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Original Article

Energy Harvesting Techniques for Extending the Range of Electric Vehicles

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Abstract

The rapid rise of electric vehicles has brought major improvements in battery technology and in the efficiency of motors, but range anxiety remains a major concern and barrier to wider usage. One of the promising options to extend electric car travel without increasing the size of the batteries is energy harvesting methods. Energy harvesting is a process of collecting and storing energy from the environment, such as solar, thermal, mechanical, and regenerative systems. Adding another power source provides more freedom to cars. This paper reviews in detail and summarizes various methods of energy sourcing considered friendly for electric vehicles: photovoltaic systems, thermoelectric generators, piezoelectric and triboelectric mechanisms, and regenerative braking. The focus then shifts to analysing the level of implementation, the efficiency of energy conversion, cost, and the range extension provided by each method in a given EV. The current research focuses on hybrid sources of energy. Various aspects of generating hybrid energy are pursued; particularly, it proposes a multiple sources integration strategy that includes various methods of energy harvesting for performance enhancement. We demonstrate a mathematical model that can predict energy produced and the impact on the range of a vehicle using simulations and case studies. Each energy harvesting system contributes to the range, but altogether, they can make a big difference. In the best possible conditions, they can give an EV an extra 10-20% of its range. The proposed system architecture and power management strategies ensure compatibility between the primary battery system and the new system, enhancing overall energy efficiency. Therefore, adding more advanced energy harvesting technologies is one of the best ways to make electric cars better, make them less dependent on big battery packs, and contribute to making them much better for the environment. The paper paves the way for future improvements in self-sustaining electric mobility systems and facilitates the path of wise energy utilization by a vehicle.

Keywords

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

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1. Introduction

A. Background and Motivation

Driving electric vehicles contributes to drastic carbon emission reductions and helps minimize the use of fossil fuel. Enormous amounts of investment flow from both governments and businesses into EV technologies and infrastructure. The result is that the business of moving people and products is dramatically changing. But in spite of these improvements, one of the prime issues that continues to make their use difficult is their inability to travel great distances.

With one tank of gas, a regular car with an internal combustion engine can drive from 500 to 800 km. However, most electric vehicles cannot even travel 400 km using one charge. Increasing the space for batteries is quite easy; however, it will make your product heavier, more difficult to manufacture, and even worse for the environment when its battery is discarded. We need to find new ways to make electric cars go farther without using up too much battery life.

B. Need for Energy Harvesting in EVs

Energy harvesting provides an exciting frontier in addressing this issue. By converting ambient and operational energy into electrical energy, EVs can sustain themselves longer without significantly altering their structure or weight.

This energy can be harvested from multiple domains:

- Kinetic energy from vehicle motion (e.g., regenerative braking)
- Solar radiation using photovoltaic panels
- Mechanical vibrations through piezoelectric or triboelectric materials
- Heat energy using thermoelectric generators

When integrated effectively, these systems can recover energy that would otherwise be lost during normal vehicle operation.

C. Objectives and Contributions

The objectives of this paper are as follows:

- Review the state-of-the-art energy harvesting techniques applicable to EVs.
- Analyse the feasibility, efficiency, and implementation challenges of each method.
- Propose a hybrid architecture integrating multiple energy harvesting sources.
- Present mathematical models and simulations estimating energy contribution and range extension.
- Discuss the real-world applicability and performance of these systems through case studies.

D. Scope and Organization

Table 1: The paper is structured as follows:

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

E. Statistical Snapshot of EV Energy Loss

Table 2: Simplified Schematic of Potential Energy Harvesting Zones in a Typical EV.

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)

Table 3: How EV Energy-Loss Recovery Systems Work in Conjunction

Energy Source / Loss	How the Loss Occurs	Recovery Method	How It Works Together with Other Systems
Braking Energy	Kinetic energy is converted into heat during braking.	Regenerative Braking	Feeds electrical energy back to the battery during deceleration. Works alongside thermoelectric, piezoelectric, and solar systems by contributing the largest recoverable energy surge during driving.
Heat from Electronics	Power electronics and motors generate waste heat during operation.	Thermoelectric Generators (TEGs)	Continuously converts heat into small amounts of electricity. Complements regen braking by providing steady energy recovery even when the vehicle is not slowing down.
Vibration and Motion	Structural and road vibrations occur from tire–road interaction and	Piezoelectric Harvesting	Generates bursts of electricity from vibration. Works simultaneously with TEGs as a background recovery source and adds minor energy during

	chassis motion.		normal driving.
Solar Radiation on Body	Sunlight impacts the roof, hood, or body panels.	Photovoltaic Panels	Produces electricity whenever the car is exposed to sunlight. Works in parallel with all other systems and helps offset auxiliary loads when the car is stationary.

F. Challenges in Energy Harvesting

While promising, energy harvesting in EVs presents multiple technical challenges:

- Power quality and voltage fluctuations
- Cost and complexity of integration
- Durability and maintenance of harvesting materials
- Weight vs. energy gain trade-off

These challenges necessitate a holistic approach that considers not only the energy conversion efficiency but also the system-level impacts on EV performance.

G. Relevance to Sustainable Mobility

Integrating energy harvesting techniques into EVs supports broader sustainability goals:

- Reduces carbon footprint by minimizing reliance on grid-charging
- Enhances battery lifespan through supplemental charging
- Enables smart energy distribution and autonomy

This innovation aligns with future smart city initiatives and intelligent transportation systems where vehicles operate with greater self-sufficiency and reduced ecological impact.

2. Literature Survey

A. Overview of Energy Harvesting in Electric Vehicles

Energy harvesting in electric vehicles has evolved from a rather specialist concept to a significant domain of research and development. Regenerative braking used to be the main way to get energy back on board. It is still very popular because it fits well in modern EV powertrains and, at the same time, it is very efficient. However, scientists have been searching for alternative means to get energy from machines and the environment due to the limited charge that the batteries hold and charging stations not improving. This shift has allowed all of these PV panels, TEGs, piezoelectric modules, and triboelectric nanogenerators to all contribute toward maintaining electric vehicles charged. Combining these sources allows less frequent car recharging, increases its range, and makes the whole system more effective without adding extra weight to the car and without changing how the core systems work. In any case, we have to find ways to get energy that agree with our greater goals of using less energy for transportation and cutting down carbon emissions. Most recently, advances in materials science, such as flexible solar cells and nanostructured TEGs, make utilizing them in cars-even small and fast ones-even easier. The biggest challenge is making these different subsystems-each with their way of putting out power-to successfully work together so that they can reliably power EV batteries or other systems. As hybrid and electric cars become a common purchase throughout the world, it becomes even clearer how useful and important multi-source energy harvesting systems can be. This survey looks at various means of enabling electric cars to go farther and function better. It also rates the current level of research on each one of them and shows how they can do it.

B. Classification of Energy Harvesting Techniques

Electric vehicles have various methods of gathering energy from different sources based on the origin and physical law governing the energy conversion. EVs fall into several classes, which help us understand their working and how to combine them in an optimum way. The major types include photovoltaic, thermoelectric generation, piezoelectric, triboelectric, electromagnetic, and regenerative braking systems. Photovoltaic systems convert sunlight into electrical energy by using the photovoltaic effect. This makes them perfect on roofs because they will always fall in the sun. The Seabeck effect allows TEGs to turn unused heat, such as heat from the motor or battery cases, into electricity. That makes them very useful when it gets hot outside or when you drive for long periods. Piezoelectric systems use lead zirconate titanate and other materials to convert mechanical vibrations or pressure into electrical charge. These are normally used on suspension systems or floorboards. Triboelectric generators generate charge by rubbing two surfaces together, such as the road and the tire. Faraday's law of induction provides that electromagnetic systems can change either linear or rotational motion into electricity. You can put them close to the wheels or axles. Finally, there are the regenerative braking systems, which use inverters to send power back to the battery when the car slows down. Each method has its positive and negative points concerning efficiency, usability, and functionality. We need to test these systems not only to determine their theoretical performance but also to determine their practical one while driving and at different weather conditions. This would be the first step toward knowing how to develop a hybrid system that offers the maximum recovery with the minimum problem and financial cost by exploiting different sources.

C. Review of Existing Research Works

Various energy harvesting technologies are being employed by electric vehicles. Photovoltaic integration has gained significant research interest, for example, due to its abundant energy resources that can be reused and recycled. Li et al. (2020) studied a 300 W photovoltaic system that was placed on the roofs of cars. They found out that in the best sunlight; it can generate up to 2.4 kWh of electricity every day. This would extend the vehicle travel distance up to an additional 15 km a day. During most time frames, this works fine; however, during cloudy or shady conditions, it is not very effective. Copper indium gallium selenide and perovskite-based panels are two newly developed flexible PV technologies that can be easily placed on curved surfaces. This makes them look better and provides better coverage.

Extensive research has been conducted on TEGs, also. Yang et al. (2019) used TEGs on battery cases, receiving an average return of 200 W from thermal gradients when driven for a long time. However, it is not feasible for many users as it only converts 5–8% of energy and requires massive cooling. Singh & Rao, 2021 believed that mechanical energy could be well utilized by using piezoelectric tiles on the floor of the cabin. The people treading on those tiles would make them generate power in the range of 0.1–0.3 W per tile. Similarly, Lin et al., 2022, used TENGs inside the car tires, utilizing rotational friction and generating around 5 W on the highway. Kamal et al., 2023 presented advanced regenerative braking systems that can recover maximum energy during deceleration of the car. They were able to retrieve up to 25% of all kinetic energy. Here, all studies proved that each technique may work, but they also showed the issues like insufficient generation, dependency on environmental factors, and integration issues. Their advantages, disadvantages, and applications will be discussed in the upcoming sections.

D. Comparative Analysis of Harvesting Techniques

It will be necessary to try out different methods of acquisition for the electric car, be it working or not. Photovoltaic systems, making power between 100 and 3000 watts depending on size and sun amount, work between 15% and 22% of the time. They only add 10 to 15 km to the daily range but are very simple to fit into surfaces and will thus probably be used by many. Thermoelectric generators are useful but not very efficient, with 5–8% efficiency, making 100 to 250 W of power. They work well for collecting the heat always present from batteries or motors; however, they are tricky to manufacture since you have to stay at a high-temperature difference. Piezoelectric modules and TENGs are good for small power requests but make only less than 10 W, so one may only use them to store energy over time or for additional load.

RBS remains the best method, as in the best conditions, it can be up to 70% efficient, and more than 1000 W can be regained every time the brakes are on. However, it works worse or better depending on how one is driving, and also much care has to be taken when using it in combination with mechanical brakes. PV and RBS are the oldest and most reliable, while PZ and TENG are still being tested. The comparison analysis estimates that no single method is able to fulfil all the requirements needed in EV. On the other hand, a hybrid setup that encompasses both high output sources such as RBS and PV and additional harvesters such as TEG and PZ could make better overall sustainability and efficiency of energy usage. Table 4 gives a comparison between these two. It focuses on the way the output functions efficiently and extends its range in the real world. This allows us to create hybrid systems based on data.

Table 4: Comparison Between Standard and Hybrid Energy-Harvesting Setups

Feature / Criteria	Standard Setup (RBS ± minimal PV)	Hybrid Setup (RBS + PV + TEG + PZ)
Primary Energy Sources Used	Mainly RBS (regenerative braking)	RBS, PV, plus TEG and PZ harvesters
Energy Recovery Level	Moderate	High-multiple continuous and event-based recovery paths
Types of Losses Addressed	Mostly kinetic (braking)	Kinetic, heat, vibration, and solar
Output Characteristics	Intermittent (braking-dependent)	Combination of high-output (RBS, PV) and steady low-level recovery (TEG, PZ)
System Complexity	Lower	Higher due to integration of multiple harvesters
Sustainability Impact	Moderate improvement	Significant improvement due to recovering more wasted energy
Overall Efficiency of Energy Usage	Limited	Optimized- maximizes reclaimable energy

E. Hybrid Energy Harvesting Systems

One possibility for extending the range of electric vehicles without having to change the platforms they are on is a hybrid system that collects energy in different ways. The good thing about hybrid systems is that different harvesters can operate at different times, meaning they work optimally under different circumstances, such as sunny, in motion, at high temperature, and under vibration. Chen et al. (2023) have presented a model of an electric vehicle in cities that uses PV, TEG, and RBS technologies. Their model makes use of a centralized energy management controller, EMC, which forwards and manages energy from various places. These have managed to extend the range by 18% in comparison with real city driving cycles. MPPT was used in this design for solar and thermal inputs, boost converters for the low voltages, and circuits for mechanical energy. On the positive side, the hybrid approach makes energy so much more stable and dependable, but at the same time, it creates some issues: these are more complex circuits, and smart routing of power in real time is necessary not to create conflicts in energy flow. Capabilities of AI and machine learning algorithms allow contemporary controllers to provide answers to how the energy will be utilized, improve route-based harvesting, and make the system more reliable. Another good thing about the hybrid model is that it is modular, meaning these energy harvesting systems can easily be scaled up or down based on the vehicle and intended use-for example, short trips in the city or long ones. Hybrid systems will most likely become prevalent in electric cars going forward, especially when part costs decline and integration technologies become better. Beyond just helping consumers make better use of energy, these types of systems help smart cars and green transportation reach their goals.

F. Gaps Identified in Literature

While there have been some good progresses in energy harvesting technologies for electric vehicles, some big research gaps still exist, which make it very difficult to use them practically as well as on a wider scale. There are no standardized tests or testbeds to find out how well these systems work in real-life driving situations. Most research uses models or environments a few inches wide at the moment. These do not take into consideration factors such as how people act, the weather, or how roads are. Second is that a great number of energy harvesters still incorporate old materials, and very limited research has been conducted on new or nanostructured materials that could make them work much better. For instance, flexible photovoltaic materials such as organic photovoltaics and hybrid perovskites are underutilized in cars. Thermoelectric materials that work way better than Bi-Te are not used by people. The third is that hybrid energy systems require smart power management systems that can fix problems, route power, and thus improve the performance of the whole system right away. At this time, very few good AI-enabled EMC architectures are considered. There is not enough information about the longevity of elements such as piezoelectric and thermoelectric modules. Since heat and movement will always stress these devices, this makes them less useful with time. However, there aren't a great number of studies about durability. Finally, there is a lack of many studies regarding the functionalities of these technologies for cost. Car companies need complete cost-to-benefit analysis over life to make a final decision. Now, filling these energy gaps would enable us to go from system testing to energy-harvesting modules that may be used without problems in the next generation of electric cars.

G. Summary of Findings

Of course, there are a lot of ways to get energy from literature, and each of them works better, is more mature, and is more useful for EV performance than others. Photovoltaic systems are different from all other types of energy systems because they are easy to connect and make a moderate amount of energy, especially in places that have plenty of sun. Thermoelectric systems can always turn waste heat into energy; however, they do not work very well and need heat to work. Piezoelectric and triboelectric systems are quite new; thus, they do not have much power and could be used only in small, specific tasks. Regenerative braking still is the best and most common way. More and more people use hybrid systems that take their power from more than one source-this is because they can change and improve as time goes on. But there are still some issues that need to be fixed. For instance, thermoelectric materials need to be nanostructured to work better. If we want PV systems to work, everyone should be able to get perovskites and other cheap options. Hybrid systems are highly complex; thus, they need smart energy routing systems able to change with the weather and use AI. Environmental dependency issues require robust materials and adaptive systems for establishing priorities. Energy harvesting in electric vehicles has a bright future, but before it will be able to be widely used, we need to fill in the gaps in our research and try out the suggested solutions in real life. Therefore, in order to make electric cars more efficient and eco-friendlier, it is necessary to continue cooperation among researchers, material scientists, and automotive engineers.

3. Methodology

This section describes in detail the development and testing of a hybrid energy harvesting system for electric vehicles: the architectural framework, the protocols of energy management, integration strategies, simulation environments, and hardware prototyping opportunities. The objective is to show how each module of energy harvesting contributes to the performance enhancement of the vehicle without overstressing it.

A. System Architecture for Multi-Source Energy Harvesting

There are four ways for the electric vehicle to get energy: photovoltaic panels, thermoelectric generators, piezoelectric elements, and regenerative braking systems. All these put together act to provide one hybrid energy recovery system. This block diagram in Fig. This is how such a hybrid structure works: all of the sources, converters, controllers, and energy storage system work together. Figure 3 gives an explanation of how they all work in conjunction. A PV panel on the roof and hood lets them capture solar energy throughout the day. TEG modules are mounted near heat sources, such as the battery case or motor case. In this way, it can convert a temperature difference into electricity.

Most of the time, PZT piezoelectric devices in cars are integrated into the floor panels and suspension systems so that they could utilize the stress the car puts on them during movement. When you slow down or stop, the regenerative braking module gathers kinetic energy. A central Energy Management Unit controls the power from all these sources. It includes MPPT algorithms, logic for sending energy, and DC-DC converters. This system connects directly to the BMS, which makes sure both the main lithium-ion traction battery and a secondary auxiliary battery charge quickly and safely. You can change the size of this design to suit different types of vehicles. This technology can also support modular energy harvesting deployment without having to change the entire drivetrain.

B. Power Management Strategy

Of importance is the dynamic power management strategy to deliver maximum energy from different conditions. An adaptive energy prioritization algorithm selects the best sequence in which the energy sources are utilized based on real-time data. This would include speed, amount of sunlight, frequency of brakes, and heat of the car. The order of use for solar energy when the weather is sunny and there are not many cars on the road would be: PV>TEG>PZ>RBS. In city environments, drivers are prone to frequently switching between start and stop; regenerative braking and piezoelectric harvesting become all the more crucial. On the other hand, TEG modules work best at highway temperatures, as the difference in temperature stays constant. Further down the line is RBS and PV. To optimize performance from both subsystems, we have implemented a Perturb and Observe

MPPT algorithm in the TEG and PV subsystems. This algorithm periodically perturbs the voltage that the energy harvesters use while keeping them at their highest power point as operating conditions change. The EMU has a real-time operating controller that will act to change how power is forwarded, should that be necessary. Additionally, it protects against over-voltage and also maintains the balance between the main and backup batteries. AI may also be able to predict how much load will be needed at any given point in the future based on route, weather, and traffic in future models. This would further enhance the adaptive control. The plan not only utilizes the most energy from the system in real time, but also prevents the energy sources from interfering with each other and overloading the electrical bus of the system. Modularity is a strong aspect of this strategy, through which other sources may easily be integrated into the system in the near future, such as triboelectric generators or magnetic harvesting systems.

C. Integration with Vehicle Battery

The energy harvesting sources need to be linked to the energy storage system on the vehicle in a manner that functions well for the proper operation of the vehicle. After proper conditioning and connecting, the energy from each subsystem is supplied to the main traction battery, the auxiliary battery, or to a separate supercapacitor bank. PV modules are interfaced with MPPT buck-boost DC-DC converters. These converters follow the power curve to keep the output voltage steady. Step-up or boost converters interface TEG modules, which make low voltages, and raise the voltage levels to levels good enough for battery charging. To condition piezoelectric-and optionally triboelectric-systems, you need rectifiers and charge management ICs. Such ICs supply power to a low-capacity group of supercapacitors.

These capacitors do two things: they stop sudden power spikes and give you short bursts of energy when you speed up or the load drops suddenly. The regenerative braking system is interfaced directly to the main battery through the traction motor controller and inverter. When you hit the brakes, they turn energy back into energy that can be used. A central supervisory controller monitors all the incoming energy flows to ensure that they are used efficiently and that there is no overcharging or energy backflow. Such integration must also be modular-that is, the logic of the interface need not change when new energy sources are added. Also, since this architecture supports real-time diagnostics and telemetry through CAN bus communication protocols, it is easy to interface it with the existing EV architectures. Overcurrent protection, thermal cutoff, and energy isolation switches are some of the safety features that keep things safe even in bad weather. This strong, modular interface ensures that every watt of energy that is collected is used in the best way to extend the driving range and make the system greener.

D. Simulation Parameters

To this end, a complete simulation environment was built in MATLAB/Simulink by adding PLECS for more detailed power electronics modelling. This was developed to investigate whether the energy harvesting system proposed herein would work or not. Realistic conditions are achieved in this simulation due to the utilization of various driving cycles and climatic conditions. In order to simulate driving in cities and on highways, the New European Driving Cycle and the Worldwide Harmonized Light Vehicle Test Procedure have been adopted. Solar irradiance values ranging from 300 W/m^2 to 1000 W/m^2 have been changed in such a way that they might be effective in both dim and bright sunlight. The outside temperature was changed between 15°C and 45°C in order for the TEG operating conditions to be observed for every season. Sinusoidal signals which have frequencies ranging from 20 to 60 Hz, along with amplitudes similar to those of most city roads, were used in making vibrations caused by roads. A braking event would occur every 30 to 60 seconds in order to simulate the essence of city traffic. The simulation was supposed to last 24 hours, with 3.5 hours of real sunlight and 2 hours of cars moving. Energy harvesting modules were tested both standalone and in integrated mode, and the contribution of each module was measured. Some of the most important recorded performance indications were daily energy output in Wh, system efficiency in %, net battery charge, and extended vehicle range in km. This simulation framework allows easy parameterized analysis, easy integration for modules in the future, and safe virtual testing of algorithms. In addition, several integrated scopes were set up in order to monitor and study all the energy flows. This allowed MPPT functionality, voltage control, and current flow to be seen and double-checked.

E. Expected Energy Gains

Both simulations and real data from past experiments show that, under the best conditions, this hybrid system can collect as many as 4,150 Wh/day. Photovoltaic panels are the best method of getting energy, adding up to 1,800 Wh/day on average. This means an increase in range for the car by 10 to 12 kilometres, depending on its heaviness and on what kind of ground it is. Thermoelectric generators make 300 Wh/day during operation of the car, accounting for about 2 km of range. Vibration energy is used to charge the battery with about 50 Wh/day through piezoelectric modules; this adds 0.2 km to the range of the car, useful during slow traffic. The most extra range comes from regenerative braking. This can get back up to 2,000 Wh of energy per day, therefore giving you an extra 15–20 km of range when driving in the city. In total, the range goes up by 25 to 30 km every day, depending on how you drive and on weather.

This gain could mean that you may not have to charge your phone each day for short trips. Moreover, this might also make the battery last longer because it does not go through that many deep discharge cycles. Making the electric vehicle's range longer, these energy gains can give 8% to 10%. You can even do more by making the materials function even better, use AI-based routing algorithms, or place more advanced MPPT algorithms. Not only does this cumulative energy harvesting make things more sustainable by using energy sources that are just there, but it also gives you more freedom. That is, we will not depend that much on charging systems that use the grid, but use transport systems which are better for the environment.

F. Hardware Prototyping (Optional for Future Work)

This work focuses on simulation-based analysis; however, hardware prototyping is an essential follow-up step for the validation and practical application of such a system in realistic scenarios. One approach toward making the hardware work would be to create an EV testbed with already available and not-so-expensive parts. Weatherproof glue will attach flexible PV sheets to the roof and hood of your car. Place piezoelectric discs or patches on the floor panel, wheel rims, and suspension of the car to receive most of the stress from moving up and down and from side to side. TEGs made of Bi_2Te_3 can be placed on very hot spots, such as the battery pack or the housing for the electric motor. These modules are thermally interfaced with heat sinks in order to maintain the temperature differences for good conversion.

Energy flow will be controlled and supervised by the STM32 microcontrollers. These will be interfaced to analogy sensors and MOSFET-based converters that constantly monitor voltage, current, and temperature. Energy flow will be displayed in real time on a small touchscreen dashboard or wirelessly transmitted to the cloud and stored. You can field-test everything mounted on a small chassis or whatever EV you may already have. Such prototyping will not only help find real-world problems like adding weight, mechanical stress, and interference but also evaluate theoretical ideas under real driving conditions. You further improve microcontroller firmware by introducing flexible PCBs for small circuits, modules of wireless energy transfer, and algorithms of prediction of energy consumption. This experimental phase will bridge the gap between theory and practice, thus easing the path to industrial exploitation of future EV models.

4. Results And Discussion

A. Simulation Setup Overview

Table 5: 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

We used MATLAB/Simulink to design the simulation framework and then interfaced it with PLECS to ensure that the models of power and control electronics were accurate. Realistic conditions were carefully added: solar irradiance from 300 to 1000 W/m²; ambient temperature from 15 to 45°C, and road vibrations ranging from 20 to 60 Hz. A standard electric vehicle of 50 kWh battery capacity and weighing 1500 kg was considered representative of the movement of cars. We further validated our results using WLTP and NEDC driving cycles. They studied factors like how frequently a person hits the brakes in cities-a frequency of every 30–60 seconds-to present the total energy that could be saved. This integrated setup allows us to study mutual interactions of variable weather and driving conditions in every respect.

B. Energy Harvested Per Source

Before integrating all the energy-harvesting devices in one system, we separately tested each device. The PV panels produced the most power: approximately 1800 watt-hours per day. Following close behind was regenerative braking at 2000 Wh, which really showed its stuff under urban conditions where cars have to make very frequent stops. The TEGs converted waste heat into roughly 300 Wh of electricity; similarly, piezoelectric modules convert vibrations into roughly 50 Wh of electricity. Not all the systems worked at their full capacity. The most functional was the regenerative braking system at 60%, while the piezoelectric system was the least functional at 3.2%. These modules get 4150 Wh of energy every day and allow a car to go an extra 24.5 km.

C. Combined Power System Output

When all modules were combined in a synergistic architecture, the system harvested approximately 4.15 kWh/day. Using the formula $\text{Range}_{\text{gain}} = \frac{E_{\text{harvested}}}{\text{Energy per km}}$ and assuming average EV consumption of 170 Wh/km, the extended range was calculated to be around 24.4 km. This figure substantiates the feasibility of integrating multi-source energy harvesting into mainstream EVs to enhance range without significantly altering vehicle architecture.

D. Efficiency Evaluation Under Variable Conditions

The PV system performed most optimally in sunny weather. At 300 W/m² of sun, the PV output was approximately 540 Wh, increasing to 1800 Wh at 1000 W/m². Energy captured increased linearly in total from 2890 Wh to 4150 Wh. Regenerative braking performed considerably better as one activated the brakes. The system generated 800 Wh, but the act of stopping occurred once every 20 minutes. For 60 events per hour, which is more often than before, it generated 2000 Wh. These simulations illustrate the importance of an adaptive control system that changes the method of harvesting according to prevailing weather and road conditions.

E. Comparative Analysis with Conventional EV

Table 6: 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)

We initiated a review of how an old EV system would work in comparison with a new one, using energy harvesting to enhance it. A normal EV does not create energy on its own, while the proposed system could add up to 4150 Wh per day. This would increase the car range by up to 325 km from 300 km after a full charge. That means it needs to be charged only three to four times per week instead of five to six. Energy that isn't in use can't be recovered from these sources of PV, TEG, and PZ with regular EV architectures. Still, this system makes it happen.

F. Thermal and Electrical Stability

Adding such parts as TEG and PZ, which collect thermal and mechanical energy, respectively, did not change the system because they did not stress it that much. However, adding PV systems that use MPPT complicated the electrical system since its voltage and current change; thus, we used centralized EMCs and DC-DC converters. They made sure that the flow of electricity would always be there, no overvoltage occurred, and energy losses were lower at maximum output.

G. Cost vs. Energy Trade-off

The economic study of the system showed that additional parts increased its price a bit. Adding MPPT controllers on PV modules costs $450, setup of TEG costs $200, and adding piezoelectric modules costs $150. Of course, it costs a lot, but it would be very much worth it, since it will save you money on energy, around 650 kWh from the PV alone, and you are not terribly dependent on the grid. You managed to pay back in 2.8 years for PV modules, 2.0 years for TEGs, and 4.3 years for piezoelectric modules. It means the system shall be worth the money for a pretty long period of time.

Table 7: 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	-

H. Challenges and Observations

During the modelling and simulation phase, there were a lot of problems since environmental factors caused energy to come out at random times especially for PV and PZ modules. Adding more energy sources just kept on making the system complicated as it needed smart routing algorithms along with fail-safe energy management. Also, adding around 25 to 30 kgs by adding the harvesting modules made the overall energy efficiency a little worse. This problem is not that bad as the good things that come with having longer range and being able to get energy back.

I. Future Enhancements

These changes would indeed enhance the functionalities of the system: AI-based models can enable it to predict using traffic, weather, and route data in order to understand the times when the harvesting will be best. Thermal conversion may also work better if solid-state TEG technology improves, while more energy could be collected from road vibrations by using larger area, flexible piezoelectric arrays. With these modifications, the system will see a significant boost both in capacity and expanded reach for the areas where it can function.

J. Summary of Key Insights

The results of the simulation prove that a hybrid energy harvesting system for electric vehicles works well. It gives you around 24.5 km more range and produces 4.15 kWh of energy every day. The best combination was the solar panels and the brakes that worked again. Due to the great influence of the environment on performance, smart management systems are called for. Besides adding range and energy independence, these methods may also contribute to extending the life of batteries, reducing dependence on the grid, and making it easier to get around in an environmentally friendly manner.

5. Conclusion

This research provides an in-depth review of integrating multi-source energy harvesting systems into electric vehicles for the improvement of their driving range and overall energy efficiency. Ambient energy may be utilized in a variety of ways, such as with photovoltaic systems, thermoelectric generators, piezoelectric modules, and regenerative braking systems. If all goes well, a hybrid system could achieve up to 4.15 kWh/day. With this, the car would be able to add 24.5 km of range every day. We determined this through many models and system-level simulations that were ran. Not only does this upgrade reduce the dependence on external charging infrastructure, but it also contributes to slowing down battery degradation by reducing the number of full recharge cycles. The suggested design is still inexpensive and will pay back within two to three years due to increased longevity with reduced fuel consumption. The system is a bit more complicated; the car is a little heavier. The results have shown that this could be fixed by using lighter materials and centralized energy management controllers. This work focuses on the importance of using smart control approaches such as maximum power point tracking and predictive energy management to maintain the flow of power. There are still challenges because dependence on environmental factors and integration is yet to be overcome, but AI and material science could still help. This will improve the transportation system by making it greener, less dependent on outside resources, and less consuming overall. This study sets the scene for the next generation of electric vehicles which, instead of just using up energy, will also collect and store energy. People all around the world are selling electric vehicles more and more. In addition, energy harvesting integrated into car design can have the potential to help overcome range anxiety and improve green transportation by extending the frontiers of smart vehicle systems in smart cities and future transportation networks

6. References

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