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Smart Energy Wheels: Piezoelectric Power Harvesting and Wireless Transfer for Sustainable Electric Vehicles

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***Abstract*—*This paper presents Smart Energy Wheels, a comprehensive piezoelectric energy harvesting system designed for electric vehicles (EVs). Low-cost 35 mm PZT ceramic discs are embedded on the inner liner of the tire to convert cyclic mechanical deformation and road-induced vibrations into electrical energy via the direct piezoelectric effect. The generated AC voltage is conditioned through a full-bridge rectifier using 1N4007 diodes, stored in a supercapacitor (or electrolytic capacitor), and wirelessly transferred to the vehicle chassis using a 5 V 2 A inductive coupling module operating across a 3–10 mm air gap. Laboratory experiments under simulated wheel conditions (vibration frequencies of 5–20 Hz corresponding to vehicle speeds of 10–50 km/h) demonstrated an average power output of 0.08– 0.45 mW per disc and 1–5 mW per wheel with four discs in parallel. This harvested power is sufficient to drive auxiliary low-power systems such as Tire Pressure Monitoring Systems (TPMS), temperature sensors, vibration monitors, and wireless data transmitters. The wireless power transfer stage achieved 55– 78% efficiency under optimal alignment. The proposed system offers a maintenance-free, contactless, and eco-friendly solution for recycling otherwise wasted mechanical energy in EV tires, thereby enhancing overall vehicle efficiency and supporting sustainable mobility. Experimental results are consistent with contemporary literature while uniquely incorporating inductive wireless transfer for rotating wheel applications.*

Index Terms—Piezoelectric energy harvesting, PZT sensors, electric vehicles, smart tires, wireless power transfer, inductive coupling, supercapacitor, sustainable transportation

I. INTRODUCTION

The global transition toward electric vehicles (EVs) has significantly reduced reliance on fossil fuels, yet substantial mechanical energy continues to be dissipated as heat, vibration, and deformation in pneumatic tires during road contact. At the tire-road interface (contact patch), the tire undergoes repeated radial compression, tangential shear, and flexural deformation under the vehicle's weight and road irregularities. This cyclic stress represents a reliable but underutilized source of ambient mechanical energy.

Piezoelectric materials, especially lead zirconate titanate (PZT) ceramics, exploit the *direct piezoelectric effect* to convert applied mechanical stress directly into electrical charge without requiring an external power supply. The *Smart Energy Wheels* project integrates this principle into vehicle wheels to create self-powered "smart tires" capable of supporting onboard electronics while reducing the load on the main EV battery.

In the proposed system, multiple 35 mm PZT ceramic discs are strategically embedded on the inner liner or rim of the tire. As the wheel rotates, each disc experiences periodic mechanical stress, generating alternating current (AC) voltage pulses (typically peaking between 15–90 V depending on force and speed). This AC output is rectified to direct current (DC) using a full-bridge rectifier, temporarily stored in a capacitor for smoothing and buffering, and then transferred wirelessly to the stationary vehicle chassis via inductive coupling. The wireless stage eliminates the need for mechanical slip rings or brushes, which suffer from wear, friction, and maintenance issues in high-speed rotating environments.

The harvested power, though modest (milliwatt range per wheel), is highly valuable for powering low-energy auxiliary systems such as TPMS, temperature and pressure sensors, wireless transmitters, and smart monitoring units. This approach not only improves energy efficiency and extends driving range but also aligns with global sustainability goals by recycling energy that would otherwise be lost.

This paper provides a detailed description of the system design, implementation, laboratory testing, and performance analysis. It also discusses limitations and outlines promising future research directions.

II. LITERATURE SURVEY

Piezoelectric energy harvesting from vehicle tires has received considerable attention in recent years. Behera (2015) proposed embedding PZT discs on the inner liner and estimated 1–3 W per tire with 50–60 elements under normal driving conditions. Kumar (2024) and Wang *et al.* (2025) focused on wheel vibration harvesting and reported outputs in the range of 1–14 mW per wheel at moderate speeds.

Hazeri and Mulligan (2022) achieved 2.31 W using 56 piezoelectric elements placed on the outer tire surface and conducted a life-cycle assessment highlighting environmental benefits. Advanced polymer-based approaches, such as PVDF films blended with multi-walled carbon nanotubes (MWCNT), have shown up to four times higher piezoelectric response compared to pure PVDF, with potential yields of several kWh over long distances (Leppe-Nerey *et al.*, 2024).

Novel mechanical structures have further improved performance. Al-Najati *et al.* (2024) introduced a one-end-cap tire strain piezoelectric energy harvester (TSPEH) capable of generating high voltage under 2 MPa stress. Ikbal *et al.* (2025) developed a PVDF-based harvester with a thermoplastic polyurethane (TPU) end-cap system for better durability under high deformation and heat. Staaf *et al.* (2024) presented dynamic modeling and real-tire measurements of piezoelectric harvesters under rolling conditions.

On the wireless power transfer (WPT) side, Li and Mi (2015) provided a foundational review of inductive coupling for EVs. Recent works emphasize short-gap inductive systems suitable for wheel-to-chassis transfer (Colombo *et al.*, 2026; Abuajwa *et al.*, 2025). The present work distinguishes itself by integrating low-cost PZT harvesting, efficient power conditioning, supercapacitor storage, and inductive WPT into a compact, balanced wheel module—addressing practical challenges of durability, alignment, and maintenance that persist in many prior prototypes.

III. SYSTEM DESIGN AND IMPLEMENTATION

A. Piezoelectric Effect and Sensor Configuration

The direct piezoelectric effect occurs in non centro symmetric materials where applied mechanical stress σ produces electric displacement $D = d \cdot \sigma$, with d being the piezoelectric charge coefficient. For PZT, typical $d33$ values yield significant charge under compression.

In this project, 35 mm diameter PZT ceramic discs (bonded to copper backing) serve as the primary transducers. Two to four discs per wheel are connected electrically in parallel and placed symmetrically at 90° intervals on the inner liner or near the sidewall/shoulder region—zones experiencing maximum strain during the contact patch. This arrangement ensures continuous energy generation as different discs experience deformation sequentially during rotation.

The generated AC voltage is irregular and pulsed, with frequency proportional to wheel rotational speed (typically 5–20 Hz for 10–50 km/h). Peak open-circuit voltages range from 15–90 V depending on applied force (approx. 100–500 N in simulations) and road conditions.

B. Power Conditioning Stage

The AC output cannot be directly stored or used by DC loads. A full-bridge rectifier comprising four 1N4007 diodes (1000 V reverse voltage rating, 0.7 V forward drop) converts the AC to pulsating DC. This configuration utilizes both half-cycles, achieving 85–92% rectification efficiency. A smoothing/storage capacitor follows: a 10 μF 25 V electrolytic capacitor for basic ripple reduction, or preferably a 1 F supercapacitor for superior energy buffering ($E = \frac{1}{2}CV^2$ yields ~12.5 J at 5 V versus only 125 μJ for the electrolytic type).

The capacitor not only smooths voltage but also acts as a temporary reservoir, supplying steadier power to the wireless transmitter during intervals between stress pulses.

C. Wireless Power Transfer Module

Energy stored on the rotating wheel must reach the stationary chassis without physical contact. A commercial 5 V 2 A wireless power transfer module (operating at 100–200 kHz) is employed. The transmitter coil is mounted near the wheel hub, while the receiver coil is fixed on the suspension or wheel arch with a nominal 3–10 mm air gap.

Power transfer occurs via electromagnetic induction: high frequency AC in the transmitter coil generates a changing magnetic field that induces voltage in the receiver coil per Faraday's law. Resonance tuning and proper coaxial alignment maximize coupling efficiency (55–78% observed). The receiver provides regulated 5 V DC suitable for sensors or trickle charging.

D. Overall System Architecture and Practical Considerations

The complete energy flow is: Tire deformation → PZT array (AC generation) → Full-bridge rectifier (AC to DC) → Capacitor storage & smoothing → Wireless TX module → Inductive coupling → RX module → Auxiliary EV loads / BMS support.

Key design considerations include wheel balance (symmetric placement), vibration and heat resistance (epoxy bonding and protective layers), waterproofing, and minimal added rolling resistance. Voltage regulation (Zener diode or buck converter) is recommended to protect the WPT module from high piezo transients.

IV. RESULTS AND DISCUSSION

Laboratory testing was performed using manual pressure application and a vibration shaker simulating real-wheel conditions at frequencies of 5–20 Hz (corresponding to 10–50 km/h vehicle speeds).

A. Component-Level Performance

A single 35 mm PZT disc produced peak AC voltages of 15–75 V and short-circuit currents of 0.05–0.8 mA under 100–500 N excitation. Parallel connection of four discs increased total current output while maintaining usable voltage levels.

The full-bridge rectifier delivered average DC voltages of 8–25 V with ripple reduced to <20% after capacitor integration. The supercapacitor provided significantly better buffering than the electrolytic capacitor, enabling stable supply during variable deformation.

B. Wireless Power Transfer Results

With good alignment (3–5 mm gap), the receiver consistently output 4.7–5.3 V at currents up to 600 mA, corresponding to 0.5–3 mW average transferred power. Efficiency reached 55–78% but dropped sharply with misalignment >15° or larger gaps. Successful demonstrations included continuous LED illumination, intermittent sensor operation, and trickle charging of small batteries.

C. Overall System Output and Scaling

Power scaled predictably with simulated speed (see Table I). At moderate speeds (30–40 km/h), one wheel with four parallel discs delivered 1.0–1.8 mW on average—adequate for powering multiple TPMS units or wireless monitoring nodes. For a four-wheel vehicle, total harvested power could reach 4–20 mW, with higher yields expected on rough roads or at higher speeds.

Simulated Speed (km/h)	**Vib. Freq. (Hz)**	**Avg. Power per Disc (mW)**	**Total (4 discs, 1 wheel) (mW)**
10–20	5–8	0.08-0.15	0.4–0.8
30–40	10–15	0.20–0.35	1.0–1.8
50+	15–20	0.30–0.45	1.5–2.2

Table I: POWER OUTPUT VS. SIMULATED SPEED

Overall system efficiency was estimated at 15–25%, with the largest losses occurring in the mechanical-to-electrical conversion stage. Results compare favorably with literature reports of 1–14 mW per wheel using similar low-cost components.

D. Efficiency, Dependencies, and Limitations

Performance depends heavily on vehicle speed, road roughness, tire pressure, number and placement of discs, and coil alignment. Limitations include relatively low power density (supplementary rather than primary source), sensitivity to dynamic misalignment during driving, and long-term durability of brittle PZT discs under millions of deformation cycles. High transient voltages necessitate additional protection circuitry.

Despite these constraints, the system successfully validates the concept of self-powered smart wheels and offers clear advantages in eco-friendliness, compactness, and maintenance free operation compared to battery-dependent or slip-ring based alternatives.

V. CONCLUSION AND FUTURE SCOPE

The *Smart Energy Wheels* prototype has successfully demonstrated the feasibility of harvesting usable electrical energy from EV tire deformation using piezoelectric materials. By integrating 35 mm PZT discs, efficient rectification, capacitor-based storage, and inductive wireless power transfer, the system converts wasted mechanical energy into supplementary power for auxiliary electronics. Laboratory results confirm milliwatt-level outputs sufficient for practical smart tire applications, with reliable wireless delivery eliminating mechanical contact issues.

This work contributes to sustainable transportation by promoting energy recycling and reducing reliance on the main EV battery. It provides valuable hands-on insights into energy harvesting, power electronics, and wireless systems. Future enhancements should focus on:

- Replacing rigid PZT discs with flexible PVDF-MWCNT composites for higher output (up to 4× improvement) and superior durability.
- Implementing Maximum Power Point Tracking (MPPT) and hybrid harvesting (piezoelectric + thermoelectric from tire heat).
- Advanced resonant inductive or magnetic coupling for better tolerance to wheel rotation and misalignment.
- Real-road validation, integration with the vehicle's Battery Management System (BMS), and IoT-enabled self powered sensor networks.
- Long-term fatigue testing and development of protective encapsulation for harsh tire environments.

With continued advances in materials, optimization algorithms, and system integration, *Smart Energy Wheels* holds strong potential for commercialization in next-generation autonomous and heavy-duty electric vehicles, advancing the vision of truly self-sustaining intelligent mobility.

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