RESEARCH ARTICLE

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Hybrid Energy Harvesting in Electric Vehicles: Integrating Rotational and Solar Power for Extended Range and Energy Autonomy

S. Bhavani [a,*], Sudha [a], Priscilla Sophia [a]

[a] Department of Electronics and Communication, Sri Shakthi Institute of Engineering and Technology, Tamil Nadu, India

[*] Corresponding Author: bhavanisridharan7@gmail.com

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Abstract: Electric vehicles (EVs) offer a cleaner alternative to internal combustion engines but face persistent challenges including limited driving range, dependence on grid-based recharging infrastructure, and battery degradation. This paper proposes a hybrid energy-harvesting system that supplements conventional charging methods by integrating two passive, continuous energy sources: rotational kinetic energy from wheel motion and solar energy via rooftop photovoltaic panels. The system aims to reduce range anxiety, enhance energy efficiency, and improve battery longevity by offloading auxiliary loads and supplying trickle charge during operation and rest. Technical feasibility, energy output modeling, and integration challenges are analyzed. The results suggest that up to 800W of supplementary power can be generated under optimal conditions, translating to significant weekly range extension and auxiliary system support. Limitations, implementation barriers, and future research pathways are also discussed, positioning the system as a scalable solution for enhancing EV autonomy, especially in remote or grid-limited environments.

Keywords: Electric Vehicles (EVs), Energy Harvesting, Rotational Kinetic Energy, Photovoltaic Panels, Range Extension, Battery Management, Hybrid Energy System, Sustainable.

1. Introduction

The rapid global shift toward electric vehicles (EVs) is driven by the need to reduce carbon emissions, improve air quality, and decrease dependence on fossil fuels. Despite significant progress in battery technologies, EV adoption continues to face critical barriers, most notably limited driving range, high battery cost, and inadequate charging infrastructure. These challenges are particularly pronounced in developing regions, remote areas, and for long-distance commuters.

This paper presents a hybrid energy-harvesting framework that supplements traditional plug-in charging by utilizing two passive energy sources: the rotational kinetic energy generated by the wheels and solar radiation absorbed via rooftop photovoltaic (PV) panels. Unlike regenerative braking, which is limited to deceleration events, rotational harvesting works continuously, capturing energy across all motion phases. Combined with solar energy—which operates even when the vehicle is stationary—this system aims to deliver consistent auxiliary power, thus reducing the load on the main propulsion battery and increasing the vehicle's effective range. The concept is not designed to replace primary charging systems, but to serve as a complementary solution that enhances energy autonomy, system resilience, and operational efficiency.

2. Objectives

The primary objective of this research is to develop an efficient and sustainable hybrid energy harvesting system for electric vehicles (EVs) by integrating rotational energy recovery and solar power harvesting technologies. This system aims to augment the existing battery energy supply by capturing and converting otherwise wasted mechanical and solar energy into usable electrical energy, thereby significantly extending the driving range and improving energy autonomy of EVs. Specifically, the research focuses on:

2.1 Rotational Energy Harvesting

Designing and implementing mechanisms such as regenerative braking systems, suspension-based energy recovery, and wheel-mounted generators to capture kinetic and mechanical energy generated during vehicle motion (e.g., braking, rotation, and vibration) and convert it into electrical energy.

2.2 Solar Energy Integration

Developing a high-efficiency photovoltaic (PV) system mounted on the vehicle's body (roof, bonnet, etc.) optimized for automotive conditions to harvest solar energy during daylight hours, with emphasis on lightweight materials and aerodynamic integration. Hybrid Energy Management System (HEMS): Creating an intelligent energy management and control unit to efficiently regulate, store, and distribute harvested energy from both sources (rotational and solar) to the EV’s powertrain or auxiliary systems, prioritizing real-time energy optimization and minimal loss.

2.3 Performance Analysis and Optimization

Conducting simulations and real world testing to evaluate the performance improvements in terms of extended driving range, battery life enhancement, and overall energy efficiency. The goal is to quantify the additional energy gained and assess the economic and environmental viability of the hybrid system.

2.4 Scalability and Practical Implementation

Investigating the feasibility of integrating the hybrid system into various types of EV platforms, including passenger cars, two-wheelers, and commercial vehicles, ensuring adaptability, cost-effectiveness, and minimal impact on vehicle design and weight. The project aims to contribute to the advancement of sustainable transportation solutions, reducing reliance on conventional charging infrastructure, and promoting the widespread adoption of EVs through improved energy independence.

3. System Architecture

Figure 1. System Architecture

The figure 1 provided illustrates a system architecture for a hybrid energy harvesting mechanism in electric and hybrid vehicles. Here's a textual breakdown of the architecture as depicted

3.1 System Architecture: Hybrid Energy Harvesting in Electric Vehicles.

3.1.1 Vehicle Types

Full Electric Vehicle (EV)

Hybrid Electric Vehicle (HEV) these vehicles serve as the platform for integrated energy harvesting systems.

Energy Harvesting Modules: Mechanical Harvesting

Regenerative Braking: Converts kinetic energy during braking into electrical energy.

Regenerative Shock Absorber: Harnesses vibration and suspension movement during driving.

3.1.2 Solar Harvesting

Solar Panel (Photovoltaic Module) mounted on the car roof captures sunlight and converts it into electricity.

3.1.3 Thermal Harvesting

- **Thermoelectric Generator (TEG):** Converts heat from exhaust or engine components into electricity.
- **Thermoelectric Module Structure:** P-type and N-type semiconductor materials**,** Works based on the See beck effect (temperature difference → voltage generation

3.1.4 Energy Flow

Energy from all three sources (mechanical, solar, thermal) is directed towards a centralized battery system. A power management system coordinates the storage and utilization of this energy to supplement or recharge the main EV battery.

3.1.5 Key Functions

Energy Recovery: Captures waste energy that would otherwise be lost.

Energy Storage: Stores harvested energy in the vehicle battery. Energy Efficiency: Enhances vehicle range and reduces dependency on external charging.

This hybrid system architecture integrates mechanical, solar, and thermal energy harvesting subsystems into electric vehicles to Extend battery life Improve energy efficiency Promote sustainable and autonomous transportation.

3.2 Conceptual Framework

Electric vehicles (EVs) represent a major shift in transportation, reducing reliance on fossil fuels and lowering greenhouse gas emissions. However, limitations in battery range, recharging infrastructure, and cost remain significant barriers to broader adoption. This paper introduces a hybrid energy-harvesting concept that supplements traditional plug-in charging with two continuous and passive energy sources: rotational kinetic energy from the wheels and solar radiation captured via rooftop photovoltaic (PV) panels.

This dual-harvesting approach aims to reduce "range anxiety" and enhance energy autonomy for EV users. By leveraging the constant motion of the vehicle and available ambient solar energy, the hybrid system provides a continuous trickle charge to the battery or auxiliary systems, thus extending operational range and improving energy efficiency. Unlike conventional regenerative braking, which is event-dependent (braking), rotational harvesting occurs during all driving phases— acceleration, cruising, and deceleration—ensuring higher utilization.

3.3 Implementation

Here's a structured explanation for the implementation of Hybrid Energy Harvesting in Electric Vehicles integrating Rotational (mechanical) and solar power systems to achieve extended range and energy autonomy. Implementation of Hybrid Energy Harvesting in Electric Vehicles Rotational energy harvesting (via regenerative braking and suspension systems)Solar energy harvesting (via photovoltaic panels) A Power Management Unit (PMU) to control and optimize energy flow into the battery storage.

Components and SubsystemsRotational (Mechanical) Energy Harvesting Regenerative Braking SystemInstalled in the drivetrain.Converts kinetic energy during braking into electrical energy using a motor-generator.Integrated into the vehicle's braking system with dynamicSwitching between frictional and regenerative modes. Regenerative Suspension/Shock Absorbers Embedded in the suspension system.

Uses linear or rotary electromagnetic generators to convert vertical movement (caused by road irregularities) into electrical energy. Output is fed into the auxiliary energy storage system.

Solar Energy Harvesting Photovoltaic (PV) Panel Installation High-efficiency flexible solar panels are mounted on the vehicle roof, hood, or rear windshield. Monocrystalline silicon or thin-film solar panels for optimal weight-to-efficiency ratio. Encased in protective layers to withstand outdoor and automotive conditions.

3.3.1 Solar Charge Controller

Regulates voltage/current from the solar panel to the battery. Includes Maximum Power Point Tracking (MPPT) for maximum efficiency. Energy Storage and Management Battery Integration Energy harvested from both sources is stored in the main EV battery or auxiliary battery pack. Must support bidirectional energy flow and efficient charging. Power Management Unit (PMU) Controls energy flow from mechanical and solar sources. Prioritizes energy harvesting depending on driving mode, sun exposure, braking frequency, etc. Includes microcontroller or embedded system for intelligent decision-making.

Figure 2. Caption not given

Control Algorithms and Communication MPPT Algorithm for solar harvesting optimization. Energy Prioritization Logic to decide. When to use harvested energy for propulsion vs. storage. Which energy source to prioritize under various conditions. CAN Bus Integration to synchronize data with the vehicle's onboard control system (e.g., battery status, braking events, GPS for solar angle prediction).

3.3.2 Testing and Validation

- Simulation Environment (e.g., MATLAB/Simulink or ANSYS)
- Simulate energy harvesting performance under varying speed, braking frequency, sunlight conditions.
- Prototype Vehicle Setup Install subsystems in a test EV.
- Collect real-world data on energy harvested, battery usage, range improvement.
- Performance Metrics
- Additional kWh generated/day Battery charge contribution (%)
- Increase in driving range (km)
- Payback period of the hybrid system

3.4 Safety and Efficiency Considerations Voltage Regulation to Prevent Overcharging.

Weight-to-energy trade-off to ensure added systems don't negatively affect vehicle efficiency. Thermal management for both PV panels and mechanical harvesters. Maintenance and durability of moving and exposed parts.

3.5 Future Scalability

- Integrate with IOT systems for remote monitoring.
- Adaptive algorithms based on machine learning to optimize energy harvesting patterns.
- Expandable to other vehicle types: e-bikes, delivery vans, buses.

4. Results and Discussion

Enhanced Rotational Energy Harvesting Mechanism Rotational energy harvesting hinges on converting Mechanical wheel movement into electricity via electromagnetic induction. The key components of this subsystem include:

Permanent Magnets: Embedded in the rotating part of the wheel hub.

Stationary Coils: Mounted on the non-rotating suspension or frame components.

Electromagnetic Induction Zone: Where relative motion between magnets and coils induces a current.

Rectification and Control Circuitry: Converts AC to DC and conditions the output before battery input.

Advanced designs may use axially aligned flux paths to reduce size and weight or utilize Halbach arrays to intensify magnetic flux without increasing mass. To minimize parasitic drag and energy loss, low-friction magnetic bearings and lightweight composite housings are proposed. The power output varies with speed and magnet configuration. A typical 150W module per wheel, operating at 80% efficiency, could generate approximately, 480W during city driving, assuming regular traffic movement, Up to 600W in highway conditions with high-speed rotation, Lower but steady output even at low speeds, ideal for stop- and-go urban driving. Energy is first fed to a super capacitor bank to handle fluctuations, and then relayed through a DC-DC converter to the main battery pack.

4.1 Advanced Solar Energy Integration

The vehicle's rooftop serves as an ideal platform for a compact, lightweight solar panel array. The use of monocrystalline silicon PV cells, with efficiencies reaching 22–25%, offers a high-energy yield per square meter. Innovations in thin-film and perovskite-based panels further improve flexibility and temperature tolerance.

Assuming a Roof Area of 1.5 m^2: Under peak sunlight (1000 W/m^2): 300W–400W can be expected. With daily average sunlight (5 hours/day in temperate regions): ~1.5–2.0 kWh/day harvested.

Combined with MPPT (Maximum Power Point Tracking): Efficiency is increased by dynamically adjusting internal resistance based on light intensity and angle of incidence. The solar subsystem is especially useful during stationary periods (e.g., parking)—ideal for commuters leaving their vehicles outdoors.

Low-speed movement in traffic, where solar generation may rival or exceed consumption of auxiliary loads like air conditioning or infotainment systems.To maximize energy collection, anti-reflective coatings, self- cleaning glass, and bifacial panel configurations (absorbing light from both directions) are proposed. Total System Output and Use Case Modeling In ideal combined operation:

- **Wheel Harvesting:** ~480W at urban speeds. Solar Input: ~300W at peak sun.
- **Total Supplementary Power:** ~780–800W. Over a 1-hour drive
- **Energy Gained:** ~0.8 kWh.
- **Equivalent Range Extension:** ~5.5 km (for vehicles averaging 150 Wh/km).

In practical terms, this could add 30–40 km of extra range per week, or more if the vehicle spends long periods stationary in direct sunlight. This harvested energy can also power. HVAC systems (heating/cooling), Lighting and safety systems, Infotainment and navigation devices, Cabin pre-conditioning (when parked). This reduces the load on the main propulsion battery, indirectly increasing driving range and improving thermal and charge-cycle stability. Technical Design and Integration Challenges (Expanded) Key challenges in system integration include Mechanical Considerations:

- **Weight Distribution:** Added components must not disturb the vehicle's balance.
- **Increased Rotational Inertia:** Can affect handling and energy efficiency.
- **Durability:** Systems must withstand temperature extremes, vibration, and exposure to debris.

4.2 Electrical Integration

- **Power Quality:** Harvested power is often unsteady and must be filtered.
- **Multi-Source Energy Routing:** Requires a sophisticated BMS (Battery Management System) capable of prioritizing and balancing input from wheel generators, solar panels, and grid charging.
- **Thermal Management:** Especially for electromagnetic systems under high load.
- Aesthetic and Structural Constraints
- **Aerodynamic Design:** Solar panels must not impair drag coefficients.
- **Roof Geometry:** Curved or panoramic roofs require flexible or segmented panels.

Despite these challenges, modular system design and adaptive electronics can allow manufacturers to scale solutions to different vehicle classes—ranging from urban compact EVs to larger delivery vans.

4.3 Expanded Advantages of the Hybrid System

In addition to range extension and sustainability, the hybrid energy-harvesting model offers:

- **Energy Security:** Especially valuable in off-grid or emergency scenarios.
- **Battery Health:** Reduced depth-of-discharge cycles through supplemental energy reduces wear.
- **Sustainable Fleet Operations:** Ideal for logistics firms aiming to decarbonize delivery fleets.
- **Smart Grid Compatibility:** Vehicles can potentially become mobile micro-generators during peak solar hours.

4.3.1 Limitations, Risks, and Trade-Offs

Cost vs. Benefit: Upfront cost and engineering complexity must be justified by long-term energy savings.

Marginal Net Gains: Without optimized design, system friction or inefficiencies could negate energy output.

Weather Dependency: Solar performance drops significantly in cloudy or shaded environments.

Consumer Perception: Some users may overestimate the energy independence provided by such systems. Simulation and road testing under diverse real-world conditions are essential to optimize design parameters and validate claimed benefits.

4.4 Future Research and Development Opportunities

The hybrid system can evolve into a multi-modal energy harvesting platform, incorporating:

- **Piezoelectric Elements:** In tires or suspension systems to capture vibration energy.
- **Thermoelectric Generators:** Exploiting temperature differentials in battery or motor housing.
- **AI-Powered Energy Management:** Machine-learning algorithms that adaptively adjust harvesting and routing strategies based on route, weather, and usage history.

- **Further Advances May Also Explore** Graphene-based supercapacitors for rapid energy storage and discharge.

Flexible organic PV materials for full-surface coverage without compromising vehicle aesthetics. Vehicle-to-Everything (V2X) systems where surplus energy can be shared with buildings, grids, or other vehicles.

5. Conclusion

The proposed hybrid energy-harvesting system offers a compelling supplement to traditional EV charging methods, addressing key concerns such as range anxiety, energy sustainability, and battery longevity. By harvesting rotational kinetic energy and solar power simultaneously, the system delivers a passive, continuous energy source capable of generating up to 800W under ideal conditions. This can translate to a weekly range increase of 30–40 km and substantial power support for auxiliary systems. While technical and integration challenges remain—including mechanical wear, energy conversion efficiency, and cost— advancements in materials, electronics, and control systems show strong potential for scalable deployment. Furthermore, the model supports broader sustainability goals, enabling smart grid interaction and promoting energy resilience in off-grid settings. Future developments in piezoelectric, thermoelectric, and AI-based management technologies may further amplify the benefits of this hybrid approach, laying the groundwork for the next generation of energy-autonomous electric vehicles.

6. Future Scope

Here's a well-structured Future Scope section for the implementation of Hybrid Energy Harvesting in Electric Vehicles (EVs) integrating rotational (mechanical) and solar power systems:

The integration of hybrid energy harvesting systems in electric vehicles represents a transformative step toward more sustainable, efficient, and autonomous transportation. The future scope of this technology spans multiple dimensions— technical, commercial, and societal:

6.1 Advanced Materials and Technologies

Lightweight & Flexible Solar Panels: Future solar cells (e.g., perovskite or organic PV) with higher efficiency and flexibility can be integrated seamlessly into EV surfaces.

Enhanced Energy Storage: Development of advanced battery technologies (solid-state, graphene-based) to store energy more efficiently from multiple sources.

Smart Suspension Systems: Integration of advanced regenerative suspension capable of adaptive energy harvesting based on road conditions and load.

6.2 Artificial Intelligence and Smart Control

AI-Based Energy Management Systems: Future systems could use machine learning to predict driving behavior, weather conditions, and road patterns to dynamically optimize energy harvesting and usage.

Self-Optimizing Systems: Autonomous control units that self-tune energy harvesting parameters in real time for peak efficiency.

6.3 Integration with IOT and V2X

IoT-Enabled Monitoring: Real-time tracking of energy input/output, battery status, and environmental conditions using cloud-connected devices.

Vehicle-to-Grid (V2G) Integration: EVs with hybrid harvesting could contribute excess harvested energy back to the grid, making each vehicle a potential micro-energy source.

Vehicle-to-Vehicle (V2V) Sharing: Future platforms may allow energy sharing between EVs in a fleet using wireless or contact-based energy transfer.

6.4 Commercial and Large-Scale Applications

***Public Transportation*:** Buses, trams, and delivery vehicles equipped with hybrid harvesting systems could reduce operational costs and grid dependence.

Off-Grid Rural and Remote Deployment: Vehicles can be deployed in areas with limited charging infrastructure, using solar and mechanical harvesting for extended autonomy.

Autonomous EVs: Self-driving vehicles benefit greatly from increased energy independence enabled by hybrid harvesting systems.

6.5 Policy and Environmental Impact

Government Incentives: Policymakers may introduce subsidies or mandates to encourage the adoption of self- sustaining energy harvesting systems.

Reduced Carbon Footprint: By minimizing grid dependency and increasing renewable energy use, the environmental impact of EVs can be significantly lowered.

Circular Energy Economy: Hybrid harvesting supports a move toward decentralized, sustainable energy ecosystems.

6.6 Research and Development Opportunities

Hybrid Harvesting Algorithms: Exploration of more efficient algorithms for prioritizing and balancing energy from solar, mechanical, and thermal sources.

Miniaturized and Modular Systems: Future designs may focus on creating compact, plug-and-play energy modules for easy retrofitting into existing EVs.

Multi-Source Integration: Expansion to include thermal, piezoelectric, and wind energy harvesting in future multi- modal platforms.

The implementation of hybrid energy harvesting in EVs is still in its early stages, but holds immense promise for revolutionizing energy-efficient mobility. As technologies mature, such systems will become integral to next-generation electric vehicles, enabling longer ranges, lower costs, and true energy autonomy.

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Conflict of interest

The Author’s have no conflicts of interest to declare that they are relevant to the content of this article.

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