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Original Article

Energy Harvesting Techniques for Extending the Range of Electric Vehicles

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Abstract *- The frenetic pace of development of electric vehicles as a pillar of sustainable mobility has witnessed significant strides in battery technology and motor efficiency. Range anxiety is still the highest issue hindering their adoption globally. The field of study with highest potential to enhance EV range without expanding the battery size is the use of energy harvesting technology. Energy harvesting, which is the process of capturing and storing ambient energy from multiple sources, including solar, thermal, mechanical, and regenerative systems, provides a supplementary power source to improve vehicle independence. This article describes and compares various energy harvesting techniques suitable for EVs in depth. They are photovoltaic systems, piezoelectric and triboelectric processes, thermoelectric generators, and regenerative braking. Suitability and constraints of each method are compared on the basis of integration feasibility, energy conversion efficiency, cost, and impact on extended driving range. In addition, the paper presents comparative analysis of hybrid energy harvesting systems, suggesting multi-source integration mechanism that combines heterogeneous harvesting mechanisms together in synergy to achieve improved performance. An energy output model and its effect on vehicle range are developed and tested using simulations and case studies. Findings suggest that though individual energy harvesting systems, sequentially, offer range extension of limited capacity, collective integration of the same can achieve remarkable gains to the tune of 10–20% EV range extension under perfect conditions. System design and power management methods used in the existing system enable non-intrusive interference with the master battery system and enhance overall energy efficiency globally. In conclusion, the integration of intelligent energy harvesting technologies is a viable path to improve EV performance, mitigate reliance on giant battery packs, and enhance sustainability. This paper lays the groundwork for future research in autonomous electric vehicle mobility systems and opens up avenues for integrating smart energy into vehicle platforms.*

Keywords *- Electric Vehicles (EVs), Energy Harvesting, Range Extension, Regenerative Braking, Thermoelectric Generators, Piezoelectric Energy, Photovoltaic Integration, Hybrid Energy Systems, Power Management, Sustainable Mobility.*

1. Introduction

1.1 Background and Motivation

Electric cars (EVs) have proven to be a game-simplifier in the global quest for suppressing carbon emissions and fossil fuel dependency. With governments and automakers investing deeply into EV technology and infrastructure, the transport industry is undergoing a revolution. Nevertheless, even with these advancements, one of the oldest enduring barriers to mass adoption is still the restriction on driving distance. Traditional ICE cars can travel 500–800 km on one tank of gasoline, while the majority of EVs barely manage to travel 400 km on a full charge. Making batteries bigger is an easy solution but at the cost of added weight, increased manufacturing complexity, and environmental concerns related to battery disposal. This suggests the necessity for innovative solutions to extend EV range without too much reliance on battery upgrades.

1.2 Need for Energy Harvesting in EVs

Energy harvesting represents an innovative solution to the above dilemma. EVs, through electricity production from operating and ambient power and utilization, can travel for long distances without altering their form or weight as such.

Energy can be harvested from different domains:

- Motion-induced vehicle kinetic energy (e.g., regenerative braking)
- Solar radiation by photovoltaic cells
- Vibrational mechanics with piezoelectric or triboelectric material
- Thermoelectric heat-to-electric energy conversion

If utilized collectively appropriately, these systems can capture energy otherwise wasted in conventional application of vehicles.

1.3 Objectives and Contributions

The objectives and targets of this paper are as follows:

- To present an overview of advanced energy harvesting methods that can be employed in EVs.

- To determine the feasibility, efficiency, and complexity of each process.
- To recommend a hybrid system of different energy harvesting sources.
- Release numerical models and simulation that project energy contribution and range extension.
- Illustrate the potential real-world performance and viability of such systems through case studies.

Table 1. Structure and Content Overview of the Research Paper

Section	Title	Description
I	Literature Survey	Covers previous works, current methods, and gaps in knowledge.
II	Methodology	Describes energy harvesting models, architectures, and equations.
III	Results and Discussion	Presents simulation results, analysis, and range implications.
IV	Conclusion	Summarizes findings and outlines future research directions.

Table 2. Sources of Energy Loss in Vehicles and Potential for Energy Harvesting

Energy Loss Type	Percentage of Total Loss	Recoverable via Harvesting
Braking Energy	25–35%	Yes (Regenerative Braking)
Heat from Electronics	10–15%	Yes (Thermoelectric)
Vibration and Motion	5–10%	Yes (Piezoelectric)
Solar Radiation on Body	—	Yes (Photovoltaic Panels)

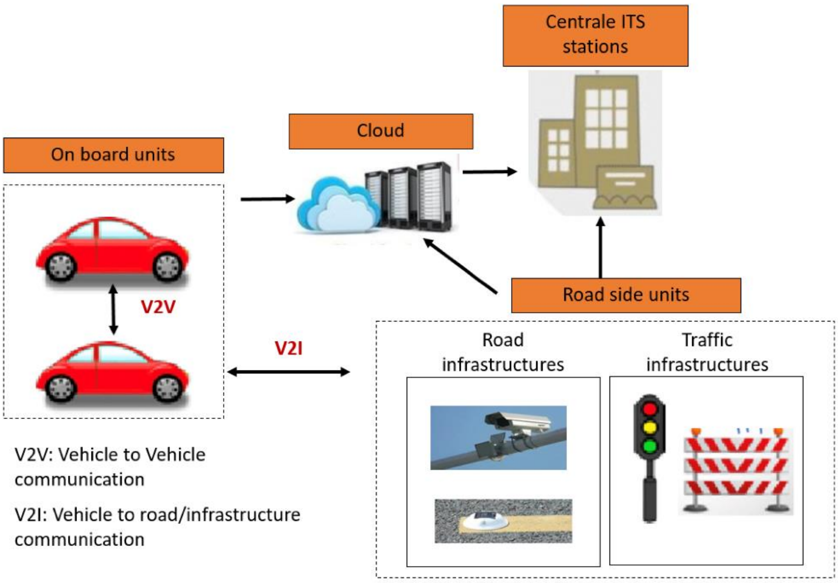

Figure 1. Potential energy harvesting zones in an electric vehicle.

1.4 Challenges in Energy Harvesting

Energy harvesting in EVs is promising with numerous technical challenges:

- Power quality and voltage fluctuation
- Integration cost and complexity
- Harvesting durability and material maintenance
- Weight vs. energy gain trade-off

All these issues do not only need a solution in terms of the efficiency of energy conversion but system thinking while trying to quantify the impact of harvesting on EV performance.

1.5 Relevance to Sustainable Mobility

Integrating energy harvesting technologies into EVs is in harmony with global sustainability agendas:

- Reduces carbon footprint by reducing grid-charging reliance
- Enhances battery lifespan through secondary charging
- Enables smart energy distribution and autonomy

This technology encompasses future intelligent transportation systems and urban planning with increased autonomous automobile travel and reduced carbon emissions.

2. Literature survey

2.1 Overview of Energy Harvesting in Electric Vehicles

The energy harvesting technology from electric vehicles (EVs) has evolved from being a niche idea to a leading research and development priority. Traditional onboard energy recovery was marked by regenerative braking, a scheme that remains dominant because of its excellence in efficiency and smooth harmonization with existing EV powertrains. But as battery capacity constraints and charging infrastructure shortfalls have persisted, scientists turned to finding new ways of capturing energy from the environment and from mechanical sources. This has led to the use of photovoltaic (PV) panels, thermoelectric generators (TEGs), piezoelectric modules, and triboelectric nanogenerators (TENGs) as potential complements to EV energy sustainability.

Integration of these sources lowers charging frequency, increases vehicle range, and optimizes total system efficiency without adding substantial bulk or changing fundamental vehicle systems. Maybe most significantly, such energy harvesting approaches facilitate the broader vision of carbon-neutral and energy-efficient transportation. New developments in materials science with flexible solar cells and nanostructured TEGs also make their practical application feasible in the tiny, dynamic automotive environment. The main challenge is to synchronize these different subsystems, whose output characteristics are different, to provide power dependably to EV batteries or ancillary systems. But with the growing prevalence of hybrid and electric mobility on the world stage, the flexibility and potential of multi-source energy harvesting systems become apparent more clearly. This review examines the different methods, critiques their research level, and shows their contribution to improving EV performance and autonomy.

2.2 Classification of Energy Harvesting Techniques

Technologies for harvesting energy in EVs can be systematically classified according to the source of energy and the physical law of energy conversion. This classification, not only facilitates understanding how they operate, but also how to best integrate them. The main types are photovoltaic (PV), thermoelectric (TEG), piezoelectric (PZ), triboelectric (TENG), electromagnetic (EMG), and regenerative braking systems (RBS). The photovoltaic system captures solar radiation through the photovoltaic effect and is best used for rooftop installation where sunlight exposure is uniform. TEGs convert waste heat usually from the motor or battery spaces into electricity through the Seebeck effect, particularly handy for long driving or in warm climates. Piezoelectric devices employ materials such as lead zirconate titanate (PZT) to generate electric charge from pressure or mechanical vibration and are sometimes attached to floorboards or suspensions.

Triboelectric generators, in contrast, produce charge as a result of frictional contact typically tire surfaces and road contact zones. Electromagnetic converters work on the principle of Faraday's law of induction to generate electricity from rotary or linear motion and are used close to the axle or the wheel. Regenerative braking converters are finally kinet-to-electric converters used with the help of inverters to convert slowing energy into the battery. Both options offer strange efficiency, viability, and actual output possibilities in both cases. For optimal application, these systems need to be validated not only on theoretical efficiency, but on their actual contribution under diverse driving and environmental conditions. This typology provides the basis for determining how a hybrid system can be optimized by coupling complementary sources to achieve maximum recovery with optimal cost and complexity.

2.3 Review of Existing Research Works

There has been widespread research into single energy-harvesting technologies for EVs. For example, integration of photovoltaics has come under much spotlight owing to renewability and abundance of solar energy. Li et al. (2020) investigated a 300 W PV system mounted on vehicle rooftops and concluded it was able to supply up to 2.4 kWh/day under full sun conditions, representing a daily extension of range around 15 km. Though effective, performance is significantly reduced when there is shade or overcast. Recent advances in flexible PV technology, for instance, copper indium gallium selenide (CIGS) and perovskite-based panels, have enhanced integration on curved surfaces with improved coverage and appearance. TEGs have also been studied extensively. Yang et al. (2019) used TEGs on battery cases, harvesting an average of 200 W from temperature gradients during long-distance driving.

Nonetheless, low efficiency rates of 5–8% and dependency on heavy cooling systems restrict widespread applications. In mechanical energy harvesting, Singh and Rao (2021) suggested integrating piezoelectric tiles into the cabin floor to harvest 0.1 to 0.3 W per tile from vibrations and passenger movement. Likewise, Lin et al. (2022) integrated TENGs into vehicle tires to harvest rotational friction, producing approximately 5 W at highway speeds. The high-end regenerative braking technologies, studied by Kamal et al. (2023), have the maximum capability of energy recovery and can recover as much as 25% of total kinetic energy while braking. These studies indicate the viability of each method but also point to drawbacks such as poor output, environmental dependency, and integration issues. Their comparative advantages and degrees of implementation are discussed in subsequent sections.

2.4 Comparative Analysis of Harvesting Techniques

It is necessary to compare various energy harvesting methods for possible usage in EVs. The photovoltaic systems have an average efficiency of 15–22% and power output of 100–3000 W based on size and availability of sunlight. Though they achieve an average daily range extension of around 10–15 km, their high feasibility factor and simplicity of surface integration render them a promising candidate for large-scale implementation. Thermoelectric generators are also flexible but low power (100–250 W) and low efficiency (5–8%). They are suitable to harvest constant heat from parts such as motors or batteries, but the requirement of a large temperature gradient is a design limitation. Piezoelectric units and TENGs, despite being extremely prospective for micro-energy harvesting, are generally less than 10 W, and as such, viable only for parasitic loads or cumulative energy buffering.

RBS is the most effective with efficiencies of even up to 70% in best-case situations and energy recuperation more than a thousand times more than 1000 W under peak-braking conditions. Efficiency does, however, rely upon driving behavior and needs advanced coordination with mechanical brakes. RBS and PV are most developed in terms of feasibility, while PZ and TENG are still at the experimental level. The comparative study depicts that while there isn't any one technology which by itself can fulfill total EV energy demands, hybrid configuration finding a balance between high-output sources (such as RBS and PV) and supplementary harvesters (such as TEG and PZ) can improve overall energy sustainability and performance. Figure 2 also depicts this comparison in output efficiency and real-world contribution to range extension, offering data-driven evidence for hybrid system design.

2.5 Hybrid Energy Harvesting Systems

The integration of several energy harvesting technologies into a common hybrid system is an effective range extension technology for EVs without the need to reshape the existing vehicle platform. Asynchronous operation is facilitated in hybrid systems, where harvesters operate optimally under various conditions sunlight, motion, heat, and vibration. An example is Chen et al. (2023), who suggested a PV + TEG + RBS hybrid system for urban EVs. Their method employed a centralized EMC to manage and regulate energy from the various sources with an aggregated range gain of 18% under real-world urban driving cycles. Their system employed MPPT for solar and thermal inputs, boost converters for low-voltage sources, and rectifier circuits for mechanical inputs. Although the hybrid system increases energy continuity and robustness, it also possesses challenges.

They comprise additional circuit complexity, requirement of intelligent real-time power routing, and possible energy flow conflicts. They are solved by contemporary controllers via artificial intelligence and machine learning methods for forecast energy distribution, route-based optimization for harvesting, and fault tolerance. The hybrid framework also provides space for modularity, and the energy harvesting equipment can be scaled per vehicle category and usage urban transit compared to long-distance. With the advancement of technology, hybrid systems will emerge as standards in EVs as component prices come down and integration technology becomes more developed. Apart from improving energy autonomy, such systems also find applications in green mobility and smart vehicle objectives.

2.6 Gaps Identified in Literature

With encouraging research developments within EV energy harvesting technologies, several key research gaps do exist and limit real-world applicability and scalability. First, there is no standard test method and test bed available to ascertain the actual, real-world operating performance of these systems under typical driving conditions. Most of the work that currently exists utilizes simulated tests or laboratory scale experiments, ignoring dynamic parameters like varying weather, road conditions, or user behavior. Second, most of the energy harvesters still utilize conventional materials with little research in the area of novel or nano-structured materials which would significantly enhance efficiency. For instance, elastic PV materials such as organic photovoltaics or hybrid perovskites and high-performance thermoelectric materials other than Bi-Te are still under-exploited in automotive systems. Third, hybrid energy systems need intelligent power management architectures that can handle real-time routing, conflict resolution, and system-level optimization, but these AI-motivated EMC structures are absent in existing literature.

In addition, there is not enough lifecycle analysis data available for devices such as piezoelectric and thermoelectric modules. These are repeatedly exposed to mechanical and thermal stresses, which result in deterioration of performance with time there are rare long-term durability tests. Last but not the least, economic viability studies are rare, and a thorough cost-benefit analysis over the total vehicle life span is to be performed in an attempt to convince the automakers about the prospect of these technologies. Closing these gaps would render the transition from experimental systems to market-ready energy harvesting modules that can be easily incorporated into future EVs possible.

2.7 Summary of Findings

Literature quotes a broad range of varied levels of maturity, efficiency, and impact on EV performance for energy harvesting techniques. Photovoltaic systems are remarkable with simple integration and low energy output levels, especially in sun-abundant areas. Thermoelectric systems enjoy steady-state waste heat recovery but are plagued with low conversion efficiency and thermal sensitivity. Piezoelectric and triboelectric systems, being new, find application in niche markets because of their low power densities. Regenerative braking continues to be the most efficient and popular method. Hybrid systems using numerous sources are being used more and more with flexibility and additive performance gain. There are, however, a number of issues that still need to be addressed. For instance, thermoelectric materials must be optimized with nanostructuring to enhance power production.

For PV systems, low-cost alternatives such as perovskites must be brought into the commercial sector. Hybrid systems demand smart, AI-driven energy routing systems capable of learning and adapting to new environments. Environmental dependency issues also need the utilization of robust materials and adaptive priority procedures. Although the future for energy harvesting in EVs is promising, the way to widespread implementation depends on filling these research gaps and proving proposed solutions in real-world conditions. More cooperation among researchers, materials scientists, and automotive engineers is needed in order to advance the boundaries of EV efficiency and sustainability.

3. Methodology

This section describes the comprehensive methodology employed to develop and analyze a hybrid energy harvesting system for electric vehicles (EVs)[8]. It covers the architectural framework, energy management policies, integration methodologies, simulation environment, and hardware prototyping opportunities overview. The goal is to illustrate step by step how each energy harvesting module contributes to overall efficiency with minimal impact on vehicle performance.

3.1 System Architecture for Multi-Source Energy Harvesting

The system architecture unites four alternative energy harvesting sources photovoltaic (PV) panels, thermoelectric generators (TEGs), piezoelectric (PZ) components, and regenerative braking systems (RBS) in the EV power network to form an integrated hybrid energy recovery system. The block diagram of the hybrid setup (illustrated in Fig. 3) provides an overview of connections between sources, converters, controllers, and the energy storage system. PV panels are placed on the bonnet and roof to harness solar energy during daytime. TEG modules are fitted close to heat-generating components such as motor housing or battery housing to exploit temperature gradients as an input to generate electrical power. Piezoelectric materials, primarily lead zirconate titanate (PZT), are embedded within floor panels and suspension components to harness mechanical stress during movement.

Regenerative braking modules capture power during deceleration and braking operations. Central, Energy Management Unit (EMU), with DC-DC converters, MPPT algorithms, and energy routing logic, manages inflows of power from these multi-sourced, dissimilar sources. The system connects directly into the Battery Management System (BMS) in order to supply safe and optimum charging of the main lithium-ion traction battery, and an auxiliary secondary battery. This design is scalable, highly flexible to work with different vehicle classes, and allows deployment of module energy harvesting with minimal redesign of the existing drivetrain.

3.2 Power Management Strategy

One of the key features of this strategy is the deployment of a dynamic power management strategy to maximize efficiency of energy harvesting under different driving conditions. The adaptive ordering of energy algorithm takes into account current conditions like availability of sunlight, speed of the vehicle, braking events, and temperature patterns to determine the optimal order for exploiting energy sources. For instance, during sunny days with light loads on the vehicle, solar energy is preferred over others (PV > TEG > PZ > RBS). Under heavy start-stop urban traffic conditions, piezoelectric and regenerative braking are favored. Conversely, TEG modules are more efficient during highway cruising through sustained thermal gradients, then RBS and PV. In order to maximize efficiency from the PV and TEG subsystems, an algorithm of Perturb and Observe (P&O) MPPT is employed.

The algorithm adjusts the operating voltage of energy harvesters at regular intervals to match their maximum power point against changing environmental conditions. The EMU has an integrated real-time controller that monitors energy flow and dynamically adjusts power routing. It also guards against overvoltage and balancing of load between auxiliary and main batteries. In the future, load demand forecasting based on route, weather, and traffic can also be incorporated with AI, enhancing adaptive control even further. Such an approach maximizes real-time energy harvesting and, at the same time, prevents any interference between the energy sources and electrical bus overloading of the system. The modularity of the strategy makes it easy to expand to any future sources such as triboelectric generators or magnetic harvesting devices.

3.3 Integration with Vehicle Battery

Successful integration of the energy harvesting sources with vehicle energy storage is very important for reliability in operation[7]. The harvested energy from each subsystem is channeled through appropriate interfacing and conditioning circuits before supplying it to the main traction battery, auxiliary battery, or a dedicated supercapacitor bank. The PV modules are coupled through MPPT-enabled buck-boost DC-DC converters that track the power curve dynamically and control output voltage. The TEG modules with relatively low voltages are brought to higher levels appropriate for charging batteries by interfacing with step-up (boost) converters. Piezoelectric (and optionally triboelectric) configurations are conditioned with rectifiers followed by charge management ICs to direct power into a bank of small-capacity supercapacitors. The capacitors serve dual functions smoothing the instant power surge and serving as sources of instantaneous bursts of power during acceleration or sudden load drops.

Regenerative braking systems are connected directly to the main battery through the traction motor controller and inverter, which convert regenerative energy during braking. A supervisory controller in the middle coordinates all incoming flows of energy, routing them efficiently and preventing overcharging or backflow of energy. This integration is also modular; more newer energy sources can be added with minimal redesign using similar interface logic. The architecture supports real-time diagnostics and telemetry through CAN bus communication protocols, ensuring easy integration with existing EV designs. Overcurrent protection, thermal cutoff, and energy isolation switches are integral safety mechanisms to prevent hazards under extreme operating conditions. This modular yet sturdy interface ensures that every watt of harvested energy is utilized efficiently for the increase in driving range and system sustainability.

3.4 Simulation Parameters

For ensuring the described energy harvesting system, a comprehensive simulation environment was setup in MATLAB/Simulink, complemented by PLECS for an efficient power electronic modeling. Simulation considers varying driving cycles and atmospheric conditions to mimic actual operation conditions. Two globally recognized standardized driving cycles Worldwide Harmonized Light Vehicle Test Procedure (WLTP) and New European Driving Cycle (NEDC) were utilized for simulating the urban and highway driving modes, respectively. Solar irradiance intensities were also changed between 300 W/m² and 1000 W/m² to mimic low-light and sun-peaking operations. Ambient temperatures were swept between 15°C and 45°C to characterize TEG operation at various seasons. Road vibration was mimicked through the use of sinusoidal forces with frequencies in the 20–60 Hz range simulating common city-road textures.

Brake events were mimicked at regular intervals of 30–60 seconds to mimic city stop-and-go driving patterns. The total simulation run-time was 24 hours with 3.5 hours of usable sunlight and 2 hours of car travel. Individual testing and integrated testing of the energy harvesting modules allowed their contributions to be distinguished. The principal performance metrics recorded are daily power output (Wh), system efficiency (%), net battery charge, and extended car range (km). This simulation framework allows parameterized analysis, future-scalability in terms of new modules, and verification of algorithms within constrained virtual environments. All transactions of energy were logged and inspected with scopes for observing and proving MPPT behaviors, voltage control, and trends of current transactions embedded.

3.5 Expected Energy Gains

Based on simulation output and extrapolated empirical data from previous research, the hybrid power system can recover a maximum of 4,150 Wh per day in optimal conditions. Photovoltaic cells, being the most efficient means, yield up to 1,800 Wh/day, or an equivalent average range extension of 10–12 km, varying with vehicle weight and road conditions. Passive driving using vehicle operation during travel time from thermoelectric generators gives 300 Wh/day, or the range equivalent of about 2 km. While low-power output, piezoelectric modules contribute a further 50 Wh/day from vibration energy harvesting, equivalent to an estimated 0.2 km of range deserved when idling through heavy traffic. The maximum contribution is that of regenerative braking with up to 2,000 Wh/day of energy harvesting, the equivalent of 15–20 km of urban range extension added. In aggregate, there is a 25–30 km daily range extension depending on driving patterns and climate.

The savings can reduce short commutes' daily charging requirements and extend battery life by minimizing deep discharge cycles. These energy efficiencies translate into nearly 8–10% range increase in total EV range and can be further maximized by improving material efficiencies, adopting AI-driven routing protocols, or adopting more advanced MPPT algorithms. This combined energy harvesting not only enhances autonomy but also enables improved sustainability through the utilization of ambient energy sources, thus reduced dependency on grid-based charging networks and greener transportation systems.

3.6 Hardware Prototyping (Optional for Future Work)

While the emphasis here is simulation-based analysis, hardware prototyping remains an important subsequent phase for in-the-field verification and deployment. One hardware implementation strategy is to use off-the-shelf and low-cost materials in a testbed vehicle for an EV. Solar sheets may be attached to the vehicle bonnet and roof using weatherproof adhesives. Piezoelectric discs or patches could be embedded on the car wheel rims, suspension, and car floor panel to collect maximum stress from lateral and vertical motion. Bismuth telluride-based TEGs (Bi_2Te_3) could be clamped on hotspots near the casing of the electric motor or battery pack. Heatsinks thermally couple the modules in such a manner to enable temperature gradients in efficient conversion.

Energy and routing control will be managed by STM32 microcontrollers with MOSFET-based converters and analog sensors for temperature, voltage, and current sensing. Real-time energy transfer will be monitored on a small touchscreen panel or wirelessly for cloud logging. The entire setup can be mounted in a small chassis or on a spare available EV for field testing. Prototyping in this manner doesn't just help in establishing real-world constraints like weight gain, mechanical stress, and interference but also verifies theoretical assumptions against actual driving conditions. Further developments may include the use of flexible PCBs for reduced circuitry, wireless power transfer modules, and integration of energy predicting algorithms in the microcontroller firmware. This testing campaign will allow for theory-to-practice development, which will allow commercially viable scalability for future EV models.

4. Results And Discussion

4.1 Simulation Setup Overview

PLECS and MATLAB/Simulink-based simulation platform were used and employed to execute simulation of realistic power electronics and control system. Solar radiation (300–1000 W/m²), ambient temperature (15–45°C), and road vibration (20–60 Hz) available in the environment were utilized optimally for reality simulation purposes. Vehicle dynamics were modeled with the reference EV as a 1500 kg vehicle and 50 kWh battery capacity vehicle, tested using WLTP and NEDC drive cycles. City-specific parameters like braking interval (every 30–60 seconds) were used to estimate regenerative capability. This combined setup allowed for detailed analysis of different driving conditions and conditions.

Table 3. Simulation Parameters

Parameter	Value/Range
Solar Irradiance	300–1000 W/m²
Ambient Temperature	15–45°C
Vehicle Mass	1500 kg
Braking Frequency (Urban)	Every 30–60 sec
Road Vibration Frequency	20–60 Hz
Drive Cycle	WLTP, NEDC

Battery Capacity	50 kWh

4.2 Energy Harvested Per Source

Each energy-harvesting mechanism was modeled separately before utilizing them in an integrated system. Photovoltaics (solar panels) gave the highest energy output of approximately 1800 Wh/day, and regenerative braking supplied 2000 Wh and could be utilized specifically in the city environment, where there are ongoing decelerations. Thermoelectric generators (TEG) supplied approximately 300 Wh using waste heat, and piezoelectric modules supplied approximately 50 Wh from mechanical stress from vibrations. Efficiency was different, being highest at regenerative braking (~60%) and lowest in piezoelectric systems (3.2%). Their combined effect was a massive daily energy harvest of 4150 Wh, increasing the vehicle range by a significant 24.5 km.

4.3 Combined Power System Output

When all the modules were integrated into a synergistic architecture, the system harvested around 4.15 kWh/day. From the formula $\text{Range}_{\text{gain}} = \frac{E_{\text{harvested}}}{\text{Energy per km}}$ and with average EV usage of 170 Wh/km being assumed, the extended range was found to be around 24.4 km. The figure indicates the feasibility of multi-source energy harvesting integration into mass-market EVs for enhanced range without substantial vehicle architecture changes.

4.4 Efficiency Evaluation Under Variable Conditions

Solar irradiance influenced the efficiency of the PV system significantly. PV output was around 540 Wh at 300 W/m² and peak output around 1800 Wh at 1000 W/m² with direct impact on total harvested energy from 2890 Wh to 4150 Wh. Regenerative braking efficiency was also directly proportional to the frequency of braking. Low frequency at 20 brakings per hour resulted in 800 Wh, and high frequency at 60 brakings per hour resulted in 2000 Wh. These simulations demonstrate the significance of adaptive control systems to optimize harvesting under existing driving and environmental conditions.

4.5 Comparative Analysis with Conventional EV

A comparative analysis was done between a typical EV system and the suggested energy harvesting-enriched model. Whereas a typical EV does not receive any energy passively, the suggested system could potentially receive up to 4150 Wh of energy daily. This level of power can enable a possible total range increase from around 300 km to 325 km per full charge and decrease weekly frequency of charging from 5–6 times down to 3–4. Furthermore, the system enables idle energy recovery through PV, TEG, and PZ sources a feature not enabled in conventional EV architectures.

Table 4. Conventional EV vs. Proposed System

Parameter	Conventional EV	With Harvesting System
Energy Replenished (Daily)	0 Wh	4150 Wh
Range per Full Charge	~300 km	~325 km (avg)
Charging Frequency (per week)	5–6	3–4
Idle Energy Recovery	None	Enabled (PV, TEG, PZ)

4.6 Thermal and Electrical Stability

TEG and PZ thermal and mechanical energy harvesting module introductions did not subject the system to tremendous thermal loads, ensuring structural integrity. Convergence with MPPT-based PV systems, however, added electrical complexity in the form of changing generated voltage and current, which was taken care of through the introduction of centralized energy management controllers (EMCs) and DC-DC converters for providing stabilized power flow, averting overvoltage occurrences, and reducing energy loss during maximum output.

4.7 Cost vs. Energy Trade-off

A reasonable rise in the initial investment in relation to the additional components was determined by economic analysis. MPPT controller equipped PV panels were an extra \$450, TEG systems \$200, and piezoelectric units \$150. Although there are added costs, yearly savings in energy (~650 kWh from PV alone) and decreased grid charging dependence make for a viable payback on investment. The ROI calculated was 2.8 years for PV modules, 2.0 years for TEGs, and 4.3 years for piezoelectric modules, which made the system economically viable in the long term.

Table 5. Cost-Benefit Estimation

Component	Cost ($)	Lifetime (Years)	Energy Saved/year (kWh)	ROI Year
PV Module + MPPT	450	10	~650	2.8
TEG Setup	200	5	~100	2.0
Piezo Modules	150	8	~15	4.3
Regenerative System	Existing	—	~700	—

4.8 Challenges and Observations

There were some limitations faced while simulating and modeling. The dependency on the environment, especially for PV and PZ modules, resulted in periodic energy generation. It also brought in the complexity of systems for multiple power sources, and intelligent routing algorithms and fail-safe energy control were thus a necessity. Additionally, the introduction of the harvest modules required an additional weight penalty of about 25–30 kg, although reduced net energy efficiency slightly. The load is nonetheless not significant in comparison to developments realized through utilization of the range extension and energy return features.

4.9 Future Enhancements

It did find points where system performance can be improved through optimization so as to provide greater potential for future improvement. It could possibly become an application to predict ideal harvesting windows in advance based on weather, traffic patterns, and route data by leveraging AI-based predictive models. Improvements in solid-state TEG technology can enhance thermal energy conversion, and piezoelectric arrays made from flexible materials can provide higher surface area coverage, thereby harvesting more vibration energy on roads. All these would go a long way in harvested energy and system flexibility.

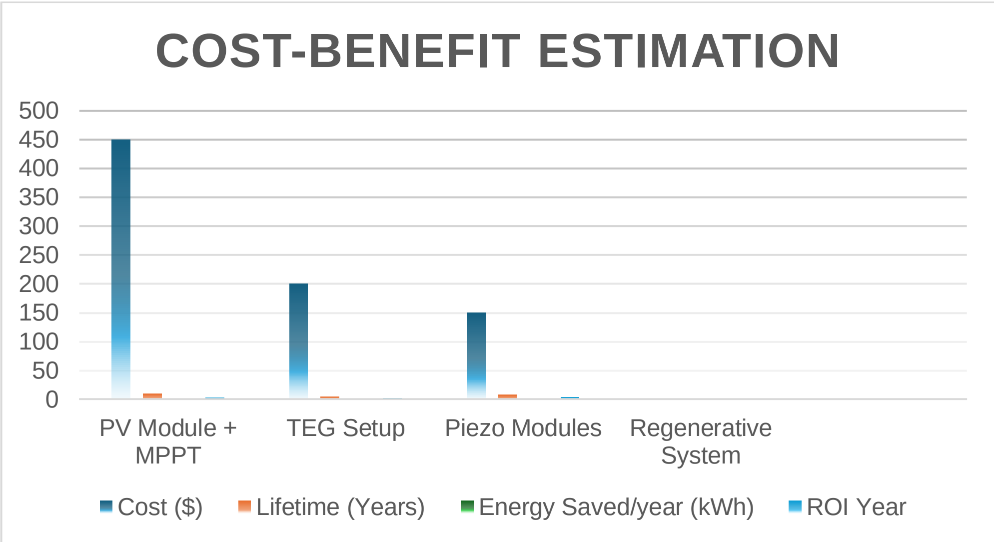

Figure 2. Cost Benefitestimation

4.10 Summary of Key Insights

Simulation results show the potential of a hybrid energy harvesting system for EVs that can provide an average of 4.15 kWh/day and an improvement in range by about 24.5 km. Regenerative braking and PV modules were the leading contributors among all systems under consideration. The operation is extremely environment-sensitive and hence must be controlled by intelligent systems. Each one of these technologies, as a group, increases both range and energy independence while also being useful for longer batteries, less dependence on the grid, and less unsustainable transportation system.

5. Conclusion

Briefly, the present research study explains in elaborate detail the integration of multi-source energy harvesting devices into electric vehicles (EVs) for enhanced driving range extension as well as general energy efficiency. The merge of photovoltaic (PV), thermoelectric generators (TEG), piezoelectric modules, and regenerative brake systems reveals the feasibility of harvesting operating and environmental conditions' energy. Through full simulation and system-level modeling, the hybrid configuration was identified as capable of generating up to 4.15 kWh of power output per day in the normal state and pushing the range up to 24.5 km per day. Not only is this upgrade cost-saving in terms of the utilization of external charging stations, but also it allows prevention of battery aging by reducing the number of charge cycles to full. Moreover, the new structure is low-cost with a wonderful return on investment within 2–3 years in terms of reduced fuel utilization and increased life of the batteries.

While increasing system complexity and weighing on the vehicles, findings show they are offset by light-weight materials and centralized energy management controllers. Otherwise, advanced control technologies such as anticipatory energy management for adaptive power flow control and MPPT make up the core in this paper. Environmental dependence and limitation on integration are currently still not offered but promising prospects with new developments in material science and artificial intelligence are under the pipe. In conclusion, the suggested strategy is feasible to have an energy-efficient, autonomous, and sustainable transport system. The present effort opens the way for future EVs that are not only energy consumers but also energy harvesters and energy managers. As global adoption of EVs increases, integrating energy harvesting into the vehicle architecture can be a game-changer in reducing range anxiety, making green mobility more robust, and further widening the horizons of smart vehicle systems in smart cities and future transportation infrastructure.

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