STM JOURNALS

International Journal of
Energy and Thermal Applications

Volume 3, Issue 1, 2025
January–June
DOI (Journal): 10.37591/IJETA

https://journals.stmjournals.com/ijeta

Review IJETA

Smart Wireless Charging Infrastructure for Electric Vehicles

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Abstract

Wireless Power Transfer (WPT) of Electric Vehicles (EVs) is a potential technology with large scale potential to change how EVs may be charged, eliminate range anxiety, and simplify charging infrastructure. As opposed to the existing conductive charging systems that necessitate physical contact between two charging points, WPT makes power transfer possible regardless of an air gap between charging and the receptive points, making it possible to recharge EVs practically automatically, both when they are parked, and when they are in motion. This non-contact method of energy transfer is usually accomplished in two ways, which are termed as inductive power transfer (IPT) and capacitive power transfer (CPT). However, IPT, which uses magnetic coupling between two coils (primary and secondary), is the best-studied in the EV usage, thanks to its comparatively high power and efficiency levels. Important developments of WPT to EVs are resonant compensation topologies to achieve high transfer power efficiency, optimization of placement alignment between the transmitter and receiver coils, and adaptive control methods that can ensure high performance considering operating variations. Nevertheless, wireless EV charging has a number of engineering and commercial obstacles to overcome notably the power transfer efficiency in low misalignment cases, the cost of coil designs and power electronics and the issue of stray electromagnetic emissions as a safety issue. The state of affairs is similar in the field of interoperability and scaling the technology to its broader application to the masses, which are places of inquiry by researchers and industry stakeholders. The current study seeks to summarize the status of WPT technology in the EV market, explain the technical issues that need to be addressed to empower the commercialization of wireless charging, and point out some recent developments that can lead to the popularization of wireless EV charging as an effective and safe means of doing automobile energy transfer.

Keywords: Wireless power transfer, electric vehicles, charging infrastructure, inductive power transfer, capacitive power transfer, adaptive control methods

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Received Date: June 04, 2025
Accepted Date: June 28, 2025
Published Date: July 07, 2025

Citation: Ravikant Nanwatkar, Ashish Baad, Atharv Hole, Kunal Abhang, Nirankar Dhotre, Mandar Dalvi. Smart Wireless Charging Infrastructure for Electric Vehicles. International Journal of Energy and Thermal Applications. 2025; 3(1): 30–42p.

INTRODUCTION

The global adoption of electric vehicles (EVs), as shown in Figure 1, has witnessed rapid growth due to rising environmental concerns, tightening emission regulations, and advancements in battery technologies. Governments across the world are offering incentives, subsidies, and policy support to promote EV adoption as a key strategy to reduce carbon emissions and fossil fuel dependency.

However, one of the major bottlenecks in achieving large-scale EV deployment is the lack of efficient, user-friendly, and accessible charging infrastructure. Traditional charging stations are often limited in number, require long charging times, and are inconvenient for users in densely populated urban areas. As the number of EVs continues to rise, there is a critical need to develop smarter and more efficient charging solutions that can support a seamless, scalable, and grid-integrated charging experience, as shown in Figure 2.

Wireless power transfer (WPT) technology emerges as a promising solution to address these challenges by offering a new paradigm in EV charging systems.

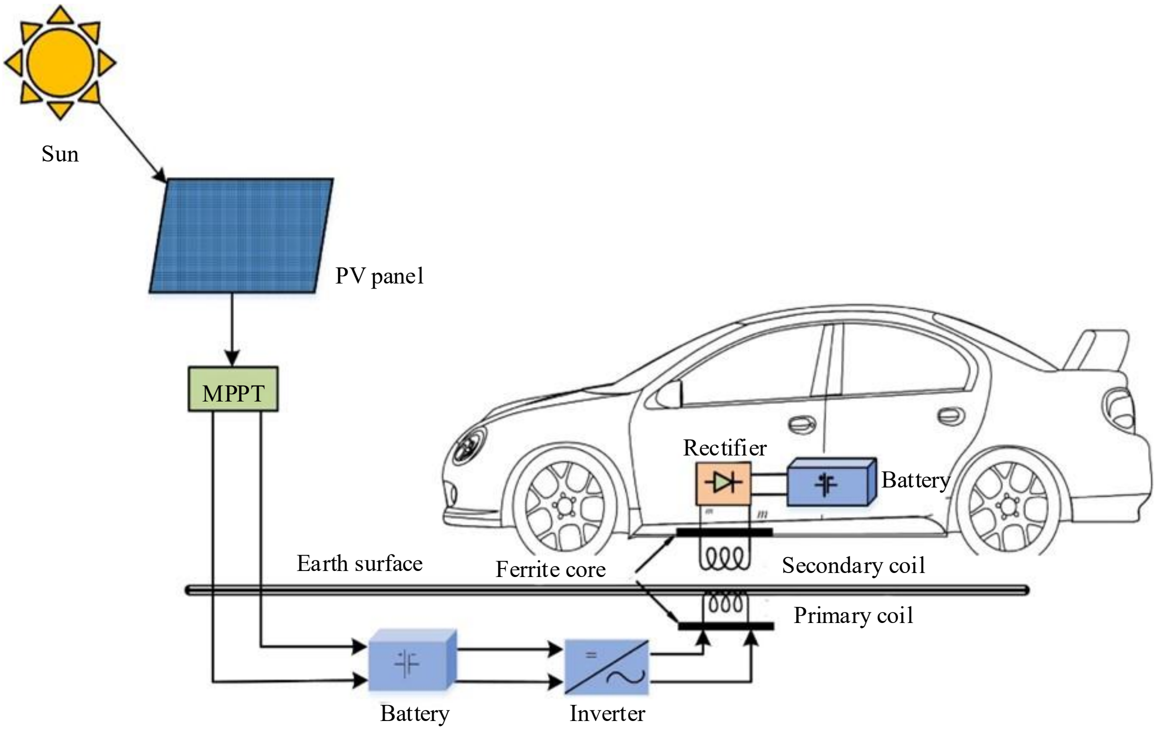

Figure 1. Graphical abstract [1].

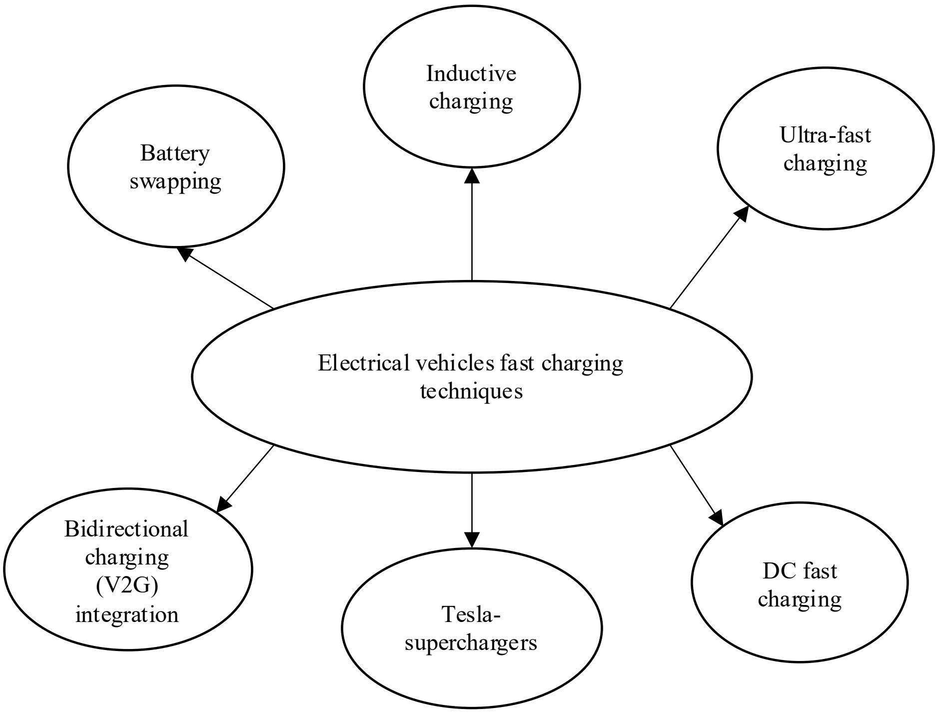

Figure 2. EV charging techniques [1].

Conventional plug-in charging systems, although widely used, suffer from several limitations that hinder their long-term feasibility and user convenience. First, the physical connection required between the charger and vehicle introduces wear and tear, and poses challenges in public or outdoor environments where vandalism or harsh weather can affect the hardware. Second, plug-in charging stations are often stationary and require dedicated parking spaces, resulting in infrastructure rigidity. Additionally, cable management, connector compatibility, and the need for manual intervention can lead to user inconvenience and increased maintenance costs. The time-intensive nature of Level 1 and Level 2 charging also adds to user dissatisfaction, especially in high-density or fleet operations. These constraints highlight the urgent need for alternative, contactless, and automated energy transfer solutions for EVs.

Wireless Power Transfer (WPT) presents a compelling alternative to conventional plug-in systems by enabling contactless energy transfer through electromagnetic coupling, offering users a seamless and automated charging experience. With WPT, EVs can be charged simply by parking over a charging pad or while driving over embedded coils, removing the need for cables, connectors, or user intervention. This not only improves convenience for individual users but also allows automation in applications such as autonomous vehicles, shared mobility fleets, and logistics. Moreover, the concept of dynamic wireless charging: charging vehicles while in motion on electrified roads, has the potential to drastically reduce battery size requirements and eliminate range anxiety. This continuous charging capability could revolutionize the transportation infrastructure and make EVs more practical, efficient, and accessible, thus motivating intensive research and development in this domain.

PROBLEM STATEMENT

Despite the promising advantages of Wireless Power Transfer (WPT) systems for electric vehicles, there remain significant challenges that prevent their widespread commercialization and deployment. Key technical issues include limited power transfer efficiency under coil misalignment, restricted transmission distance, high infrastructure cost, and electromagnetic field safety concerns. Furthermore, interoperability between different EV models and charger types is still lacking, with no universally accepted standards. The integration of WPT systems with existing grid infrastructure and renewable energy sources also poses operational complexities. Therefore, there is a need to explore innovative WPT architectures, materials, alignment strategies, and control algorithms that can enhance performance, safety, and economic viability for real-world deployment.

OBJECTIVES

The primary objectives of this research are to:

1. Analyze and review current WPT technologies applicable to electric vehicle charging.
2. Investigate the impact of coil design, alignment, and compensation techniques on power transfer efficiency.
3. Develop a simulation-based or experimental framework to evaluate the performance of WPT systems under different operational conditions.
4. Assess the feasibility of integrating WPT with dynamic (in-motion) charging infrastructure.
5. Explore standardization, safety protocols, and real-world case studies to propose a roadmap for scalable deployment.

NOVELTY AND SCOPE OF WORK

- This work offers a comprehensive investigation into the technical, infrastructural, and economic dimensions of WPT for EVs, with a particular focus on enhancing transfer efficiency under realistic conditions. Unlike many existing studies that isolate individual components, this research integrates multi-disciplinary perspectives: coil design, power electronics, electromagnetic safety, and grid interface, into a unified analysis. Additionally, it explores the future potential of dynamic wireless charging through embedded roadways, a topic still in its early experimental stage, offering new insights into the future of smart mobility and infrastructure integration.

- The scope of this research encompasses the design, simulation, and evaluation of wireless charging systems for both stationary and dynamic EV applications. It includes theoretical modeling of WPT principles, performance analysis under variable alignment and load conditions, and a review of safety and standardization guidelines. The work also extends to assessing real-world deployment scenarios, including the economic and policy implications of rolling out wireless charging networks in urban and highway settings. By covering both technical and systemic aspects, the research aims to bridge the gap between lab-scale prototypes and commercially viable WPT systems.

LITERATURE SURVEY

The concept of Wireless Power Transfer (WPT) for electric vehicles (EVs) has evolved rapidly due to its convenience and potential to enable continuous energy supply without physical connectors. Early reviews highlight the fundamentals of contactless power transfer, discussing its principles and applications for EVs and grid integration [1–4]. One of the earliest comprehensive overviews of EV wireless charging emphasized magnetic resonance coupling and induction-based techniques [5, 6]. Dynamic wireless charging, allowing EVs to charge while moving, is gaining attention. Studies have explored its energy efficiency benefits and potential for range extension. Key performance parameters and design considerations in dynamic wireless charging systems have been reviewed [7]. Recent advances leverage new materials like gallium nitride-based inverters for high-power transfer and precise control techniques to optimize coil alignment and maximize efficiency in real-time [8–11]. Compensation networks improve power transfer efficiency and load adaptability. Early studies of high-power compensation networks led to investigations of LCC and double-sided LCC topologies for their high efficiency and misalignment tolerance. Further research examined compensation designs that support dynamic and misaligned operating conditions, which are vital for on-road EV charging [12]. The design of the magnetic coupler is equally crucial. Investigations into coil shapes and magnetic structures aimed to enhance coupling efficiency. Strongly coupled magnetic resonance was introduced as a fundamental enabling technology [13–18].

Additional work focused on sensitivity analysis and stable power delivery over varying distances. Multi-coil structures and autonomous coil alignment systems further address lateral misalignment and maximize effective transfer power. Standardization is essential for interoperability and safety. The SAE International's J2954 standard defines key requirements for wireless EV power transfer systems. Technical architecture has been explored that aligns with these standards. The deployment challenges of large-scale dynamic wireless systems and their implications for grid integration and infrastructure planning have also been examined [19–23]. Reviews have addressed practical feasibility, power levels, and magnetic coupling techniques for commercial EV adoption. WPT is also studied in the context of Vehicle-to-Grid (V2G) integration. Discussions have included how bi-directional wireless power links can enhance grid stability and enable V2G energy exchange [24]. These investigations show that optimization of power flow, energy management strategies, and communication protocols between EVs and the grid will be pivotal for the success of V2G-enabled wireless charging [25–29]. Simulation-driven analyses have supported the understanding and optimization of WPT systems. System-level simulation studies and parametric optimization of magnetic couplers have been conducted. Recent works systematically evaluated different WPT configurations under realistic conditions [30]. Machine learning and control techniques like LSTM-based adaptive position control further enhance system flexibility [31, 32]. In summary, wireless power transfer for electric vehicles is a multidisciplinary area integrating advanced power electronics, electromagnetic design, control strategies, and smart grid integration. The literature reviewed reveals that dynamic wireless charging supported by optimal coil designs, robust compensation topologies, autonomous alignment, and adherence to standards like SAE J2954 can significantly enhance the usability and sustainability of EVs [33–36]. Ongoing research into high-power density components (e.g., GaN inverters), real-time control systems, and sensitivity-optimized power transfer techniques continues to drive progress toward practical implementation at scale [37–40].

METHODOLOGY AND SYSTEM ARCHITECTURE

Basic Working Mechanism of WPT

Wireless Power Transfer (WPT) is a technology that transmits electrical energy without physical connectors by exploiting electromagnetic fields. The most widely adopted method is electromagnetic induction, where a time-varying magnetic field generated by a primary coil induces an electromotive force (EMF) in a nearby secondary coil. Magnetic resonance coupling enhances this process by tuning both coils to resonate at the same frequency, thereby increasing efficiency even when misalignment or distance is present. On the other hand, capacitive coupling transfers energy via electric fields formed between two plates acting as capacitors. Although it has potential advantages such as lighter components and smaller size, capacitive coupling is less common in EVs due to lower efficiency and safety concerns related to high electric field exposure, as shown in Figure 3.

Types of WPT used in EVs

1. *Inductive power transfer (IPT):* IPT is the most mature and widely implemented WPT method in electric vehicle charging. It works on the principle of electromagnetic induction, requiring precise alignment between the transmitting coil on the ground and the receiving coil on the vehicle. It is safe, reliable, and can deliver moderate to high power but suffers from efficiency losses when the coils are misaligned.
2. *Capacitive power transfer (CPT):* CPT uses electric field coupling between conductive plates instead of magnetic fields. Although CPT systems can be lightweight and potentially lower in cost, they face challenges with field shielding, lower power levels, and safety, making them less suited for large EVs.
3. *Resonant inductive coupling*: This technique involves tuning both primary and secondary coils to the same resonant frequency, dramatically improving efficiency and power transfer distance. It is particularly useful in dynamic wireless charging scenarios, where coil alignment varies continuously as the vehicle moves, as per Table 1.

Power Transfer Mechanism and Energy Conversion Pathway

The power transfer mechanism in WPT systems involves several stages of energy conversion. Initially, AC power from the grid is converted into high-frequency AC using an inverter. This high-frequency current energizes the transmitter coil, creating an alternating magnetic field. When a vehicle is correctly aligned above the transmitter, the magnetic field induces a current in the receiver coil through electromagnetic induction or resonance coupling. The received AC is then rectified into DC power and regulated by power electronics to charge the vehicle's battery. Throughout this process, compensation circuits are employed to reduce reactive power and enhance efficiency, while control systems ensure proper alignment, safety, and communication between vehicle and infrastructure.

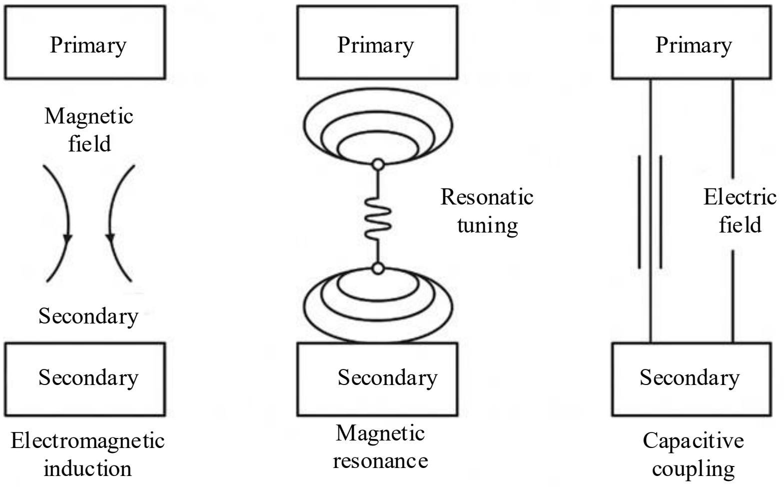

Figure 3. Basic working mechanism of WPT.

Table 1. Types of Wireless Power Transfer (WPT) used in EVs.

WPT type	Advantages	Disadvantages	Applications
Inductive Power Transfer (IPT)	High efficiency at close alignment	Sensitive to coil misalignment	Stationary EV charging (parking spots, garages)
	Mature and proven technology	Requires large coils and ferrites	Wireless taxi and bus charging stations
	Safe (low EMI)	Efficiency drops with distance	
	Scalable for different power levels		
Capacitive Power Transfer (CPT)	Lightweight components	Requires very high voltage	Experimental setups
	Potential for low-cost implementation	Electric field safety and shielding issues	Lightweight or micromobility EVs (e-scooters, bikes)
	Less magnetic loss	Lower power transfer capacity	
Resonant Inductive Coupling	Improved tolerance to misalignment and air gaps	Requires careful frequency tuning and compensation	Dynamic charging (on-road EV charging)
	Increased power transfer range and efficiency at resonance	Complex control electronics	Semi-dynamic public transport charging stops
	Scalability to dynamic charging	Increased EMI and design complexity	Rapid charging at commercial stations

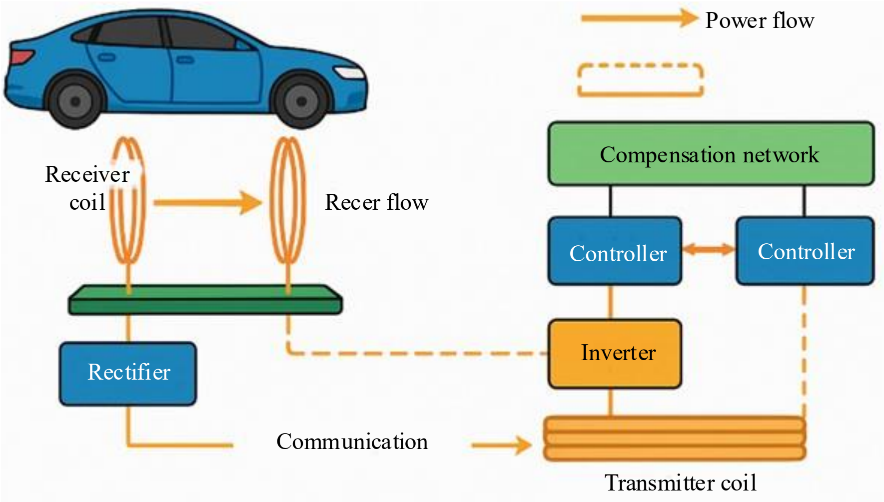

Figure 4. WPT system architecture and components.

SYSTEM ARCHITECTURE AND COMPONENTS

Figure 4 shows the WPT system architecture and components.

Primary Components

- *Transmitter and receiver coils*: These are the core components responsible for transferring energy wirelessly. The transmitter coil is typically embedded in the ground or charging pad, while the receiver coil is mounted on the underside of the EV. Coil geometry, number of turns, and magnetic core design significantly affect coupling efficiency and spatial tolerance.
- *Compensation networks*: Compensation circuits, such as series-series (SS), series-parallel (SP), and LCC compensation, are used to improve the efficiency of power transfer by minimizing reactive power losses. These networks help maintain resonance conditions and ensure the system remains stable under varying load and alignment conditions.
- *Power electronics (inverter, rectifier, and controller):* The power electronics system converts low-frequency grid power into high-frequency AC through an inverter at the transmitter side and back to DC through a rectifier on the receiver side. Controllers manage the switching operation, load balancing, and synchronization between both ends for optimized energy transfer.

- *Communication and control systems*: These systems are crucial for monitoring charging status, ensuring alignment, managing start/stop charging operations, and maintaining safety standards. Communication is often achieved through near-field communication (NFC), Wi-Fi, or other wireless protocols to coordinate data exchange between the vehicle and charging infrastructure.

Coil Design and Alignment Issues

Coil alignment directly impacts the coupling coefficient, which in turn affects efficiency and power transfer capacity. Lateral and angular misalignments between the transmitting and receiving coils can cause a significant drop in efficiency. To mitigate this, advanced coil designs using ferrite cores, double-D shapes, and rectangular configurations are employed. Dynamic alignment mechanisms and position feedback systems are also integrated to guide the vehicle into an optimal charging position, especially in dynamic or semi-dynamic wireless charging scenarios as shown in Table 2.

Frequency Selection and Resonance Tuning

The operating frequency of WPT systems significantly influences the size of the coils, system losses, and electromagnetic interference. Typical EV WPT systems operate in the range of 85 kHz (as standardized by SAE J2954) to balance efficiency and practical implementation. Resonance tuning involves adjusting circuit components so that both primary and secondary coils resonate at the same frequency, maximizing energy transfer. Adaptive tuning methods may be used to accommodate variations in load, coil separation, and environmental conditions as shown in Table 3.

DYNAMIC OF WIRELESS CHARGING, STANDARDIZATION AND SAFETY REGULATIONS

Dynamic wireless charging as shown in Figure 5, often referred to as in-motion charging, enables electric vehicles to receive power continuously as they drive over equipped roadways, reducing the need for long stationary charging stops. This concept is vital to address some of the most persistent challenges in EV adoption: limited driving range, long refueling times, and the weight of large onboard batteries. By allowing EVs to top up their batteries during regular travel, dynamic charging extends range, decreases battery size and cost, and improves grid flexibility. It also enhances the utility of electric public transit and commercial fleets, encouraging widespread adoption of EVs and helping to reduce greenhouse gas emissions.

Table 2. Coil design and alignment issues for wireless power transfer (WPT).

Aspect	Description	Challenges	Possible solutions
Coil Shape and Geometry	Determines magnetic flux paths and coupling efficiency; shapes like circular, rectangular, DD coils.	Designing for uniform flux distribution and compact size	Optimize coil shape via FEM simulations
Material Selection	Ferrite, copper or Litz wires to reduce losses and enhance coupling.	Eddy currents, core losses, and thermal management	Use high-permeability ferrites and Litz wires
Air Gap Distance	Distance between primary and secondary coil directly affects coupling and efficiency.	Larger gap lowers coupling and power transfer efficiency	Adaptive systems to adjust coil height, better designs
Alignment Tolerance	Relative position of coils must be precisely aligned for optimum power transfer.	Misalignment reduces efficiency and can cause heating	Guidance systems, position sensors, or dynamic control
Stray Electromagnetic Fields	Leakage of magnetic flux around the coils.	Interference with nearby electronics and safety concerns	Shielding and better containment of magnetic flux
Resonance Tuning	Compensation networks must maintain resonance despite variations in position and load.	Frequency shift due to misalignment and temperature changes	Adaptive resonance control, active tuning circuitry

Table 3. The features and effects of Wireless Power Transfer (WPT) system in EVs.

Feature	Effects on efficiency and performance
Coil Misalignment and Effect on Efficiency	Reduces mutual coupling and power transfer efficiency; may cause significant power losses and uneven heating of components.
Air Gap Distance Constraints	Larger gaps decrease coupling coefficient and power transfer efficiency; tight distance control is required for optimal performance.
Heat Generation and Cooling Systems	Increased losses lead to heat buildup; requires active or passive cooling; excessive heat reduces lifespan of electronic and magnetic components.
Electromagnetic Interference (EMI) and Shielding	Stray magnetic fields can interfere with nearby electronics and pose safety hazards; shielding and proper grounding reduce EMI but may add weight and cost.
Safety Standards and Human Exposure to EM Fields	Exposure must comply with ICNIRP, IEEE, and ISO standards; proper design prevents harmful leakage fields and ensures public safety.
Power Transfer Efficiency (PTE)	Influenced by coil design, operating frequency, alignment, and compensation networks; critical for reducing energy losses and improving system viability.
Coupling Coefficient and Quality Factor	Determines the strength of magnetic coupling and resonant behavior; higher coupling and Q-factor improve power transfer but require careful design and tuning.
Load Conditions and Dynamic Behavior	Variations in EV battery load affect efficiency and require adaptive control; dynamic misalignment or speed variations necessitate real-time adjustment of operating parameters.
Simulation and Experimental Validation of Performance	Modeling validates designs and predicts losses; experiments identify real-world effects like thermal behavior, misalignment sensitivity, and practical power output.

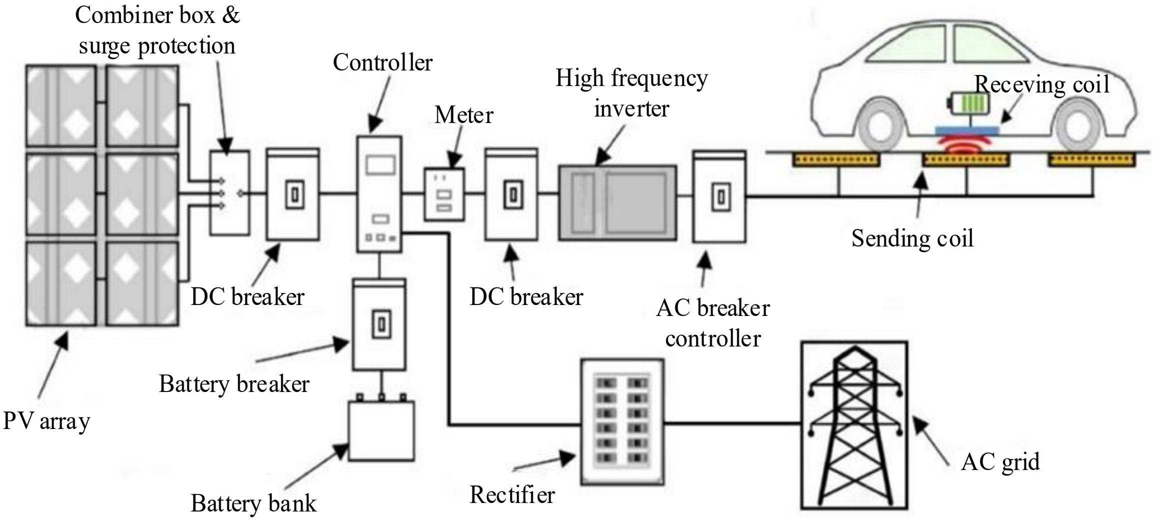

Figure 5. Dynamics of wireless charging method for EVs.

Roadway Infrastructure and Embedded Coil Design

Implementing dynamic wireless charging requires specialized roadway infrastructure and precisely engineered coil designs embedded beneath the surface of the road. The infrastructure consists of segmented primary coil arrays installed in the pavement that transfer energy to secondary receiver coils mounted on the EV’s underside. The primary coil design must ensure uniform magnetic fields, minimize losses, and tolerate variations in vehicle height and lateral misalignment. These coils are powered sequentially as the vehicle passes overhead to optimize efficiency and reduce stray emissions. Advanced materials and power electronics help manage the system’s thermal performance and reliability under continuous operation and diverse weather or traffic conditions as shown in Figure 6.

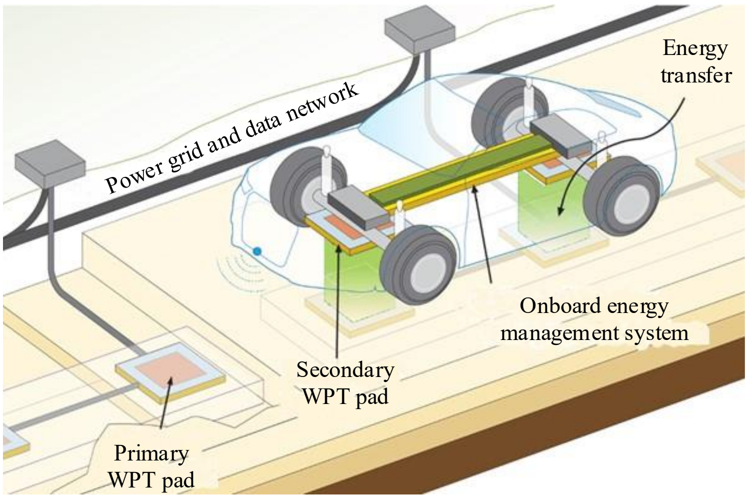

Figure 6. The in-motion WPT system implementation.

Vehicle-to-Infrastructure (V2I) Communication and Energy Management

Seamless V2I communication is critical for safe and efficient dynamic charging. Vehicles must exchange real-time data with roadside systems to authenticate the connection, initiate power transfer, and optimize energy consumption. Information such as the EV's battery state-of-charge, speed, and position is sent to the infrastructure controller, allowing dynamic control of power flow and coil activation. Energy management strategies also ensure that the power grid is not overloaded and that the power demand is balanced across multiple users. Emerging solutions leverage 5G or DSRC communication standards to achieve the low-latency, high-reliability data exchange that dynamic wireless charging requires for practical deployment as per Figure 7.

Existing and Emerging Standards (e.g., SAE J2954, ISO/IEC 61980)

Standards bodies like SAE and the International Electrotechnical Commission (IEC) have established frameworks for the safe and interoperable deployment of wireless charging. SAE J2954, for example, outlines interoperability, safety, and communication requirements for wireless power transfer at up to 11 kW for light-duty EVs. Meanwhile, the ISO/IEC 61980 series governs safety, performance, and EMC considerations for stationary wireless power transfer. These standards are being extended to cover dynamic wireless systems and V2G scenarios. Emerging standards will address higher power levels, new topologies, harmonization with different regional grid requirements, and testing protocols to validate dynamic systems' performance and reliability in real-world environments.

Interoperability and Compatibility across Manufacturers

Interoperability is crucial for wireless EV charging networks to scale successfully. Without uniform coil sizes, power electronics interfaces, communication protocols, and control algorithms, drivers would face fragmented, manufacturer-specific charging options. Standards like SAE J2954 promote compatibility between different EVs and infrastructure suppliers. Industry consortia and multi-stakeholder pilot projects also work toward common coil shapes, pad placement tolerances, and shared V2I communication protocols. Achieving interoperability will reduce costs, simplify user experience, enable roaming between networks, and encourage the broad deployment of public wireless charging corridors across cities and highways.

Safety Protocols and EMI Compliance

Safety is a primary concern for any wireless power transfer system due to its high-power electromagnetic (EM) fields. Safety protocols include fail-safes like automatic shutoff if foreign objects (e.g., metal debris or animals) enter the magnetic field and thermal management to prevent overheating. Standards require all systems to comply with rigorous electromagnetic interference (EMI) limits to protect nearby electronics, humans, and animals.

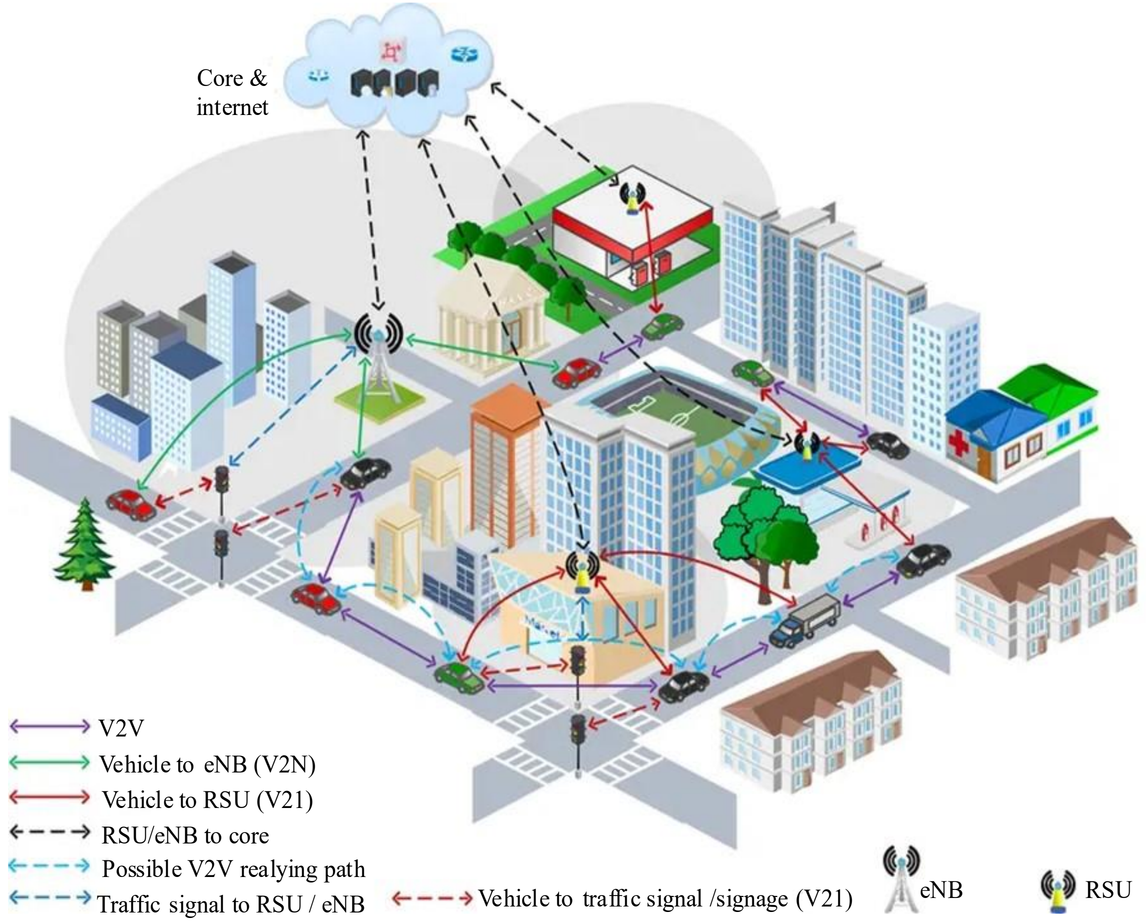

Figure 7. Vehicle-to-infrastructure (V2I) communication.

Leakage fields must be well below International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. The design must also incorporate shielding, magnetic field cancellation techniques, and control algorithms to limit emissions while ensuring high power transfer efficiency. Comprehensive safety tests and certification processes ensure that dynamic charging infrastructure can operate continuously in public spaces without health or electromagnetic compatibility concerns.

CONCLUSION AND FUTURE TRENDS

Conclusion

Integrating wireless EV charging with renewable energy sources, such as solar and wind, supports a more sustainable and decentralized energy ecosystem. By linking dynamic charging infrastructure to local renewable generation and energy storage, the system can reduce grid dependency, cut emissions, and take advantage of surplus green energy. This synergy enhances overall energy efficiency and further supports the transition toward zero-carbon transportation.

Artificial intelligence and machine learning algorithms can optimize energy distribution in wireless EV charging systems by predicting demand, adjusting power output in real time, and minimizing losses. These algorithms use vehicle data, traffic patterns, and weather forecasts to make decisions that enhance system reliability and reduce operating costs. AI-driven control also enables predictive maintenance, further improving performance and service continuity.

Advances in lightweight materials and compact coil designs help reduce the weight and footprint of onboard and embedded hardware for wireless charging. Innovative composites and miniaturized magnetic structures improve power transfer efficiency while minimizing added vehicle weight and road construction depth. This supports easier integration into existing EV designs and simplifies the deployment of dynamic wireless charging lanes.

Smart grid integration enables dynamic wireless charging infrastructure to participate in bidirectional power flow, allowing EVs to not only receive energy but also feed excess energy back into the grid when parked or during off-peak periods. This two-way capability enhances grid stability, supports peak shaving, and promotes better utilization of renewable energy resources, turning EVs into active grid assets.

Future Scope

Current research indicates that dynamic wireless EV charging is technically feasible, environmentally beneficial, and economically promising. Advances in coil design, power electronics, communication protocols, and control algorithms have paved the way for safer, more efficient systems. Continued progress on standards and interoperability will help drive the commercial viability of wireless charging networks.

By extending driving range, reducing downtime, and lowering battery size requirements, dynamic wireless charging could greatly enhance the appeal of EVs for both personal and commercial use. Its widespread deployment would complement existing charging infrastructure and encourage faster adoption of electric mobility, helping to reduce emissions and improve public confidence in EV technology.

The future of dynamic wireless EV charging looks promising as pilot projects expand into commercial installations and standards mature. Continued innovations in coil designs, safety protocols, and communication systems will support scalable deployment across highways and urban centers. With increasing policy support and investments from automakers and energy companies, dynamic wireless charging could become a mainstream feature of future sustainable transportation networks.

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