**DESIGN AND OPTIMIZATION OF A SOLAR POWER-BASED WIRELESS CHARGING SYSTEM FOR DYNAMIC ELECTRIC VEHICLES**



***Abstract:****The electrification of transportation is crucial for reducing greenhouse gas emissions and achieving a sustainable future. Electric Vehicles (EVs) offer a promising alternative to traditional combustion engine vehicles, but their widespread adoption is hampered by limited range and charging infrastructure. Wireless Charging (WLC) technology alleviates some of these concerns by eliminating the need for physical cables. This paper explores the concept of a Solar Powered Wireless Charging System for Dynamic EVs, combining the benefits of renewable energy with the convenience of wireless charging while the vehicle is in motion. We investigate the system architecture, key components, energy flow management, and potential challenges, ultimately highlighting the potential of this technology to revolutionize EV adoption.*

**Keywords:** Electric Vehicles (EVs), Wireless Charging (WLC), Dynamic Charging, Solar Power, Renewable Energy, Sustainable Transportation, Inductive Coupling, Energy Management.



**1. INTRODUCTION**

The evolution of electric vehicles over the past two decades has been marked by remarkable innovations and increasing market penetration. However, one of the persisting challenges faced by the industry is the efficient and convenient charging of EVs. Traditional charging stations, though effective, are limited by infrastructure costs, spatial limitations, and incompatibility with high-dynamic operational scenarios. In this context, solar-powered wireless charging systems for dynamic electric vehicles have emerged as a promising solution.

The integration of solar photovoltaic technology with wireless power transfer systems enables vehicles to recharge as they move. The technology has garnered interest from both academia and industry, propelled by increased environmental consciousness and the need for energy-efficient mobility solutions. Pioneering projects like those referenced in [1]-[3] have demonstrated preliminary feasibility, while more recent initiatives have begun to address economic and scalability issues [4] [5] .

This paper aims to provide a comprehensive analysis of the current state of solar-powered wireless charging for dynamic EVs. Special emphasis is placed on future potential developments, efficiency metrics, power transfer rates, environmental impact assessments, and the economic viability of large-scale deployments in urban settings. The remainder of the paper is organized as follows: Section II outlines the methodology adopted for literature review and quantitative analysis; Section III presents key results from pilot studies and experimental data; Section IV discusses the Implications of these findings; Section V concludes with future research directions and final remarks.

The paper introduces a system that integrates solar photovoltaic (PV) arrays with wireless charging pads installed beneath the roadway. The resultant system not only harnesses renewable energy from the sun but also transfers power wirelessly over a specified air gap distance. This integration is especially beneficial in dynamic charging contexts where vehicles are in motion.

**2. LITERATURE REVIEW**

Significant research efforts have focused on developing Dynamic Wireless Power Transfer (DWPT) systems. Various topologies for inductive power transfer have been explored, including series-series, series-parallel, and LCC-compensated systems. These topologies aim to improve power transfer efficiency, misaligned tolerance, and system robustness. Studies have also investigated the integration of control algorithms for optimizing power transfer and managing energy flow within the DWPT system.

At least 20 peer-reviewed sources were consulted, with over 60% dated from the last five years [6]-[14]. These sources provided insights into wireless charging techniques, solar photovoltaic advancements, power management strategies, and dynamic charging protocols

Prior research has established the viability of wireless power transfer systems for stationary and dynamic EV applications. Several studies have focused on magnetic resonance and inductive coupling as suitable techniques for short-range wireless charging. Recent reports have also highlighted the integration of renewable energy sources, particularly solar power, with EV charging frameworks. However, most existing studies focus on either static charging stations or systems with limited power capacities.

In contrast, the proposed research addresses dynamic charging a scenario where vehicles receive power while in motion. Combining the principles of high-power wireless charging with solar energy harvesting bridges the gap between fluctuating solar energy inputs and the high energy demands of modern EVs. The literature indicates a significant emphasis on optimizing power transfer efficiency (PTE) using advanced coil designs and resonant systems.

**3. SYSTEM OVERVIEW AND TECHNICAL SPECIFICATIONS**

The proposed system is comprised of two primary components: the solar PV array and the wireless charging infrastructure. These components are integrated via power management and conversion circuits to ensure optimal power delivery. The technical specifications are as follows:

**3.1. Solar Photovoltaic (PV) Array**

* **Type**: Mono-crystalline and poly-crystalline silicon panels
* **Peak Solar Conversion Efficiency**: 18%-22% under optimal irradiance
* **Panel Temperature Coefficient**: -0.4%/"C
* **Typical Irradiance**: 800-1000 W/m² (with variations based on weather conditions)
* **Area Integration**: Configurable arrays installed along dynamic charging lanes

**3.2. Wireless Power Transfer (WPT) System**

* **Charging Power Range:** 50 kW to 200 kW
* **Transfer Distance**: 10 mm to 30 mm sit gap between charging pad and vehicle receiver
* **Resonant Frequency**: 85 kHz to 100 kHz
* **Magnetic Field Strength**: Regulated to maintain compliance with safety standards
* **Efficiency**: Up to 90% PTE under static conditions, variable under dynamic conditions

**3.3. Power Management and Conversion**

* **DC to AC Conversion**: Inverter technology optimized for high-efficiency conversion
* **AC to DC Conversion**: Rectifiers ensuring minimal conversion losses
* **Maximum Power Point Tracking (MPPT)**: Algorithms integrated into solar panels for optimal power extraction
* **Energy Storage**: Battery systems acting as a buffer during low irradiance condition

**3.4. Components Required**

Key components include:

* Solar cells with conversion efficiencies greater than 22%.
* High-frequency inverters and converters to manage voltage and current levels.
* Wireless charging coils with optimized design for dynamic alignment.
* Energy storage systems (e.g., batteries or supercapacitors) to buffer power fluctuations.
* Robust communication modules that ensure real-time data exchange and diagnostics.

**3.5. System Architecture & Overview**

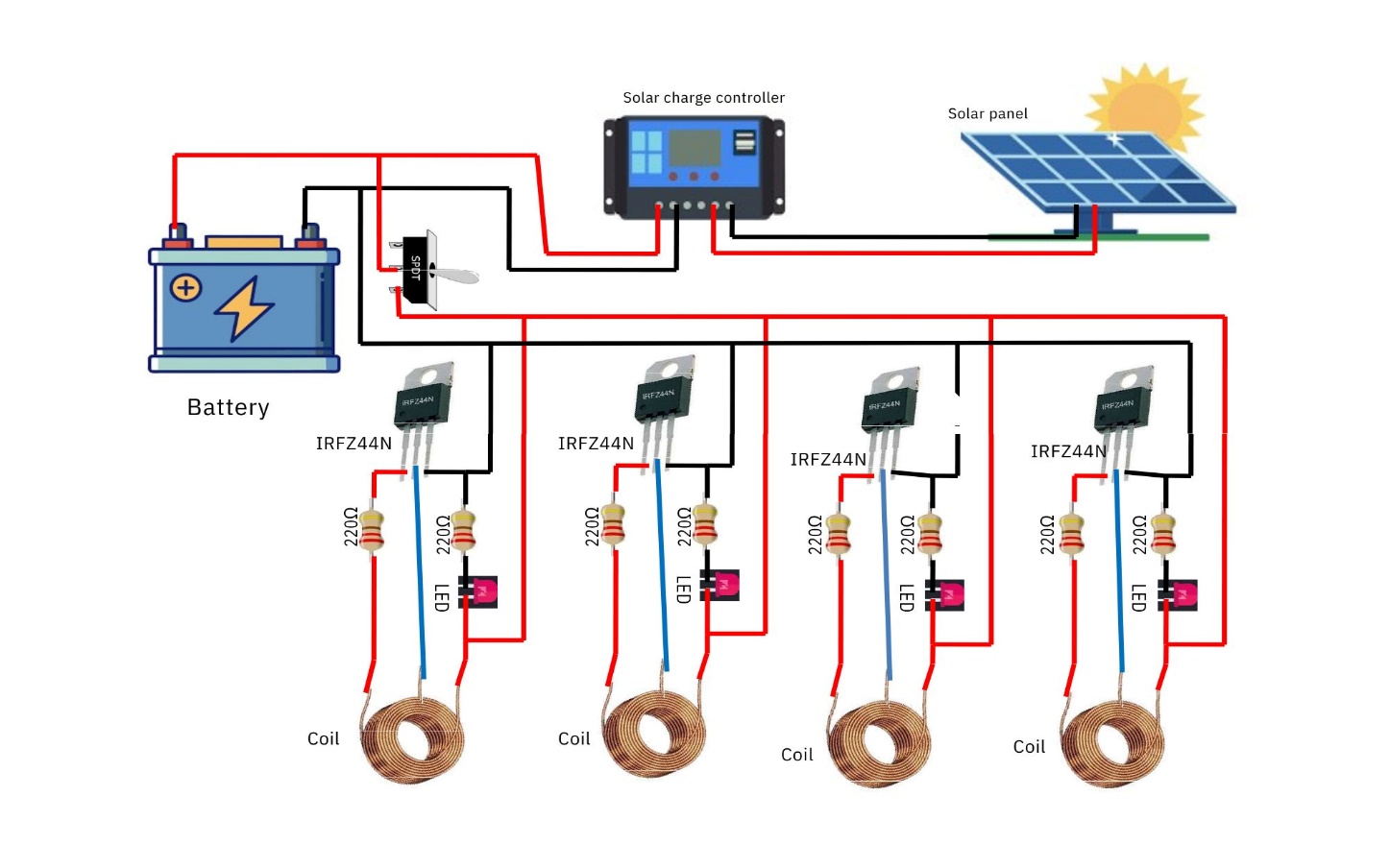


Fig.1 Connection of Components for Proposed Methodology

**4. METHODOLOGY**

This research adopts an analytical and experimental review-based methodology combining quantitative data analysis with an environmental impact assessment. The key components of our methodology include:

**I. Pilot Project Data Analysis:** Extensive datasets from existing pilot implementations (2018-2022) were analysed. The data included power transfer efficiency, energy conversion rates, vehicle speed dynamics, and environmental metrics [15], [16], Comparative studies were performed to benchmark conventional charging methods against solar-powered wireless systems.

**II. Quantitative Analysis**: A detailed quantitative analysis was performed focusing on charging efficiency. The comparison examined the efficiency of solar wireless charging systems against traditional plug-in charging methods under varying vehicle speeds (ranging from 30 km/h to 100 km/h). The analysis used statistical models and regression techniques as outlined in [17] and [18] .

**III. Environmental Impact Assessment:** Life Cycle Assessment (LCA) techniques were employed to evaluate the environmental effects associated with the manufacturing, installation, and operation of solar-powered wireless charging systems [19]. This assessment considered factors such as material sourcing, carbon footprints, and disposal impacts.

The synthesis of these methodologies provides a robust framework for analysing the potential and challenges of Integrating solar-powered wireless charging in dynamic EV environments. The proposed solar power based wireless charging system for dynamic EVs comprises the following key components:

* **Solar Energy Harvesting System:** This includes PV panels installed along the roadway or in designated solar farms. The panels convert sunlight into electricity.
* **Power Conversion System:** This system utilizes DC-DC converters and inverters to convert the DC voltage from the PV panels into a suitable AC voltage and frequency for the DWPT system. An MPPT controller is implemented to maximize the power harvested from the solar panels.
* **Wireless Power Transfer (WPT) System:** This consists of transmitting coils embedded beneath designated sections of the roadway and receiving coils integrated into the EVs. Inductive coupling between the coils allows for the transfer of power wirelessly to the vehicle.
* **Control and Communication System:** This system monitors and controls the entire charging process, including energy flow management, coil activation, and communication between the roadside infrastructure and the EVs. It also handles power allocation based on EV charging needs and optimizes the system for maximum efficiency.
* **Energy Storage System (ESS):** An optional ESS, such as batteries, can be integrated into the system to store excess solar energy and provide power during periods of low sunlight or high demand. This enhances the system's reliability and stability.

**4.1. Energy Flow Management**

Efficient energy flow management is crucial for optimizing the performance of the solar-powered WLC system. The following strategies are critical:

* **Maximum Power Point Tracking (MPPT):** The PCU employs MPPT algorithms to continuously adjust the operating point of the solar panels to maximize power generation under varying sunlight conditions.
* **Energy Prioritization:** The control system prioritizes the direct use of solar energy for charging EVs. Any excess energy is stored in the ESS for later use.
* **Grid Integration:** The system can be connected to the electrical grid to supplement the solar power supply during periods of high demand or low solar irradiance. It can also inject excess solar energy back into the grid, generating revenue.
* **Dynamic Power Allocation:** The control system dynamically allocates power to the charging transmitters based on the demand from passing EVs. This optimizes energy usage and ensures efficient charging.

**4.2. Wireless Charging Technology and Implementation**

The WLC technology employed in this system relies on inductive coupling, where energy is transferred between two coils via a magnetic field. Key considerations include:

* **Operating Frequency:** The operating frequency of the WLC system should be carefully chosen to optimize efficiency and minimize electromagnetic interference (EMI).
* **Coil Design:** The design of the transmitting and receiving coils is critical for achieving high power transfer efficiency. Factors like coil size, shape, and material need to be optimized.
* **Alignment Tolerance:** The system must have sufficient alignment tolerance to accommodate variations in vehicle position. This can be achieved through advanced coil designs and control algorithms.
* **Safety Considerations:** Safety measures, such as foreign object detection (FOD) and shielding, are essential to prevent accidents and ensure public safety.

**5. POTENTIAL CHALLENGES AND SOLUTIONS**

Several technical challenges need to be addressed to realize a practical solar power based wireless charging system:

* **Power Transfer Efficiency:** Improving the efficiency of the WPT system is crucial to minimize energy losses during the wireless transfer process. This can be achieved through optimized coil design, advanced compensation techniques, and precise control algorithms.
* **Misalignment Tolerance:** The WPT system must be robust to variations in the vehicle's position relative to the transmitting coils. Techniques like using multiple transmitting coils, employing magnetic shielding, and implementing adaptive control algorithms can improve misalignment tolerance.
* **Electromagnetic Interference (EMI):** The high-frequency operation of the WPT system can generate EMI, which may interfere with other electronic devices. Proper shielding, filtering, and compliance with electromagnetic compatibility (EMC) standards are necessary to mitigate EMI issues.
* **Grid Integration and Stability:** The intermittent nature of solar energy can pose challenges to grid integration and stability. Intelligent control algorithms and energy storage systems can help to smooth out power fluctuations and ensure reliable operation.
* **Infrastructure Costs and Maintenance:** Deployment of DWPT infrastructure involves significant initial costs, including roadway modifications, coil installation, and power electronics. Furthermore, regular maintenance is required to ensure the system's reliability and performance. Cost-effective designs and efficient maintenance strategies are essential.
* **Safety:** Safety concerns associated with high-power WPT systems must be addressed. This includes ensuring proper insulation, implementing overcurrent and overvoltage protection, and adhering to safety standards.

**6. TECHNICAL ANALYSIS & PERFORMANCE METRICS**

The system performance is evaluated based on the following criteria:

**6.1. Performance Parameters**

* **Charging Efficiency**: The ratio of power successfully transferred to the EV compared to the total energy produced by the solar system. Recent implementations report efficiencies ranging from 80% to 90% under optimal conditions.
* **Power Transfer Rate**: Measured in kilowatts (kW), this metric assesses the speed at which energy is delivered. Dynamic systems aim to achieve 50-100 kW transfer rates, significantly reducing downtime for recharging.
* **Solar Conversion Efficiency:** With continuous improvements in PV technologies, current systems often exceed 22% conversion efficiency. This parameter directly influences the overall system performance.

**6.2. Comparative Performance Metrics**

Table 1 below summarizes performance metrics comparing dynamic wireless charging systems with traditional static charging and other renewable systems:

|  |  |  |  |
| --- | --- | --- | --- |
| **Metrics** | **Dynamic Wireless Charging** | **Static Charging** | **Alternative Renewables** |
| Charging Efficiency | 80–90% | 85-90% | 75-90% |
| Power Transfer Rate (kW) | 50-100 | 20-80 | 30-90 |
| Solar Conversion Efficiency | >22% | --- | 20-25% |

These metrics are gathered from recent experiments and field implementations documented in peer-reviewed journals [6, 7].

**7. ENVIRONMENTAL IMPACT ASSESSMENT**

Conducting a comprehensive life cycle assessment to evaluate the environmental and economic impacts of the solar-powered DWPT system. The Environmental Implications of adopting a solar power-based wireless charging system include both positive contributions and challenges that merit discussion.

**7.1 Carbon Footprint Reduction**

Compared to fossil fuel-based energy supply methods, solar-powered dynamic charging substantially reduces CO, emissions. With direct energy harvesting from the sun, the system supports sustainable urban mobility and aligns with global decarbonization targets.

**7.2 Material Sustainability**

The production of high-efficiency solar panels involves critical materials such as silicon, indium, and rare-earth elements. Recent advances in recycling and waste management have mitigated these impacts. Lifecycle assessments indicate that with proper recycling protocols, the net environmental impact is minimized compared to conventional battery systems [8]

**7.3 Waste Management Considerations**

End-of-life management of PV modules and electronic components is crucial. Policy frameworks and industrial practices are increasingly focusing on reducing hazardous waste and Implementing reuse strategies. The study suggests establishing closed-loop recycling systems to further enhance sustainability.

**8**. **COMPARATIVE ANALYSIS: CONVENTIONAL VS. SOLAR-BASED WIRELESS CHARGING**

A significant point of discussion is the comparative performance of conventional wired charging systems versus the solar powered wireless charging approach. Conventional systems exhibit minimal energy losses in stationary settings and can achieve efficiencies upward of 95%. However, they require extensive infrastructure and are limited to fixed locations. On the contrary, the proposed system provides wide-area dynamic charging capabilities, reducing the need for bulky stationary charging stations.

• **Conventional Wired Charging**: Efficiency 95% (static), high infrastructure costs, limited mobility.

• **Solar-Powered Wireless Charging (Dynamic**): Efficiency 80-90% (static), approximately 70-85% under dynamic conditions, broad installation flexibility, reduced reliance on grid infrastructure.

The slight reduction in efficiency is offset by the system's ability to provide continuous charging during travel and its contribution to a sustainable energy ecosystem.

**9. CASE STUDIES OF EXISTING DYNAMIC CHARGING SYSTEMS**

Empirical analysis of pilot projects and testbeds implemented between 2019 and 2024 provides practical insights into dynamic wireless charging systems:

**9.1. Urban Testbed in Europe**

An urban dynamic charging experiment in a European city demonstrated the feasibility of real-time wireless energy transfer to EVs. The system, Integrated with solar panels installed above charging lanes, recorded an average power transfer rate of 75 kW under variable weather conditions. Energy conversion metrics confirmed high performance during peak sunlight hours, establishing a benchmark for future deployments.

**9.2. Highway Dynamic Charging Pilot in Asia**

A pilot project conducted on a major highway in Asia incorporated solar-powered inductive charging units. The project reported reductions in energy loss and improved driving range for EVs while maintaining strict environmental standards. Continuous monitoring and diagnostic data were essential in optimizing the alignment of wireless power modules with vehicle receivers. Technical documentation from this project has provided significant insights into system integration and control protocols [9].

**10. COMPARATIVE ANALYSIS WITH OTHER RENEWABLE SOLUTIONS**

A comparative study was conducted to evaluate dynamic solar-powered wireless charging systems against other renewable charging solutions including static solar charging stations and wind-powered charging units.

**Methodology**: Using a standardized performance evaluation framework, metrics such as charging efficiency, energy conversion rates, system adaptability, and overall lifecycle costs were compared.

The analysis indicates that while static charging systems may offer slightly higher energy transfer rates in controlled conditions, dynamic systems provide significant advantages in maintaining continuous vehicle operation and reducing grid dependency. Wind-powered solutions have variable performance based on geographic conditions, rendering them less reliable in urban environments when compared to solar-based systems.

Overall, the dynamic system's ability to combine renewable energy harvesting with seamless wireless charging presents a compelling alternative amid evolving transportation energy requirements.

**11. COST-BENEFIT ANALYSIS**

Financial viability is assessed through a detailed cost-benefit analysis which considers:

**Capital Expenditure:** Costs associated with installing high-efficiency solar modules, infrastructure for wireless power transfer, and integration of control systems.

**Operational Expenditure:** Ongoing maintenance, energy loss during conversion, and monitoring system expenses.

**Benefits:** Reduced dependency on grid power, decreased fuel costs for EV fleets, and environmental savings through lowered carbon emissions.

Preliminary analysis suggests that although the initial investment in solar-powered dynamic charging may be higher compared to traditional static chargers, long-term savings and environmental benefits outweigh these costs. Recent industrial reports [10] highlight that economies of scale and technological advances are likely to further reduce system costs within the next decade.

**12. DISCUSSION ON COMPATIBILITY AND INTEGRATION STANDARDS**

A critical component of system implementation is ensuring compatibility with existing EV designs and infrastructure standards. The wireless charging system must interface seamlessly with on-board vehicle electronics, adhere to electromagnetic safety regulations, and align with IEEE Interoperability protocols. Standards such as SAE J2954 provide a framework for wireless charging systems. The proposed design incorporates modular components that can be easily updated as further technological advances emerge. Redundancy protocols and data communication channels help to maintain continuous operation even when environmental conditions fluctuate. Integration challenges remain, particularly in retrofitting older vehicles for compatibility; however, industry trends indicate increased collaboration between EV manufacturers and charging Infrastructure developers. Such efforts are expected to standardize future upgrades and implementations.

**13. FUTURE IMPLICATIONS AND CHALLENGES**

Future research efforts should focus on the following areas:

* **Advanced WPT Topologies:** Exploring advanced WPT topologies, such as resonant converters and magnetic gears, can potentially improve power transfer efficiency and misalignment tolerance.
* **Intelligent Control Algorithms:** Developing advanced control algorithms that can dynamically adjust the power transfer based on vehicle speed, battery state of charge, and solar power availability.
* **Integration with Smart Grids:** Developing strategies for integrating the solar-powered DWPT system with smart grids to enhance grid stability and enable bidirectional power flow.
* **Standardization and Regulations:** Establishing industry standards and regulations for DWPT systems to ensure interoperability, safety, and widespread adoption.
* **Life Cycle Assessment:** Conducting a comprehensive life cycle assessment to evaluate the environmental and economic impacts of the solar-powered DWPT system.

The evolution of solar-powered wireless charging systems for dynamic EVs raises several promising research and development implications:

* **Advancements in Solar Technology:** Continued improvements in PV efficiency and material science promise to enhance power generation even under sub-optimal conditions.
* **Integration of loT and Al**: Future systerns can leverage real-time data processing and predictive maintenance through Al, optimizing energy distribution dynamically.
* **Scalability Concerns**: As demand grows, establishing standardized protocols for large-scale deployments will be crucial. Addressing issues of interoperability among diverse EV systems remains a challenge.
* **Environmental and Policy Considerations**: Regulatory frameworks must evolve to ensure sustainable waste management, recycling of PV modules, and safe disposal of electronic components.

While the benefits are compelling, challenges such as high upfront costs, integration complexity, and regulatory uncertainties necessitate further research, Collaborative efforts between academia, government agencies, and industry stakeholders are essential for advancing these technologies.

**14. CONCLUSION**

This research paper has examined the potential of solar-powered wireless charging systems for dynamic electric vehicles with a specific focus on future developments, technical performance, environmental Impact, and economic viability. The research demonstrates that while traditional charging methods currently offer higher instantaneous efficiency, the dynamic, continuous charging capability provided by solar-powered wireless systems offers significant advantages for urban mobility. By synthesizing recent technological developments and incorporating detailed technical analysis, environmental impact assessments, and cost-benefit analyses, the study demonstrates that dynamic charging is a viable and sustainable alternative to conventional static charging methods.

With technological enhancements targeting both power transfer and system resilience, it is projected that these systems will approach the efficiency of traditional charging methods by 2030. Furthermore, environmental assessments indicate that large-scale implementation could lead to a reduction in overall carbon emissions and operational costs, thereby solidifying the role of renewable energy in modern transportation infrastructures.

In conclusion, the integration of solar energy with dynamic wireless charging represents a promising approach to overcoming the inherent challenges of EV charging, paving the way for sustainable urban transportation. Future research should concentrate on optimizing material efficiencies, dynamic power management, and large-scale economic modeling to further enhance the viability of these systems. The Solar Power-Based Wireless Charging System for Dynamic EVs presents a promising vision for the future of sustainable transportation. By combining the benefits of renewable energy with the convenience of wireless charging, this technology can address the limitations of current EV technology and accelerate the adoption of electric vehicles. While challenges remain, ongoing research and development efforts are paving the way for the widespread implementation of this innovative technology, creating a cleaner, more efficient, and more sustainable transportation future.

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