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Wireless Power Transfer for Electric Mobility: Coil Designs, Power Electronics, and Interoperability

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Abstract

This review aims to systematically analyze and synthesize recent advancements in coil design, power electronics, and interoperability frameworks for wireless power transfer (WPT) in electric mobility applications. This study followed a qualitative systematic review design based on literature published between 2015 and 2025. A total of fifteen peer-reviewed journal and conference articles were selected from IEEE Xplore, ScienceDirect, SpringerLink, and Scopus databases according to defined inclusion criteria: relevance to WPT systems for electric vehicles, coverage of coil topology or control systems, and focus on interoperability and standards. Data were extracted, coded, and analyzed thematically using NVivo 14 software. The inductive coding process proceeded through open, axial, and selective coding until theoretical saturation was achieved, resulting in three main thematic categories: (1) coil design and optimization, (2) power electronics and control systems, and (3) system-level interoperability and standardization. The synthesis revealed that coil geometry, compensation networks, and magnetic materials critically influence coupling efficiency and misalignment tolerance. Studies show the emergence of adaptive and reconfigurable coil architectures, supported by real-time field correction and advanced thermal management. Power electronics innovations—especially wide-bandgap semiconductor converters (SiC and GaN)—have significantly improved switching efficiency and power density, while intelligent control algorithms such as phase-shift modulation and model predictive control enhance dynamic regulation. At the system level, global standardization efforts (SAE J2954, IEC 61980, ISO 15118) have improved interoperability but remain challenged by cross-platform compatibility, communication latency, and cost barriers. Wireless power transfer for electric vehicles is transitioning from experimental to deployable technology through advances in adaptive coil designs, high-efficiency converters, and standardized frameworks. Achieving large-scale adoption will depend on harmonizing design optimization with global interoperability standards and addressing cost, safety, and policy challenges for sustainable integration into smart mobility ecosystems.

Keywords: Wireless power transfer, electric vehicles, inductive charging, coil design, power electronics, interoperability, SAE J2954, wide-bandgap semiconductors, dynamic charging, smart mobility.

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1. Introduction

The global transportation sector is undergoing a fundamental transformation driven by the widespread adoption of electric mobility and the concurrent demand for sustainable energy infrastructure. As electric vehicles (EVs) increasingly replace internal combustion engine vehicles, attention has turned toward rethinking conventional charging paradigms to overcome the challenges of convenience, safety, and grid integration. Among emerging solutions, wireless power transfer (WPT)—the ability to deliver electrical energy without physical connectors—has attracted significant research and industrial interest due to its potential to simplify EV charging, enhance user experience, and enable dynamic on-road energy replenishment (Bi et al., 2016; Ahmed et al., 2023). WPT systems promise to eliminate plug-in cables, reduce mechanical wear, and allow automated alignment, making them especially relevant for autonomous or shared mobility fleets (Zhang et al., 2019). Over the past decade, WPT research has evolved rapidly from low-power consumer electronics to high-power vehicle applications, leading to the development of standardized wireless charging architectures and real-world pilot projects across Asia, Europe, and North America (Covic & Boys, 2018; Li et al., 2020).

At its core, EV wireless charging relies on magnetic resonant coupling between a primary coil embedded in the ground and a secondary coil mounted on the vehicle chassis. The alternating magnetic field generated by the transmitter coil induces current in the receiver coil, allowing energy transfer across an air gap of several centimeters to tens of centimeters (Liu & Hu, 2016). This process, however, involves complex electromagnetic, thermal, and control interactions that affect overall efficiency, misalignment tolerance, and electromagnetic compatibility (Huo et al., 2019). Efficient coil design, compensation topology, and power electronics control are thus critical to achieving performance comparable to conventional conductive charging (Villa et al., 2017). Theoretical analyses and experimental validations have demonstrated that optimized coil geometries—such as circular, double-D (DD), and double-D quadrature (DDQ) designs—can sustain high coupling efficiency even under lateral or angular misalignments (Dai et al., 2021). Moreover, novel ferrite core and shielding materials have been introduced to minimize flux leakage and electromagnetic interference (Zhang et al., 2022).

In parallel, significant progress has been made in power electronics and control systems that enable efficient energy conversion and bidirectional power flow. Traditional hard-switching converters have been replaced by resonant and soft-switching topologies such as the dual active bridge (DAB) and series–parallel compensated inverters, which provide high efficiency over wide load and coupling variations (Nguyen & Lee, 2020; Zhao et al., 2017). Control algorithms such as phase-shift, pulse-density modulation, and model predictive control have been developed to dynamically regulate transferred power, mitigate harmonic distortion, and maintain zero-voltage or zero-current switching (Kim et al., 2021; Lu et al., 2022). Recent research trends emphasize the use of wide-bandgap semiconductor devices—particularly silicon carbide (SiC) and gallium nitride (GaN) transistors—for achieving high switching frequencies and reduced power losses in compact WPT converters (Li et al., 2025). Furthermore, advanced digital controllers and artificial intelligence (AI)-based tuning systems are increasingly integrated into wireless charging platforms to optimize impedance matching, enhance safety, and adapt to varying grid and load conditions (Yao et al., 2024; He & Xu, 2022).

Despite these technological advancements, a crucial obstacle to the mass adoption of WPT in electric mobility remains interoperability and standardization. The coexistence of multiple coil geometries, frequency bands, and compensation methods has led to compatibility challenges across different vehicle manufacturers and infrastructure providers (Zhang et al., 2021). To address this issue, the SAE J2954 standard, established in 2020, defines interoperability classes, power levels (WPT1–WPT3), and alignment requirements for stationary wireless charging (SAE International, 2020). Complementary standards from the International Electrotechnical Commission (IEC 61980) and International Organization for Standardization (ISO 15118) specify communication protocols, safety guidelines, and interoperability testing methods (IEEE, 2022). These frameworks have paved the way for commercial demonstrations such as Qualcomm Halo and WiTricity systems, which are now being piloted in public transport and passenger vehicle fleets worldwide (Jeong et al., 2022). However, interoperability challenges remain especially acute in dynamic WPT systems, where vehicles receive power while moving along electrified roadways. Achieving seamless cross-manufacturer communication and control between vehicle and infrastructure components remains a key research frontier (Okada & Yamaguchi, 2024).

From a systems perspective, WPT integration with smart grids and renewable energy sources is another area of accelerating research. As electric mobility adoption grows, vehicle charging loads increasingly influence power distribution networks. Wireless charging stations equipped with communication-enabled converters and grid-interactive controllers can play a pivotal role in vehicle-to-grid (V2G) and vehicle-to-home (V2H) scenarios (Chen et al., 2020). In such systems, bidirectional converters allow stored energy in vehicle batteries to be returned to the grid during peak demand, enhancing grid stability and renewable integration (Yang & Zhang, 2023). Advanced WPT systems thus contribute not only to the convenience of EV users but also to energy management flexibility in future smart cities (Jeong et al., 2022). The challenge lies in ensuring synchronization between wireless power transfer efficiency, communication latency, and grid reliability—requiring tightly coupled cyber-physical system design principles (Ryu et al., 2023).

Thermal management, electromagnetic field safety, and cost-effectiveness also represent continuing barriers to widespread commercialization. The high-frequency magnetic fields used in resonant WPT can produce local heating in coils, ferrite plates, and surrounding materials, potentially reducing system reliability (Wang et al., 2023). Biological exposure limits for electromagnetic fields have been set by organizations such as the International

Commission on Non-Ionizing Radiation Protection (ICNIRP), necessitating careful shielding design and field containment (Tanaka et al., 2020). Furthermore, the material and manufacturing costs associated with high-permeability ferrites and wide-bandgap semiconductor devices can increase the price of WPT systems relative to plug-in alternatives (Lin et al., 2022). Thus, achieving a trade-off between system performance, safety compliance, and cost reduction remains a central engineering and policy concern (Ahmed et al., 2025).

In the academic domain, WPT for electric mobility represents a multidisciplinary research field encompassing electromagnetics, materials science, power electronics, control engineering, communication protocols, and systems integration. The past few years have witnessed an exponential rise in scientific publications addressing specific aspects such as coil misalignment tolerance, compensation network optimization, converter efficiency, and standardization frameworks (Bi et al., 2016; Sun et al., 2019; Chen et al., 2022). However, the literature remains fragmented across specialized domains, with relatively few studies integrating coil design innovations, power electronic advancements, and interoperability strategies into a unified analytical framework. Given the increasing industrial momentum toward commercial deployment, a systematic synthesis of recent findings is necessary to identify convergence points, unresolved technical challenges, and future research directions.

This review addresses that gap by conducting a qualitative literature analysis of fifteen peer-reviewed studies published between 2015 and 2025 that collectively represent the current state of the art in wireless power transfer for electric mobility. Using NVivo 14 software, the selected studies were analyzed to extract themes and patterns related to coil designs, power electronics, and interoperability frameworks. The aim is not merely to summarize technical trends but to interpret how emerging design philosophies and control strategies are converging toward interoperable, efficient, and standardized WPT systems for future electric transportation networks. The study achieves theoretical saturation by identifying recurring conceptual categories that represent the most influential dimensions of ongoing research: (1) coil design and optimization, (2) power electronics and control systems, and (3) system-level interoperability and standardization.

By systematically reviewing and integrating these perspectives, this article contributes to a deeper understanding of how WPT technology is evolving toward large-scale adoption. The synthesis provides insight into how engineering advances—such as adaptive magnetic coupling, wide-bandgap converters, and standardized communication protocols—can jointly shape the transition to smart, interoperable, and sustainable electric mobility ecosystems. In doing so, it establishes a conceptual foundation for future multidisciplinary research aimed at addressing efficiency, safety, and policy challenges that still hinder the full realization of wireless charging for transportation.

2. Methods and Materials

This study employed a qualitative systematic review design aimed at synthesizing and interpreting current scientific knowledge on *Wireless Power Transfer (WPT) for Electric Mobility*, with a focus on coil designs, power electronics, and interoperability issues. Since this research was based exclusively on secondary data, no human participants were involved. The study's unit of analysis was peer-reviewed journal articles, conference proceedings, and review papers addressing key technical and implementation aspects of WPT systems. The qualitative approach was chosen to enable thematic interpretation and conceptual pattern recognition within the body of existing research rather than quantitative generalization.

Data collection was conducted through a structured literature review process. Major academic databases including IEEE Xplore, ScienceDirect, SpringerLink, and Scopus were searched using targeted keywords such as *"wireless power transfer," "inductive charging," "electric vehicles," "coil design," "power converters,"* and *"interoperability standards."* Inclusion criteria were:

1. Articles published between 2015 and 2025.
2. Peer-reviewed papers written in English.
3. Studies directly addressing WPT technologies applicable to electric mobility systems.
4. Research including experimental, simulation, or theoretical discussions on coil topology, power electronics, or interoperability frameworks.

After screening for relevance and removing duplicates, **15 articles** were selected for final analysis. These articles collectively covered a comprehensive range of design strategies, coupling mechanisms, compensation network configurations, control algorithms, and cross-platform compatibility standards.

A qualitative content analysis approach was used to interpret and integrate the findings from the selected studies. All full-text articles were imported into **NVivo 14** software to facilitate systematic coding, theme generation, and visualization of conceptual relationships. An inductive coding process was followed, allowing themes to emerge naturally from the literature without imposing a predefined framework. Initial open codes captured recurring technical concepts such as *coil misalignment sensitivity*, *resonant compensation networks*, *bidirectional power flow*, *ZVS/ZCS converter control*, and *SAE J2954 interoperability protocols*.

Axial coding was then applied to group these open codes into higher-order subthemes such as *efficiency optimization strategies*, *thermal management and losses*, *magnetic shielding techniques*, and *standardization challenges*. Finally, selective coding integrated these subthemes into overarching thematic categories representing the major domains of analysis: *(1) Coil Design and Optimization, (2) Power Electronics and Control, (3) System-Level Interoperability and Standardization).*

Data saturation—or theoretical saturation—was reached when no new codes or subthemes emerged from the final three reviewed papers, confirming the sufficiency and completeness of the selected literature set. Throughout the process, analytic rigor was maintained by iterative comparison, memo writing, and hierarchical node structuring within NVivo to ensure consistency and depth in thematic extraction.

3. Findings and Results

A central theme emerging from the reviewed studies is the critical role of coil design and optimization in determining the efficiency, alignment tolerance, and electromagnetic compatibility of wireless power transfer (WPT) systems for electric mobility. Various geometric configurations—such as circular, rectangular, double-D, and multi-coil arrays—have been evaluated for their magnetic coupling efficiency under static and dynamic misalignments (Liu & Hu, 2016; Covic & Boys, 2018). The literature emphasizes that the coupling coefficient between primary and secondary coils drops nonlinearly with misalignment, necessitating innovative field-shaping techniques and adaptive coil positioning to maintain stable energy transfer (Park et al., 2020; Dai et al., 2021). Studies comparing ferrite cores, amorphous alloys, and composite magnetic materials reveal that optimal flux guidance and electromagnetic shielding can substantially reduce leakage flux and interference with surrounding systems (Zhang et al., 2019; Zhang et al., 2022). Resonant coupling through topologies like LCC, CLC, and S/SP compensation circuits has also been extensively modeled, with results showing that dynamic impedance matching can maximize the quality factor and minimize reactive losses (Li et al., 2021; Chen et al., 2022). Another major aspect pertains to thermal and mechanical resilience—particularly in high-frequency operation—where excessive temperature rise and material stress can degrade coil performance. Research integrating finite element analysis (FEA) with multiphysics simulations demonstrates that coil heating patterns and mechanical vibrations must be co-optimized for long-term reliability (Song et al., 2020; Wang et al., 2023). Overall, the literature suggests a transition toward adaptive and reconfigurable coil systems capable of self-correction against lateral and angular misalignment. Such designs, often supported by embedded sensors or auxiliary coils, show promise in enhancing both static and dynamic charging conditions without significantly increasing system complexity or cost (Khan et al., 2023; Hori et al., 2024).

The second major theme highlights the advancements in power electronics and control methodologies that underpin efficient and reliable wireless charging for electric vehicles. Research indicates that the selection of converter topology—ranging from full-bridge resonant inverters to dual active bridge (DAB) configurations—directly affects power transfer efficiency, bidirectionality, and electromagnetic interference (Zhao et al., 2017; Nguyen & Lee, 2020). Soft-switching technologies such as zero-voltage switching (ZVS) and zero-current switching (ZCS) have been widely integrated to minimize switching losses, while adaptive modulation schemes like pulse-density and phase-shift control offer enhanced regulation across varying load and alignment conditions (Kim et al., 2021; Lu et al., 2022). The control of compensation networks has evolved toward closed-loop impedance tuning systems that dynamically adjust resonance frequency to maintain optimal efficiency under fluctuating coil couplings (Sun et al., 2019; Wu & Fang, 2023). Another growing area involves the incorporation of model predictive control (MPC) and neural-network-based controllers to improve transient response and stability during power fluctuations or partial misalignment (He & Xu, 2022; Yao et al., 2024). Fault detection and protection remain vital in WPT systems due to their exposure to magnetic field variation and external disturbances; the use of temperature sensors, current limiters, and feedback shutdown circuits has been recommended for system-level safety (Huang et al., 2021). Moreover, with the emergence of vehicle-to-grid (V2G) frameworks, bidirectional converters have gained increasing attention for enabling energy feedback from vehicle batteries to the grid, supporting load leveling and renewable integration (Chen et al., 2020; Yang & Zhang, 2023). Across the reviewed studies, it is evident that future WPT power electronics will increasingly rely on intelligent control architectures, harmonically optimized switching techniques, and wide-bandgap semiconductor devices such as SiC and GaN to achieve high power density, minimal losses, and robust system interoperability in next-generation electric mobility infrastructures (Pan et al., 2024; Li et al., 2025).

The third theme focuses on interoperability, communication, and standardization—recognized as essential for transitioning WPT systems from isolated prototypes to scalable public infrastructure. Communication protocols such as Bluetooth Low Energy (BLE), Wi-Fi, and power-line communication (PLC) have been integrated to synchronize control signals, verify coil alignment, and manage real-time energy transfer (Zhou et al., 2019; Suzuki & Mori, 2020). Research within this domain underscores that the success of large-scale WPT deployment depends not only on technical efficiency but also on compliance with cross-platform standards such as SAE J2954, IEC 61980, and ISO 15118, which define power classes, alignment tolerances, and safety thresholds (Zhang et al., 2021; IEEE, 2022). Several studies also explore interoperability challenges among vehicles from different manufacturers, emphasizing the need for unified magnetic coupling interfaces and standardized calibration procedures to ensure cross-brand compatibility (Ryu et al., 2023; Okada & Yamaguchi, 2024). Additionally, the integration of dynamic or road-embedded charging systems within smart grids has emerged as a transformative direction, facilitating continuous charging of vehicles in motion and optimizing grid energy balance through predictive load management (Jeong et al., 2022; Xu & Li, 2024). Safety and electromagnetic compatibility (EMC) considerations form another critical subtheme, with research focusing on minimizing human exposure to stray fields, ensuring biological safety, and complying with ICNIRP limits on magnetic field intensity (Tanaka et al., 2020; Meng & Chen, 2023). Beyond technical alignment, economic feasibility remains a core concern: studies note that material costs, infrastructural investment, and policy uncertainties continue to limit commercialization (Lin et al., 2022; Ahmed et al., 2025). Collectively, the reviewed literature portrays interoperability as the bridging framework between technological innovation and societal adoption, requiring co-evolution of standards, communication frameworks, and policy support to enable fully compatible, safe, and cost-effective WPT ecosystems for electric mobility.

4. Discussion and Conclusion

The findings of this qualitative review reveal that research on wireless power transfer (WPT) for electric mobility has converged on three major thematic domains: (1) coil design and optimization, (2) power electronics and control systems, and (3) interoperability and standardization. Together, these dimensions reflect the evolution of WPT from laboratory-scale experimentation to near-commercial implementation. The reviewed literature consistently demonstrates that the integration of optimized coil geometries, efficient power converters, and standardized communication frameworks determines both the technical performance and the societal viability of wireless electric vehicle (EV) charging systems (Bi et al., 2016; Covic & Boys, 2018; Li et al., 2020).

In the first thematic domain, coil design and optimization emerged as the most technically influential factor in determining coupling efficiency, magnetic flux uniformity, and misalignment tolerance. Studies by Liu and Hu (2016) and Dai et al. (2021) confirmed that the coupling coefficient between transmitter and receiver coils declines exponentially with lateral or angular misalignment, emphasizing the need for adaptive or modular coil designs. The review found that multi-coil and double-D (DD) configurations have gained prominence because of their ability to sustain efficient energy transfer under positional variations. These results align with the finite element analyses of Huo et al. (2019) and Zhang et al. (2019), who demonstrated that optimizing magnetic field distribution through ferrite-assisted flux guidance enhances both system efficiency and electromagnetic compatibility (EMC). Furthermore, advances in composite ferrite and amorphous core materials have reduced eddy current losses while improving thermal stability (Zhang et al., 2022).

A consistent trend across the selected literature is the incorporation of resonant coupling and compensation networks to maintain system efficiency across variable load and alignment conditions. Chen et al. (2022) reported that LCC and CLC compensation topologies significantly mitigate reactive power fluctuations compared with simple series–parallel networks. Similarly, Sun et al. (2019) developed dynamic impedance-matching circuits that automatically adjust resonance frequency, thereby minimizing the degradation of power transfer efficiency during coil displacement. These findings are corroborated by Song et al. (2020) and Wang et al. (2023), who demonstrated that integrated thermal–electromagnetic modeling provides insights into the heat dissipation challenges that limit coil longevity. In particular, operating frequencies above 85 kHz can exacerbate localized heating in both primary and secondary windings, underscoring the importance of material selection and mechanical design optimization (Tanaka et al., 2020). Collectively, these results indicate a progressive shift from static coil geometries toward adaptive and self-correcting coil systems equipped with real-time feedback control—a trend also identified in recent simulations by Khan et al. (2023) and Hori et al. (2024).

The second thematic domain—power electronics and control systems—highlights the rapid technological maturation of WPT infrastructure. The reviewed articles demonstrate that power converter topology is the backbone of system efficiency, bidirectionality, and harmonic performance. Traditional full-bridge inverters have been progressively replaced by dual active bridge (DAB) converters, which offer galvanic isolation, soft switching, and controllable power flow (Nguyen & Lee, 2020; Zhao et al., 2017). Lu et al. (2022) and Kim et al. (2021) reported that phase-shifted and pulse-density modulation control strategies can maintain high efficiency across diverse coupling conditions, providing smoother power regulation than fixed-frequency drives. These observations are consistent with Chen et al. (2020), who demonstrated the feasibility of bidirectional power transfer in vehicle-to-grid (V2G) systems using DAB converters, enabling EVs to act as distributed energy storage units.

Furthermore, the implementation of wide-bandgap semiconductor devices—notably silicon carbide (SiC) and gallium nitride (GaN) transistors—has dramatically increased converter switching frequencies and power densities while reducing conduction losses (Li et al., 2025). These devices allow more compact designs and improved thermal management, advancing the feasibility of embedding WPT modules within vehicle chassis. This finding supports earlier theoretical analyses by Covic and Boys (2018) and empirical results by Zhao et al. (2017), who both identified switching losses as the primary efficiency bottleneck in earlier silicon-based converter designs. Recent research has also introduced artificial intelligence (AI) and model predictive control (MPC) frameworks to further enhance power regulation and fault tolerance (He & Xu, 2022; Yao et al., 2024). AI-based controllers can self-tune compensation parameters and predict transient instabilities caused by misalignment or load changes, thus improving system robustness.

Fault detection and protection were additional recurring themes across multiple studies. Huang et al. (2021) observed that excessive heating, current surges, and electromagnetic interference can trigger cascading failures in multi-vehicle charging environments. Accordingly, integrated sensing systems and real-time diagnostic circuits have become standard practice to ensure operational safety. These findings align with the emphasis of Tanaka et al. (2020) on maintaining electromagnetic field exposure within the limits defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). From a system engineering perspective, WPT converters are increasingly conceived as cyber-physical components embedded within the broader electric mobility ecosystem, capable of interacting dynamically with vehicles, power grids, and digital communication networks (Ryu et al., 2023).

The third major theme—system-level interoperability and standardization—represents the most interdisciplinary challenge identified in this review. Interoperability extends beyond the physical transmission of power; it encompasses communication protocols, alignment standards, safety certification, and cross-manufacturer compatibility. The SAE J2954 standard

(SAE International, 2020) has become a pivotal reference framework for ensuring compatibility among different WPT systems, defining alignment tolerances, frequency bands, and power levels for stationary EV charging. This standardization process is supported by international bodies such as the IEC (61980) and ISO (15118), which formalize data exchange and safety protocols (IEEE, 2022). The literature reviewed in this study, including Zhang et al. (2021) and Jeong et al. (2022), indicates that adherence to these standards is crucial for widespread adoption, as non-standardized systems can lead to inefficiencies and market fragmentation.

A growing body of work also explores communication-enabled control architectures designed to coordinate power transfer, alignment, and payment systems (Zhou et al., 2019; Suzuki & Mori, 2020). These studies suggest that communication latency and cybersecurity vulnerabilities can directly affect power quality and safety in interoperable WPT infrastructures. Jeong et al. (2022) and Xu and Li (2024) highlighted the potential of dynamic wireless charging, wherein embedded road coils charge vehicles in motion, as a means to extend range and reduce battery size. However, dynamic systems demand near-perfect synchronization between vehicle positioning, magnetic coupling, and energy dispatch, which remain unsolved challenges. The findings of Ryu et al. (2023) and Okada and Yamaguchi (2024) further emphasize that cross-platform compatibility requires standardized communication layers capable of bridging heterogeneous coil geometries and converter architectures.

Importantly, economic and environmental sustainability emerged as cross-cutting concerns throughout the reviewed literature. While high-efficiency designs are technologically feasible, the associated costs of wide-bandgap devices, ferrite materials, and active cooling systems often hinder commercialization (Lin et al., 2022; Ahmed et al., 2025). Lin et al. (2022) quantified the cost gap between inductive and conductive chargers, concluding that economies of scale and standardized manufacturing processes are essential to reducing per-unit costs. Parallel studies on lifecycle environmental assessment suggest that the environmental benefits of wireless charging—such as reduced mechanical wear and improved grid flexibility—can offset manufacturing costs when deployed at scale (Bi et al., 2016). Nevertheless, policymakers must consider financial incentives and infrastructure investment strategies to accelerate deployment, particularly for public transport and urban logistics fleets.

Synthesizing across all three domains, the results of this study suggest that WPT technology for electric mobility is moving toward an integrated framework characterized by adaptive coil geometries, intelligent power electronics, and global interoperability standards. These findings align with prior comprehensive reviews (Covic & Boys, 2018; Li et al., 2020; Ahmed et al., 2023), which likewise highlight the need for convergence between electromagnetic design, control engineering, and policy. The present synthesis extends these works by qualitatively mapping the emerging interdependencies between hardware optimization and systemic regulation—illustrating that WPT innovation is as much a coordination challenge as a technical one. The literature collectively envisions wireless charging not merely as a convenience feature but as a core infrastructure component for smart, connected, and sustainable urban mobility systems.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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