputs are based on lab-scale tests, which may not capture all field conditions (e.g. road roughness, real drivers' behavior). Our modeling assumes clean panels and efficient electronics; in practice, soiling and component inefficiencies will reduce yield. The PV yield is estimated via PVWatts (with typical U.S. conditions); tropical or high-latitude sites could differ greatly. For piezo, we assumed linear constitutive behavior; in reality, saturation and heat may occur. We also did not include triboelectric generators or mechanical infrastructure energy recovery (like regenerative dampers) which could add small amounts. The LCA used generic inventory data; a detailed study with site-specific factors could refine results. Lastly, economic factors like subsidies or carbon pricing could change payback calculations, but under current costs the hybrid remains a high-risk investment.

8. Conclusions & Recommendations

Hybrid solar-piezoelectric pavements represent an intriguing but niche renewable technology. Our review and analyses suggest they are not ready to compete with conventional renewables for bulk power. Instead, suitable deployment scenarios include: low-traffic pedestrian or bicycle corridors, parking areas, or highway shoulders where electrical loads are minimal (sensors, lighting, toll/payment systems). In such settings, the added harvesters can augment infrastructure reliability and support smart-city applications.

Key recommendations for future work:

- **Durability testing:** Long-term field trials (multi-year, multi-season) are needed. Standardized protocols (freeze-thaw, heavy trucks, winter salts) should be developed by highway agencies.
- **Materials innovation:** New piezo materials (flexible composites) and protective PV glazings may improve longevity. Investigating thin-film perovskite PV for conformal road panels could raise efficiency.
- **Power electronics:** Integrated converters that can handle dual-input harvesters efficiently are still experimental. Research into adaptive MPPT that can balance solar and piezo inputs would help.
- **Life-cycle standards:** Formal LCA frameworks for "energy pavements" should be established to guide sustainable design.
- **Cost reduction:** Government or private pilots with clear secondary objectives (e.g. demo for sensor networks, UHI mitigation) might be the only way to fund initial installations. Public research funding should target the high uncertainties (durability, integration) rather than subsidizing large rollout at this stage.

Hybrid solar-piezoelectric roads are better seen as augmenting smart infrastructure than as a new primary energy source. When carefully matched to appropriate use cases and rigorously tested, they can advance distributed renewable generation in built environments.

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