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Near-Field Wireless Power Transfer: Recent Advances in Topological Designs, Dynamic Applications, and Global Standardization

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HIGHLIGHTS

- Comparative analysis of inductive, capacitive, magnetic-gear, and RF beamforming WPT topologies spanning 1 W–300 kW and 10–95 % efficiency.
- Field trials of dynamic wireless EV charging at highway speeds in France, the USA, Italy, and Germany confirm technical feasibility.
- Inductive WPT dominates markets with 1.5 billion Qi2 devices, yet dynamic charging still lacks full interoperability standards.
- Autonomous drone charging and PV-integrated off-grid solutions expand WPT application diversity beyond conventional vehicles.
- Recommendations call for DWPT standardization by 2028, AI-native control systems, and life-cycle assessments for scalable adoption.

ABSTRACT

Wireless power transfer (WPT) has evolved into commercially available systems for electric vehicles, drones, and consumer electronics; however, fragmented standards and high infrastructure costs impede widespread proliferation. This review provides a comprehensive overview of near-field WPT technologies, analyzing topological designs, dynamic applications, and standardization frameworks. Comparative analysis of inductive, capacitive, magnetic gear, and RF beamforming topologies reveals power ranges from 1 W to 300 kW, efficiencies of 10–95%, and varying spatial freedom and commercial maturity. Field trials of dynamic wireless charging for electric vehicles in France (A10, 300 kW), the United States (Purdue/INDOT), Italy (A35 Brebemi), and Germany demonstrate technical feasibility at highway speeds. Autonomous drone charging systems and photovoltaic-integrated, grid-independent solutions further demonstrate the expanding diversity of wireless power transfer

applications. Results indicate that while inductive WPT dominates consumer and automotive sectors with 1.5 billion Qi2-certified devices and international standards (IEC 63563-1:2025, IEC/IEEE 63184:2025), dynamic charging lacks comprehensive interoperability standards. Moving from laboratory demonstrations to large-scale adoption requires global roaming standards for EV wireless charging, advanced thermal management, and policy mechanisms including renewable co-location and open patent pools.

Recommendations include completing DWPT standardization by 2028, deploying AI-native commercial control systems, and conducting life-cycle assessments to improve environmental impact.

Keywords: AI-native control; Dynamic electric vehicle charging; Inductive charging standards; Unmanned Aerial Vehicles (UAVs); Wireless power transfer (WPT)

1. Introduction

1.1. Background and Motivation: Limitations of Conventional WPT

Wireless power transfer (WPT) has emerged as a transformative technology for delivering electrical energy without physical connectors, enabling applications in consumer electronics, electric vehicles (EVs), medical implants, industrial automation, and autonomous systems [1]. By eliminating wired interfaces, WPT enhances system flexibility, reliability, and user convenience while supporting sealed, rotating, and mobile devices. Among the available techniques, near-field approaches, particularly inductive power transfer (IPT) and magnetic resonant coupling, have become the dominant technologies because of their high efficiency and operational maturity over short to medium transmission distances [2].

Despite these advances, several technical barriers continue to limit the large-scale deployment of near-field WPT. The most fundamental challenge is the efficiency-distance tradeoff, whereby transfer efficiency decreases rapidly as the distance between transmitter and receiver increases. Although optimized systems have demonstrated efficiencies exceeding 90% at distances approaching 200 mm, maintaining such performance over greater transmission ranges remains difficult [3]. A second limitation is frequency splitting (bifurcation), which occurs when strong magnetic coupling shifts the resonant operating point into two distinct frequencies, thereby reducing power transfer stability under variable coupling conditions.

While compensation networks can mitigate reactive power losses, they cannot fully eliminate bifurcation effects [4][5]. A third challenge is sensitivity to lateral and angular misalignment, which substantially reduces coupling strength and output power in mobile applications. Current standards, including SAE J2954, require wireless EV charging systems to maintain efficiencies above 85% under nominal alignment and 80% during misalignment, targets that remain difficult to achieve with conventional coil architectures [6][7]. Consequently, these limitations continue to restrict conventional WPT systems to carefully aligned, static operating environments, motivating the development of more robust wireless energy transfer technologies.

1.2. Emergence of New Paradigms: Topological Physics, Multiple-Input Multiple-Output (MIMO), and Dynamic Metasurfaces

To overcome the inherent limitations of conventional near-field WPT, researchers have developed innovative approaches rooted in topological physics, MIMO systems, and dynamic metasurface technologies. These paradigms enhance transmission robustness, improve efficiency, and extend operational flexibility under challenging conditions. Topological wireless power transfer (TWPT) exploits topologically protected edge states to achieve stable and efficient energy transmission despite structural imperfections and environmental perturbations. Unlike conventional relay-resonator systems, which are highly sensitive to fabrication errors and parameter variations, TWPT employs a one-dimensional Su-Schrieffer-Heeger (SSH) chain to confine energy within localized edge states, thereby maintaining high transfer efficiency at a fixed operating frequency even under disordered conditions [8].

Furthermore, optimizing intercell and coupling strengths enables exceptional-point operation, significantly enhancing energy transfer performance and robustness [9].

Another major advancement is MIMO-based WPT, which addresses the rapid decline in transfer efficiency caused by increasing transmission distance and receiver misalignment. By dynamically controlling the phase and amplitude of transmitter arrays, MIMO systems shape magnetic field distributions to maximize coupling efficiency. Optimization techniques, including the Nelder-Mead search algorithm, have demonstrated improved performance in both aligned and misaligned configurations, with MIMO architectures exhibiting substantially greater immunity to misalignment than single-input multiple-output (SIMO) systems [1, 2].

Dynamic metasurface antennas (DMAs) further extend WPT capabilities through programmable beam steering and adaptive electromagnetic field control. Operating in the radiating near-field region, DMAs generate highly focused energy beams that improve transfer efficiency while minimizing unintended electromagnetic exposure. Their applications include misalignment compensation for EV charging and electronically programmable beamforming using reconfigurable metamaterial surfaces, enabling precise and efficient wireless energy delivery in dynamic environments [3–5].

1.3. Lab to Real-World: EVs, Drones, and Renewable Integration

The maturity of these technologies is evident in their progress from laboratory demonstrations to real-world applications in electric vehicles, drones, and renewable energy integration.

Electric Vehicles: Dynamic wireless charging has reached an inflection point, enabling in-motion EV charging that reduces battery size and vehicle cost while eliminating charging stops [6]. Recent research has examined electromagnetic and circuit performance of EV wireless charging systems, with dynamic charging utilizing model predictive control for power transfer management [7]. WPT infrastructure has been explored for in-motion EV charging combined with IoT networks for automatic payments and addressing consumer range anxiety [8]. A sustainable EV wireless charging station integrating solar power generation and in-motion charging has been prototyped [9].

Unmanned Aerial Vehicles (UAVs): Charging of UAVs is another rapidly developing field. On-board power limitations restrict mission persistence, often requiring frequent landings. Conventional near-field WPT requires close proximity and precise alignment. Mid-air wireless charging using microwave WPT technologies and distributed tiled antenna architectures enables steady power reception under tilting and rotation during flight [10]. Deep reinforcement learning has been proposed to improve wireless charging power management, charging strategy, and trajectory optimization for UAVs under real-time conditions [11]. Commercial interest continues to grow with recent acquisitions of WPT developers by drone companies, demonstrating confidence in autonomous UAV applications with unlimited endurance [12].

Renewable Energy Integration: Wireless energy transfer is being applied to sustainable energy systems. Cooperation between solar energy generation and wireless charging enables island grid and hybrid grid applications independent of fuel sources [13].

1.4. Importance of Harmonized Standards for Commercialization

Alongside technological advancement, developing harmonized international standards is essential for achieving global interoperability and successful commercialization. The Wireless Power Consortium (WPC) Qi standard is the most widely adopted, having been used on over 1.5 billion devices worldwide. Qi specification version 2.0 achieved international standards status in 2025 under the IEC 63563 series, becoming one of the first official internationally recognized standards converted from an industry consortium specification [14]. The IEC 63563 series covers Qi wireless charging topics from introduction and terminology to power, communications, and security [15], providing compliance advantages regarding EU interface regulation and antitrust concerns. Additional specialized technical reports and safety standards have been developed. IEC TR 63239:2025 (2nd edition) specifies best practices for RF beam WPT solutions across applications, including the Internet of Things (IoT), medical devices, and electronic shelf labels [16]. Critically, the joint IEC/IEEE standard IEC/IEEE 63184:2025, published in February 2025, details methods for evaluating human exposure to RF fields from static WPT devices with respect to SAR, E-field, B-field, current density, and contact current for frequencies from 1 kHz to 30 MHz [17]. This standard provides the core foundation for ensuring safety and achieving approval for WPT devices across all power levels and applications.

At the regional level, progress toward normalization has accelerated. China has issued a group standard supporting high-power converged wireless charging up to 50 W, along with national standards for EV wireless charging communication protocols and interfaces [18]. Japan has streamlined certification procedures for near-field coupled WPT systems [19]. In Europe, the regulation on eco-design requirements for wireless chargers addresses sustainability concerns [20]. Due to rapid, simultaneous progress across technology levels, applications, and regulatory frameworks, this work presents a comprehensive, up-to-date global report on near-field WPT, focusing on recent advances in topological design, dynamic applications, and wireless standards development [18–20]. The presented article summarizes and reviews the fundamentals of WPT, MIMO, and DMA-based beamforming, including their characteristics in topological contexts. Further, exploring the transition of these technologies from laboratory experiments toward implementation in EV, drone, and renewable energy systems and surveys the existing landscape of global and regional standardization on safety, interoperability, and commercialization of WPT.

2. Foundational Principles of Near-Field WPT

2.1. Inclusive versus Resonant Coupling: A Brief

There are two main mechanisms prevailing in near-field WPT technologies: the inductive coupling (also known as "inductive power transfer" or "IPT") and the magnetic resonant coupling (also known as "resonant inductive coupling" or "magnetic resonance coupling"). Both methods transfer energy via time-varying magnetic fields over the air gap but operate in fundamentally different ways and hence offer different ranges of distances and target applications.

Induced coupling is the most recognized technique, which offers the most intuitive understanding and application in the market [21]. The simplest conceptual approach for IPT is inductive coupling, exploiting Faraday's law of electromagnetic induction to facilitate the transfer of power from a transmitting coil (T_x) carrying an alternating current to a nearby receiving coil (R_x), through time-varying magnetic fields which can induce a voltage in the coil. The principal power transfer efficiency (PTE) of a purely inductive IPT device is characterized primarily by the degree of mutual inductance M between coils and load resistance, decreasing rapidly with an increase in separation; and thus, a standard inductive power transfer system can generally transfer power over distances on the order of the coil diameter [21]. Hence, due to the relatively short coil separation distances involved, standard inductive systems are often applied in applications which naturally adhere to close-contact conditions, such as consumer mobile charging mats.

Magnetic resonant coupling (MRC), introduced in the form demonstrated in this work by the MIT research group in 2007 [22], addresses this limitation through the insertion of resonant capacitors in series with the transmitting and receiving coils, effectively making the coils a pair of coupled resonators. Driving the coupled coils at their resonant frequency produces power transfer via coupling through space from the magnetic field energy of the Tx coil to the electric field energy of the capacitive elements and allows for transfer distances significantly longer than the size of the coils. Resonant coupling can achieve long-range WPT by chaining several coils together into multiple relay structures. A comparative experimental demonstration shows a 13.45 MHz operating frequency magnetic resonance system can transmit higher energy efficiency over distance compared to a similar system at a distance when using only a simple magnetic system [23]. Trade-off: inductive systems [13]-[16] are cheaper, more tolerant of variation of component values, and better at very small distances (mm to cm) but have limited range, while resonant systems [17]-[20] are much better at transfer distances of tens of centimeters up to several meters and need good frequency match and more advanced impedance compensation circuitry.

2.2. Key Performance Metrics: Efficiency, Transfer Distance, Robustness and EMF safety

2.2.1. Power transfer efficiency (PTE): This is perhaps the most important performance parameter. For a resonant system, the maximum achievable efficiency can be observed when resonance is given by:

$$\eta_{max} = \frac{k^2 Q_T Q_R}{\left(1 + \sqrt{1 + k^2 Q_T Q_R}\right)^2}$$

Where,

k is the coupling coefficient, QT and QR denoting the respective quality factors for the transmitter and receiver coils.

Present-day systems achieve static DC efficiencies of 94% in optimal configurations [24]. For EV applications, a minimum of 85% is required for the system to adhere to industry standards at nominal alignment (minimum of 80% may be acceptable at a specific misalignment) [25].

2.2.2. Transfer Distance

The coil separation or transfer distance (distance from T_x to R_x coils) is a key parameter inversely affecting the efficiency for a given coil structure. This distance-efficiency compromise has spurred many coil optimization efforts. For perspective, typical near-field systems that employ resonant coupling techniques can transfer power across separations of approximately two to three coil diameters, whereas purely inductive coupling systems are generally limited to distances of less than one coil diameter. Emerging results based on large aperture designs indicate that the power available becomes nearly independent of distance at aperture dimensions of order or larger than the propagation distance (which redefines the above problem entirely) [26].

2.2.3. Robustness

Robustness can be defined as sustaining acceptable operation under different environmental and operating conditions, like load changes, coil misalignment, and ambient fluctuations. One of the most important solutions to realize this robustness property comes from adaptive impedance matching [27]. A comparative survey between the conventional resonant matching (RM), the adaptive impedance matching (AIM), and the hybrid approach has shown that AIM ensures a constant efficiency of 90.0 ± 0.9% in load variations (20-100), coil misalignment (0-30), and transmission distances (0.1-1 cm). The comparison of efficiency under deviations reveals a significant robustness of AIM compared to the traditional RM (50% misalignment and < 1 cm distances) [27], although it has lower efficiency in the ideal case

(95%). According to these quantitative characteristics, it is observed that in the dynamic aspect, the variation rate is 0.07 for AIM against 0.15 for RM, and the stability is 102 for AIM against 20 for RM [27].

2.2.4. Electromagnetic Field (EMF) Safety

This challenge becomes more acute as WPT technologies are scaled up to higher powers, particularly in automotive EV charging and industrial use cases, making human exposure compliance essential. Measures such as specific absorption rate (SAR), internal electric fields, current density, and contact currents, based on frequency of operation, are used to measure EMF safety compliance. The authoritative international standard governing human exposure to EMFs generated by static WPT is IEC/IEEE 63184:2025 for frequencies 1 kHz – 30 MHz [28]. It has recently been demonstrated that inherent multipath propagation within near-field beamforming of the transmitted field significantly mitigates radiation away from the receiver, increasing efficiency and simultaneously satisfying EMF exposure levels in proximity to infrastructure [26]. Metasurface technologies have also demonstrated good success in minimizing leakage while simultaneously maximizing efficiency [29].

2.3. Conventional Limitations of Frequency Splitting, Load Variation and Coil Misalignment

2.3.1. Frequency Splitting (Bifurcation)

Frequency splitting, alternatively known as bifurcation, appears when the value of coupling between the two resonant coils exceeds a specific limit, and the WPT power transfer efficiency reaches its peak not at the self-resonance frequency but at two frequency points symmetrically offset from it, due to impedance mismatch between the power source and WPT system input impedance in the closely coupled regime [30]. It's a critical issue, especially when applied in dynamic environments, where coils constantly move; in fact, impedance matching networks based on Perturb and Observe (P&O) techniques were employed to obtain the optimum compensation parameters with a single step to tackle it [30].

2.3.2. Load Variation

The WPT system's input impedance is strongly coupled with load variations (during the battery, offset, a minimum in the CC or CV region), which can lead to an efficiency decrease of 10-20% without a load adaptation method [27]. The experimental work mentioned previously stated how well this works: the resonance matching condition gave optimal efficiency at 50, while adaptive impedance matching gave comparable efficiencies over the 20-100 range, and it gave a 5% advantage in efficiency at 20, so an equivalent advantage of about 2.5% on average over the entire range compared to resonance matching [27].

2.3.3. Coil Misalignment (lateral, angular)

Coil misalignment, arguably the most critical aspect for practical applications, consists of misalignments between transmitter (Tx) and receiver (Rx) coils in lateral (parallel to the Tx coils' plane) or angular directions that reduce k and consequently decrease the WPT efficiency and the power transmitted. A review study summarized the different strategies to tackle this limitation, categorized in three fields: designing specific coil geometries (e.g., rectangular, circular DD, and 2.5% on bipolar pads) and their topological arrangements; reconfiguring compensation networks; and employing active impedance matching methods [31]. For instance, SAE J2954 standards on EV WPT dictate a 50% region, minimum efficiency of 80% with a 75 mm lateral offset and a 140-210 mm range of vertical distance between the charging pads [25]. It's hard to obtain this minimum efficiency with conventional passive WPT designs, motivating the design methodologies discussed in sections 3 and 4.

2.4. Roadmap of Recent Breakthroughs (2015-2026)

It is only during the past decade that there has been an increasingly steep and exciting innovation in near-field WPT, characterized by evolutionary improvements in coil design all the way through to radically redesigning the physics governing it. Table 1 is a chronological map of major innovations.

The trajectory of development is divided into passive, active, and intelligent systems. Initially (2015-2019), efforts were made on coil design and passive compensation network synthesis. In 2020-2022, metamaterial, metasurface, and topological physical concepts were introduced with external structuring of the EM environment, influencing radiation from the coils rather than reconfiguring the coils. Starting in 2023, attention was turned to intelligent reconfigurable/adaptive systems, where, besides existing MIMO schemes and DMAs, advanced reconfigurable active elements like PT-symmetric circuits and reconfigurable impedances using AI were explored and analyzed. Around the same time, standardization of this research domain reached the first major milestone: IEC/IEEE 63184:2025, a joint IEEE and IEC international standard that defines, for the first time, a globally applicable framework for the evaluation of EM field exposure of wireless power transfer systems [28]. Integration of the topological protection of the above-cited new and promising research domain with advanced signal processing features such as MIMO beamforming, focusing via metasurfaces, and adaptive impedance matching schemes by artificial intelligence forms the edge of the state-of-the-art that is further briefly discussed in Sections 3-6 [32].

3. Topological Designs for Robust WPT

3.1. Introduction to Topological Physics in Electromagnetics

Topological physics, initially an emergent field that explained topological phenomena in solid-state physics, such as quantum Hall effects, started to penetrate classical wave physics domains like electromagnetics and photonics a decade ago. The core idea of topological phenomena in solid-state physics is the existence of invariants, which can classify certain phenomena into distinct classes that never become extinct in the presence of disorder as long as there is a clear energy gap. Topological states are inherently protected from perturbations at the edges and boundaries of the materials [33]. In wireless power transfer, on the contrary, the conventional resonator-based array system is extremely sensitive to structural faults, parameter fluctuations, and any disturbances in the surrounding environment. The application of topology to designing robust, long-distance, high-efficiency solid-state WPT has been an emerging research topic [34].

3.1.1. SSH Model and Non-Trivial Topological Invariants

One of the most fundamental tight-binding Hamiltonians in 1D with non-trivial topology is the SSH model. Historically proposed as a model for polyacetylene chains, it describes a chain of periodic sites with alternating nearest-neighbor coupling constants between adjacent sites, which we can distinguish as intra-cell (t_1) and inter-cell (t_2).

$$H = \sum_m [t_1(|m, B >< m, A| + h.c) + t_2(|m+1, A >< m, B| + h.c)]$$

where $|m, A\rangle$ and $|m, B\rangle$ denote the two sublattice sites within unit cell m. Upon varying $t_1=t_2$, the system shows a Topological phase transition between a topological non-trivial insulator with a non-zero winding number (Zak phase) for $t_1<t_2$ and a trivial insulator for $t_1>t_2$ [35],[36]. The winding number, for the topologically non-trivial phase, is 1 and can be calculated from the bulk band structure using:

$$\nu = \frac{1}{2\pi i} \oint \frac{d}{dk} \log\left(\frac{t_1 + t_2 e^{-ik}}{t_1 + t_2 e^{ik}}\right) dk$$

This invariant fundamentally distinguishes the two phases and dictates the emergence of localized boundary states.

3.1.2. Edge States and Their Immunity to Disorder

A fundamental principle in topological physics is the bulk-edge correspondence, which claims that a non-trivial bulk topological invariant must imply edge states protected by topology localized at the boundaries of a finite system [37]. For a finite SSH chain terminated so that the coupling strength t2 links the outermost two sites to the vacuum, two zero-energy degenerate edge states appear in the bulk bandgap. The two edge states localize exponentially at the two ends of the chain, with localization length determined by $\xi = 1/\ln(t_1/t_2)$. A key observation for WPT is that these two edge states do not hybridize or destroy themselves due to disorder that is chiral-symmetry breaking with respect to the SSH Hamiltonian.

3.2. Topological WPT System and Architecture

However, to translate topological edge states into a practical WPT system, the physical resonator array should be properly designed to embody the SSH Hamiltonian and avoid spurious couplings that would break the desired symmetry.

3.2.1. One-Dimensional and Two-Dimensional Topological Resonator Arrays

The most studied and first implemented 1D topological WPT is the SSH chain realized using magnetically coupled resonant coils, each designed to resonate at the same frequency f_0. By positioning the coils into a dimerized format with a repetition of tight-inter-cell spacings (k_2) and loose intra-cell spacings (k_1), or vice versa (tight intra-cell spacing and loose inter-cell spacing, $k_1 < k_2$), a chain supporting topological edge modes at both ends emerges in the non-trivial phase. The energy, once launched into one of the edge modes by being driven at the resonant frequency, flows towards the other end while minimal energy lies in the bulk. The architecture in the reported work shows an arrangement where a tightly spaced intra-chain coupling leads to its corresponding open circle (the edge mode) [38]. A more comprehensive scheme for 2D structure discussed in section 3.2.1(2) uses the same approach.

3.2.2. 2D Topological Resonators for Wireless Power Transfer

The SSH concept has been extended to higher spatial dimensions and realizes multiple load power delivery. By considering a 2D SSH square lattice where each cell hosts one resonator and is coupled only to its nearest neighbor, four topological corner states (TCSs) exist. These are zero-dimensional corner states, thus higher-order topological phases. According to the comprehensive survey presented by Wu et al., three primary architectures of topological WPT were identified: (1) periodic 1D topological structure, for which SSH chains served as primary candidates; (2) aperiodic 1D topological chains, which included, besides the SSH defect site interface, quasi-periodic chains; (3) 2D higher-order topological corner states. Building upon an advancement in using bilinear topological structures and adding next-nearest-neighbor coupling, it becomes possible to demonstrate dual TCSs [25], which makes it easier to apply to a wireless power transfer network containing multiple receivers.

3.2.3. Defect-Immune Power Transfer under Frequency Detuning

In addition, topological defect states provide another channel for robust WPT against multiple loads. By designing a composite chain with two topologically different SSH arrangements with a gapless chain of homogeneously coupled resonators inserted between the two SSH regions, it was possible to induce a large-area topological defect state (LADS) with localized energy, which can deliver energy to multiple target sites dispersed in space, using only one source [3]. Most importantly, topological WPT can be more robust against frequency deviation. As compared to conventional resonant WPT systems, where the deviation of system parameters or load not only reduce but even cause a collapse of the efficiency, certain deviations in the frequency of bulk resonators do not break the topologically protected transmission paths. The total energy will flow along the topologically localized edge states, and high-energy transmission efficiency can be realized even in the presence of disorder, which was also confirmed experimentally [38].

3.3. Experimental Demonstrations and Performance Benchmarks

Various experimental evidence proves the possibility and the performance improvement of topological WPT. A milestone result in 2021 by Zhang and co-workers demonstrates a 1D radiowave topological insulator consisting of 10 coil resonators with alternating coupling strengths (t_1, t_2) in series. When the configuration was non-trivial ($t_1 < t_2$), their measurements show the power transfer efficiency of about 80% between the two ends at resonance, while less than 30% in the trivial configuration (t1 > t2). Under random perturbation of coupling coefficients (simulating displacement and fabrication error), the topological chain is only slightly impacted, but a uniform chain collapses [35].

More recently, Wan and co-workers proposed and experimentally demonstrated a large-area defect state for multi-load WPT simultaneously. Based on a chain consisting of 15 coil resonators, two topological segments with distinct SSH parameters coupled through a homogeneous segment, at the defect frequency, a large-area defect state concentrates uniform energy on several designated sites to drive multiple LED loads simultaneously. Furthermore, the LADS maintained over 85% of ideal power transfer efficiency, compared with a conventional uniform chain, which declined to less than 40% even under random positional displacement as high as 10% coil spacing [3]. And it also has been shown that by using topological defect states at the junction of two dimer chains, multi-load WPT could achieve much higher efficiency than traditional uniform WPT chains [34].

3.3.1. Efficiency versus Misalignment: Comparison with Conventional WPT

The comparative performance of topological WPT against conventional designs under misalignment is particularly striking. Table 2 summarises key experimental benchmarks. The data indicates a sharp efficiency reduction in conventional systems as the coupling coefficient departs from the specified design parameter, whereas the efficiencies of topological systems are less affected due to the stability brought by edge modes. The robustness of the system means that real-world applications such as charging pads for EVs or medical devices can overcome challenges like inaccurate coupling or positioning.

3.4. AI-Enabled Topological Optimization

The high-dimensional and non-convex parameter space associated with the design of a topological WPT system comprising coupling strengths, number of resonators, frequency detuning, load impedance, and so forth, poses a challenge for complete exploration. Hence, various efforts have been devoted to accelerate or enhance optimization using artificial intelligence and machine learning (ML) recently. Wang et al., developed a creative cooperative optimization process using a gradient descent optimization algorithm (GDOA) coupled with non-Hermitian topological physics for accurate manipulation of the coupling strength distribution of an SSH-like chain [4]. With an ML-optimized setup, 65% efficiency was achieved forlong-range transmission, and 57.9% efficiency was achieved with 30% structure perdurability [4]. In comparison to standard SSH chains with an efficiency of 45.6% under 30% structural perturbations and a uniform chain with 24.1%, the coupled ML-assisted WPT design demonstrated significant advantages [4]. The fusion of non-Hermitian physics, topological physics, and machine learning represents a promising opportunity in the field of near-field wave functional devices, which could have broad applications for medical implant devices, or even in medical robotics [2]. Except for the gradient descent-based method, deep learning has been applied in topological optimization. As has been reported by Zhang et al., machine learning can be successfully applied to SSH-like chains in optimizing transmission efficiency and robustness [2]. Such a machine learning approach offers more efficient high-dimensional navigation capability than the traditional tuning approach in finding desired topological properties [39].

3.5. Current Changes and Future Directions

Nevertheless, despite this promising advancement, challenges in scaling up the technique must be overcome before topological WPT is widely implemented commercially. Perhaps the biggest challenge is one of scalability. To date, the largest demonstrations of topological WPT devices comprise fewer than 20 resonators. However, for WPT across a large area, such as within a room, on a roadway, or in a smart building, much larger arrays are needed. Scaling up these devices brings the problem of parasitic coupling, or unintended coupling between non-adjacent resonators. This breaks the chiral symmetry, which is what makes WPT topographically protected [38]. The cost and technical difficulty of manufacturing large, precisely aligned arrays with consistent coupling strengths remain barriers as well.

Another significant challenge concerns dynamic reconfiguration. In most demonstrations, topological protection is a static feature, since the SSH chain has been manufactured with fixed coupling strength; this has locked in the particular topology. However, in real-world applications, it must be possible for wireless power transfer systems to adapt dynamically to various loads, distances, and misalignments (especially necessary for dynamic charging of electric vehicles or at drone docking stations). Ongoing efforts are focused on developing methods of ‘tuning’ the topological phase so that coupling strengths can be altered: for example, by adding varactors (voltage-controlled capacitors), or micro-electro-mechanical (MEM) devices to control the signal coupling between resonators or using tunable metamaterials. Some success using nonlinear gain elements and higher-order PT symmetric systems in varying power transfer distances [3], but reconfigurable topological devices as a general concept remain an open area of study.

4. Methodology Description

This study employs systematic literature review methodology to comprehensively analyze near-field WPT technologies, their topological designs, dynamic applications, and global standardization frameworks. The methodology follows established guidelines for systematic reviews in engineering and technology domains [40], [41].

4.1. Literature Search Strategy

A systematic search was conducted across major academic databases including IEEE Xplore, Scopus, Web of Science, and Google Scholar to identify relevant peer-reviewed publications. The search strategy employed Boolean operators combining keywords related to near-field WPT technologies, topological designs, MIMO systems, dynamic applications, and standardization. Primary search terms included: "wireless power transfer," "inductive charging," "topological WPT," "dynamic wireless charging," "electric vehicle charging," "MIMO WPT," "metasurface antennas," and "WPT standards." The search was restricted to publications from 2020 to 2026 to capture recent advances, with particular emphasis on studies published between 2024 and 2026 that represent the cutting edge of research [33], [42]. Additional sources included official standards documents from the International Electrotechnical Commission (IEC), IEEE Standards Association, SAE International, and International Organization for Standardization (ISO), and the Wireless Power Consortium (WPC). Technical reports, white papers from industry leaders, and field trial documentation were also incorporated to provide practical implementation perspectives [43].

4.2. Selection Criteria

Publications were selected based on the following inclusion criteria: (1) peer-reviewed journal articles, conference proceedings, and official standards documents; (2) focus on near-field (non-radiative) WPT systems including inductive, capacitive, magnetic gear, and resonant coupling technologies; (3) relevance to topological designs, beamforming techniques, or dynamic applications; (4) provision of experimental results, simulation data, or field trial evidence; and (5) publication in English. Exclusion criteria included: (1) studies focusing exclusively on far-field WPT (microwave, laser); (2) publications without clear technical contributions or empirical validation; (3) duplicate publications; and (4) studies not meeting quality thresholds based on citation impact and methodological rigor [44].

4.3. Analytical Framework

The analytical framework was structured across three interconnected dimensions: technological innovation, application deployment, and standardization readiness [45]. For technological analysis, WPT topologies were classified and compared based on power levels, efficiency, spatial freedom, and commercial maturity. Performance metrics including power transfer efficiency, transfer distance, robustness, and electromagnetic field safety were systematically evaluated. For application analysis, field trials and commercial deployments were examined across electric vehicle charging, drone operations, and renewable energy integration. For standardization analysis, international, regional, and safety standards were mapped against technological maturity levels [36].

4.4. Data Extraction and Synthesis

Data extraction was performed systematically to capture key parameters including system architecture, power ratings, efficiency values, misalignment tolerance, and standardization status. Comparative tables were constructed to enable direct performance comparisons across different WPT paradigms [38]. The synthesis approach integrated findings across technological, application, and standardization dimensions to identify trends, gaps, and future research directions. Machine learning and AI-enabled optimization techniques were analyzed separately as emerging cross-cutting technologies [1]. This multi-dimensional framework ensures comprehensive coverage while maintaining analytical clarity.

4.5. Limitations

The methodology acknowledges certain limitations: (1) the temporal scope (2020–2026) may exclude earlier foundational work; (2) the focus on near-field WPT limits applicability to far-field technologies; (3) reliance on published data may introduce publication bias; and (4) rapid technological evolution means some findings may require periodic updates [2].

5. Advanced Beamforming and MIMO Techniques

5.1. Large Aperture Near-Field Beam Focusing

A fundamental challenge of typical wireless power systems is the path gain, which decreases rapidly as a function of propagation distance. The received power from a transceiving antenna of physically small aperture decreases approximately as 1/d in the far-field and at an even faster rate in the near-field. This limitation of small transmit antennas leads to an alternative strategy: not to radiate using far-field beamforming, but to focus the emitted power to the near-field device using large aperture devices.

Decoupling the Path Gain from Distance: Researchers Da Costa and others [26], [25] show there is a family of systems, which they refer to as large aperture systems, wherein if the physical size of a transmitted antenna is compared with the distance the receiver is located relative to the transmitter, then the path gain is roughly independent of distance from transceiving antennas. The logic is that the physical size of the aperture permits a maximum focused power density to be achieved at the desired remote location using a spherical wavefront within the Fresnel region of the radiated field, instead of a planar wavefront as it is assumed in far-field operation. In these cases, there exists a set of array gain patterns which exactly balance off the loss of free-space path loss. It can be shown that the power density generated by a uniformly excited rectangular antenna of size $L_x \times L_y$ with antenna aperture width L_l and height L_h on the axis at distance z is proportional to:

$$P_{rec} \propto P_{tx}.\frac{L_x L_y}{\lambda^2}.\sin c^2\left(\frac{\pi L_x \Delta x}{\lambda z}\right)\sin c^2\left(\frac{\pi L_y \Delta y}{\lambda z}\right)$$

Such that the array gain $L_x L_y / \lambda^2$ is independent of the distance. If the aperture sizes $Lx \sim Ly \sim z$ such that $L_x L_y$ grows quadratically with z, the inverse square propagation losses are exactly cancelled, providing a system that can deliver milliwatt-level power to IoT devices below 10GHz while being within human safety regulations [25]. Experimental validation through real measurements shows that the optimal beam focusing points on the device to maximize efficiency always takes into account multi-path propagation to improve safety too. By limiting power intensity around the transmitting system and concentrating it on the device, these large aperture systems can simultaneously optimize the conflicting requirements for efficiency and safety regulation [26], [25].

5.2. Dynamic Metasurface Antennas for SIPT

Dynamic metasurface antennas are one of the more popular examples that implement large-aperture near-field focusing. Whereas phased arrays need their individual active radio frequency (RF) chain per element, which implies unacceptable hardware cost, power consumption, and hardware complexity, a DMA can achieve an electrically large array configuration with only one RF feed and a planar array of adjustable metamaterial elements [38]. This configuration is naturally a good match for WPT.

5.2.1. Non-Orthogonal Multiple Access (NOMA) SWIPT Integration: Efficiency Improvement (1.16)

There have been quite a few recent investigations on applying the combination of NOMA and SWIPT in near-field scenarios [44], [46]. Typical SWIPT assumes a far-field scenario and steers the radiated energy towards designated angles. The efficiency gain may not be so good, and some energy might be radiated to unwanted locations. By moving the SWIPT into the transmitting near field (Fresnel region) with a DMA, the spherical wavefront of electromagnetic radiation brings more degrees of freedom, which could be utilized for focusing the energy transfer [44]. In the reported research, it is confirmed that the DMA-empowered near-field NOMA SWIPT gains as high as 1.16x improved energy transfer efficiency as compared with conventional near-field SWIPT systems and meanwhile maintains a good fairness among users by performing joint optimization of the DMA weights and digital precoding vectors [46].

Dynamic metasurface antennas represent a particularly promising implementation of large-aperture near-field focusing. Unlike conventional phased arrays that require a separate active RF chain per element, leading to prohibitive cost, power consumption, and hardware complexity, DMAs efficiently realize electrically large arrays using a single RF feed and a planar array of tunable metamaterial elements [55]. This architecture is ideally suited for wireless power transfer applications where cost and power efficiency are critical.

5.2.2. Fresnel Zone Focused Beams for Multi-Device Charging

A holistic scheme for DMA-assisted near-field beam focusing on multi-device charging in the Fresnel zone has already been reported [45]. DMA is viewed as an electrically large antenna array capable of transmitting a focalized energy beam utilizing spherical wave propagation. Weighted sum harvested energy maximization is formulated and efficiently solved by joint DMA weights and digital pre-coding vector design, considering various hardware limitations such as DMA element discrete phase shifts.

As seen in Fig. 1, it was observed that the normalized power density distribution at the observation plane (z = 1 m) when the DMA phases are configured to converge beams on the target at location device 2 in coordinates (0.15 m, 0.15 m) when using a 4-bit phase discretization. Sharp focuses were achieved at exactly the target device's coordinate, whereas low power densities were found throughout the remainder of the observation plane and therefore little or no electromagnetic interference was expected, in line with Ref. 58, where the researchers employed a similar concept to simultaneously charge multiple targets, though in a more far-field condition. The focused beam width (FWHM) is roughly 0.07 m, implying devices can be very densely populated on the plane, such that their closest distances are less than 7 cm. As confirmed by the simulation, the proposed system enables efficient power beaming to multiple devices in near-field radiation and causes relatively low energy pollution, which has been widely recognized as a crucial aspect in modern efficient and compliant RF wireless power transmission [45].

Fig. 2 gives an example where two independent beams are simultaneously focused at two devices, one in the center of the transmitting aperture (device 1) and the other at (0.15, 0.15) (device 2). This provides a clear illustration of two power peaks at the location of the desired devices with minimum overlap. As observed, DMA can be utilized to focus the beam on multiple devices simultaneously with minimum interference and low energy loss. This pattern can be realized either in time or orthogonal coding and verifies our prediction regarding multiple devices focusing on using DMA from [48].

5.3. MIMO-Based Misalignment Tolerant WPT

In contrast to the aforementioned techniques focused on near-field focusing, the MIMO approach seeks to address one of the greatest challenges faced by wireless power transfer systems: their vulnerability to the alignment issue. This system can deliver efficient energy transfer even when T_x-R_x is misaligned. By shaping the overall radiated magnetic field using a set of transmit and receive antennas, the efficiency can be maintained.

Nelder Mead Optimization for Adaptive Amplitude/Phase Control: The efficiency of the power transfer in MIMO WPT is strongly dependent on the optimal setting of amplitudes and phases of each signal. It is possible to determine these parameters by knowing the values of the S-parameters (scattering parameters) of the setup. The values of these parameters depend on the external environment as well as on the T_x-R_x alignment. The Nelder-Mead optimization algorithm is selected because it does not need the gradient information, which is typically expensive to calculate and not readily available for a system, especially in a dynamically varying environment. Also, the objective function, the WPT efficiency, is not smoothly varying; it's usually characterized by multiple peaks and hence not readily suitable for other optimization algorithms. The experiment clearly shows much smaller degradation of efficiency in their MIMO WPT configuration in comparison to single-input single-output (SISO) systems and even SIMO [45].

5.4. Comparative Analysis: Topological MIMO and Conventional Approaches

In this section, a comparative summary of the presented novel techniques, including the topological designs, large aperture/DMA focusing, and MIMO configurations, in light of conventional WPT methods, is presented. Table 3 includes a comparison based on various performance metrics. The comparison reveals that no single paradigm dominates all metrics. Topological WPT excels in robustness and multi-load support but is currently limited in range and static in design. Large-aperture/DMA systems enable long-distance, multi-device charging with low hardware complexity and favourable regulatory characteristics, but require the aperture to be physically large, a condition that is naturally satisfied in 6G-era distributed antenna systems but may be impractical in some form-factor-constrained applications. MIMO systems offer active misalignment tolerance and high efficiency but at the cost of multiple active RF chains and complex optimization.

5.5. Open Research Issues

5.5.1. Real-time control and adaptation

Most demonstrated MIMO and DMA systems require a complete channel estimation cycle (S-parameter measurement) before optimization. In dynamic environments, such as a moving vehicle or a robotic system, the coupling matrix changes on millisecond timescales. Reducing the latency between measurement, optimization, and reconfiguration is a key challenge. Early efforts using reinforcement learning for dynamic WPT control have shown promise: a twin-SAC² reinforcement learning controller implemented on a Siemens S7-1500 PLC achieved settling times under 14 ms and stable operation at 140 km/h in simulation [58]. Translating such approaches to near-field MIMO and DMA systems remains an open problem.

5.5.2. Hardware Complexity and Cost

While DMAs reduce the number of active RF chains dramatically, a single feed can drive hundreds of metasurface elements; the overhead of tunable elements (varactors, PIN diodes, or MEMS switches) and the associated control circuitry is non-negligible. Furthermore, the discrete phase shifts available in practical DMAs introduce quantization losses. The design of low-cost, low-power, high-speed tunable metamaterial elements is an active area of materials and device engineering.

5.5.3. Scalability to high power

Most large-aperture and DMA demonstrations operate at milliwatt to watt power levels, suitable for IoT devices but far below the kilowatt levels required for EV charging. Scaling these techniques to high power introduces thermal management challenges, nonlinear effects in the tunable elements, and more stringent EMF compliance requirements. The interaction between the focusing system and the power converter circuitry (rectifiers, DC-DC converters) is also nonlinear and not yet fully understood.

5.5.4. Integration with Power Electronics

The inherent nonlinear behavior of the battery loads as well as the rectifiers can affect the optimal field distribution pattern, and the dedicated RF field can result in the saturation or reverse leakage of the rectifiers. To realize high DC-DC efficiency, the radiator system should be designed together with the power management circuitry and should not be handled as two distinct modules.

Fig. 3 describes key technical impediments to developing DMA and high-power large-aperture WPT. The top-left subplot reveals the considerable range of power levels from typical IoT devices up to EV chargers (e.g., from 10 W up to ~1-5 kW, an ~8 order of magnitude increase). This difference underscores the limits of scaling WPT architecture Shinohara, 2014. The top-middle subplot shows a thermal constraint where power dissipation dramatically overwhelms the limits of a power-bearing device or system in operation. The temperature rises beyond reasonable operation (above 85°C) or the junction limit (125°C), prompting significant thermal dissipation effort Sample et al., 2013. The top-right subplot shows non-linearity or saturation in the power rectifier/converter-conversion efficiency is optimized at around 80% at the right power levels but suffers from a loss of efficiency at higher power levels due to rectifiers becoming nonlinear at high power levels. The bottom-left subplot highlights electromagnetic (EM) field safety issues, wherein increased beam-steering mismatch is associated with greater exposure to fields off the intended target region, as delineated by international limits ICNIRP, 2020. The bottom-middle subplot depicts the interplay of power converters, where the efficiencies are strongly dependent on matching of electrical loads. Finally, the bottom-right radar plot identifies essential shortcomings in the state of standardization, with particular attention required to the standardization of systems providing dynamic beamforming, enabling fault tolerance, providing for continuous and autonomous control, and facilitating broad implementation. In summary, the implementation of high-power DMA WPT systems has significant hurdles: the thermal, rectifier linearity, safety, and related system issues-and the necessity to standardize it-cannot be ignored.

6. Dynamic Applications: EVs, Drones, and Renewables

6.1. Electric Vehicle Wireless Charging: The Tipping Point

EV charging, a.k.a. Electric vehicle wireless charging (EVWC), promises convenience, safety, and better infrastructure integration that has a clear impact on the adoption of EVs. EVWC systems can be divided into stationary wireless charging systems (SWCS) for parked vehicles and dynamic wireless charging systems (DWCS) where charging is achieved when a vehicle is in motion. [50]

6.1.1. Static Charging: Porsche 11kW system (90% efficiency)

A major commercially available success of static EVWC has been Porsche's production-ready 11 kW wireless charging system, introduced at the 2025 IAA MOBILITY, and the company is the first automotive manufacturer to offer a 11kW system to its customer base, which is ready to go into series production on a unique 11 kW system which includes both the pad as a one box unit that simply connects to the grid, as the name suggests, is a home system designed to replace conventional wired A/C chargers, charging up to an efficiency of 90 percent from a power grid to the battery level - precisely the same as wired AC charging. The system, with a flat floor plate measuring 117 × 78 × 6 mm and capable of installation on garages or outdoor parking places - without a carport or dedicated control box- is coming to market in 2026 with the brand's latest generation of fully electric SUVs [47]. This fits with customer preferences, with 83% of American EVs charged domestically [47].

Farghly et al. [51] have provided a comprehensive review of various WPT methods for EVs (e.g., inductive coupling, capacitive coupling, magnetic gearing, resonant inductive) in terms of operation frequency, efficiency, EMI, EVWC compatibility, control and adaptation. They also emphasize the implementation of compensation topologies such as serial-serial, serial-parallel, parallel-parallel, and hybrid LCC-LCL topologies for improving the transfer efficiency, especially under varying alignment conditions [51]. They discuss available control techniques such as proportional-integral, passivity-based, adaptive, Model predictive control, sliding mode, adaptive passivity, and intelligent control approaches to adapt system dynamics according to power requirements, dynamic load conditions, and variations. The incorporation of artificial intelligence, edge devices, and dual-side control systems is analyzed to build a fully autonomous EVWC in order to make it practical for static and dynamic systems [51].

6.1.2. Dynamic Wireless Charging (DWCS): in-road coils for charging while driving

DWCS is leading edge in EV charging technology; rather than placing receiver coils on the EV (e.g. Stationary Wireless Charging (SWC)), a transmit coil is laid below the surface of the road and power is transmitted while the vehicle is charging as it moves. The technologies have the capacity to reduce battery size, remove stop time for charging, and decarbonise freight transport [52]. The most advanced DWCS demonstration to date is France’s “Charge as you Drive” project on the A10 motorway, approximately 40 km southwest of Paris. Following laboratory testing and full-scale trials on a closed site where traffic simulators reproduced the equivalent of at least 25 years of heavy truck traffic, induction coils were installed over 1.5 km of roadway [53]. Real-world tests conducted by three laboratories from Gustave Eiffel University confirmed that the installed inductive system can safely deliver peak power above 300 kW and average power above 200 kW under optimal steady-state conditions [53]. Prototype vehicles including a heavy-duty truck, utility vehicle, passenger car and bus are now driving on the motorway under real traffic conditions. Nicolas Notebaert, CEO of VINCI Concessions, noted that deploying this technology on France's main road networks will accelerate the electrification of heavy-vehicle fleets, reducing greenhouse gas emissions from the freight and logistics sector, which accounts for more than 16 % of the country’s total emissions [53].

In the United States, Purdue University and the Indiana Department of Transportation (INDOT) successfully tested the first highway segment in the U.S. that wirelessly charged an electric heavy-duty truck driving at highway speeds. The quarter-mile stretch on U.S. 52/U.S. 231 in West Lafayette demonstrated a key technology that could lower the costs of building electrified highways [49]. “This is a total paradigm shift in the transportation and power industries,” said Professor Nadia Gkritza of Purdue University. “We are moving away from the traditional gas station/charging bank model to bring the charge to the vehicle. That means vehicles will use smaller batteries and will experience less downtime” [49].

Italy has also deployed dynamic wireless charging infrastructure on the A35 Brebemi motorway connecting Brescia and Milan. Iveco placed the first road-ready eDaily electric light commercial vehicle equipped with both dynamic and static wireless charging into service, following nearly a year of testing at the Arena del Futuro site [54]. The vehicle will be used for personnel operations along the route on a 36-month lease, demonstrating how DWPT can effectively support daily operational needs while ensuring safety and service continuity [54]. Experimental evaluations of prototype DWCS systems report charging efficiencies between 40 % and 55 % at optimal coil alignment and spacing, with modular designs exemplifying scalable cost-effective solutions for future smart highway integration aimed at reducing battery size and enhancing EV usability [55]. Anwar Al Deiri et al. [52] critically review the latest research on transmitter and receiver coil design for both stretched and segmented tracks, addressing in detail different topologies of magnetic couplers.

6.2. Drone Applications

With the integration of WPT and UAVs, industrial, logistics, and public safety drones are now able to conduct fully autonomous operations for extended periods, such as continuous industrial manufacturing or constant surveillance. Automated drone charging pads utilize automated precise positioning technology, data transmission technology, and weatherproof casing, and they form a complete unmanned aircraft base station. When drones land, they automatically return to the origin location, automatically enter the charging slot, starts charging, with the inclusion of reserved multi-interface serial ports to allow for future scalability of the overall system [56]. Wireless drone charging supports free calibration charging, full compatibility with all types of drones, safe connection, and environmentally resistant charging [56]. The global drone charging pad market will only see an increase as more and more applications, such as use in agriculture, building construction, inspecting facilities, photography, package delivery, and spying, continue to use drones [56]. [57]

An example of an automated drone charging pad is an Intelligent Unmanned Airport developed by Honeycomb Aerospace, the SU50Pro, which consists of one intelligent inspection UAV and an Intelligent Unmanned Airplane Station that can remotely command the UAVs for autonomous charging, autonomous take-off and landing, and unmanned clustered flight [58]. Further commanding for weather, high-frequency UAV inspection tasks without human intervention, offering excellent performance for long-distance and mass inspection tasks of oil & gas pipelines, the management and prevention of oil & gas fires, and management of border, coastline, river, and road monitoring [58]. Similarly, the ALTUS Drone Hangar allows UAVs to automatically take off, land, and dock at the docking station, which is included with the docking of Wireless charging, so the drone would always maintain sufficient power for use [59].

6.3. Integration with Renewable Energy

6.3.1. PV-powered wireless EV Charging

Kaewthep et al. [60] described the development of a high-efficiency, eco-sustainable charging system for a fully autonomous EV that utilizes solar PV as the renewable power source for wireless EV charging, termed a "green autonomous EV". The solar energy harvested through a PV array is coupled with a wireless power transfer system, providing charging capabilities of 3.3 kW, compliant with relevant wireless power transfer standards like SAE J2954, along with guaranteed eco-sustainability through PV usage. PV-powered EV-autonomous wireless charging is presented as one solution for islanded applications, promoting renewable energy for EV charging applications to cut CO_2 emissions [60]. In the European Union Horizon project "Wireless Power Train for Electric Vehicles," a solar PV-integrated EV wireless charger was developed with automatic transfer support to the utility grid. This wireless charger operates independently of a renewable energy source (hence irrespective of weather-related gaps). The zero- emission charger offers an independent power source for recharging cars regardless of their parked location, which guarantees charging regardless of any grid failure, leading to the elimination of range anxiety for users [61].

6.3.2. Grid-independent and Hybrid Systems

Beam Global and HEVO Inc. have launched a market-ready integrated autonomous wireless charging system that combines HEVO's Rezonant wireless charging hardware with Beam Global's EV ARC off-grid, solar-powered EV charging infrastructure [62]. EV ARC provides integrated solar generation and energy storage, enabling grid-independent operation without trenching, utility interconnection, or permanent construction. Thousands of Beam's EV ARC systems are deployed globally, providing grid-independent, construction-free charging infrastructure. Beam Global also holds a U.S. patent covering a wireless/inductive EV charging system powered by renewable energy [62]. "The all-in-one solution is geared for autonomous fleet operations and larger commercial EV fleet applications where charging automation is needed. Potential use cases are logistics fleets, fleet services in urban or private areas, municipality fleets, campus transit systems, and other highly utilized fleet environments where uptime and efficient operation are the norm" [62].

6.4. Case Studies and Field Trials (2024-2026)

Between 2024 and 2026, several large-scale DWPT field trials will progress beyond closed-track testing into real-world highways.

- France A10 Motorway (2025-2026): the world's first dynamic wireless charging of EVs in a real-world motorway, an A10 segment over 1.5 km featuring coils delivering power above 300 kW to four prototype vehicles in actual traffic (one heavy truck, one utility, two passenger cars, and a bus). Technology is already undergoing 25-year lifespan durability testing following laboratory tests [53] [63].
- Purdue University/INDOT (2024-2025): first U.S. Highway (quarter-mile segment of US 52/ US 231 in Indiana) segment ever deployed to dynamically charge an electric heavy-duty truck at high speed. First

installation took place in 2024, with field demonstration and vehicle integration following in 2025 [49].

- Italy A35 Brebemi Motorway (2025-2026): Commercial launch of the eDaily vehicle, with integrated dynamic and static wireless charging, onto the A35 motorway after successful demonstration in Arena del Futuro. The project will feature a 36-month operating lease to demonstrate commercial viability [54].
- Germany E|MPOWER Program (2025-2026): The section for dynamic wireless charging of motorways in Germany will utilize Electron's wireless charging technology, and construction work is planned to commence in summer 2025 [64].
- Beam Global/HEVO off Grid Deployment (2026): The Company announced in October 2022 the commercial deployment of solar-powered and off-grid wireless EV charging systems for autonomous fleet operation [62].

6.5. Remaining Challenges: Costs, Infrastructure and Thermal Management

The commercial viability of wireless charging solutions continues to face several technical and economic barriers. Investment costs for wireless EV infrastructure remain significantly higher than those of conventional wired systems [65]. For DWCS, installation requires excavation and resurfacing of roadways, embedding of coils and power electronics, and construction of supporting roadside power infrastructure. Additional constraints include lower power-transfer efficiency relative to wired charging, elevated installation and retrofitting expenses, incomplete international standardization, and stringent electromagnetic compatibility (EMC) and safety certification requirements [66]. Infrastructure-integrated wireless solutions are particularly suited to autonomous and high-utilisation commercial fleets, including logistics, municipal, and campus mobility systems, where continuous operation and reduced downtime are critical [62].

Thermal Management at power levels of 100 kW and above: Joule heating and magnetic hysteresis generate substantial thermal losses that limit efficiency, performance, and safety [67]. These losses raise component temperatures, shorten operational lifespan, and risk damage to electronic systems. Mainstream cooling approaches include air cooling, fluid-based methods (immersion, microchannels, phase-change materials, nanofluids, and heat pipes), and hybrid combinations. Microchannel and phase-change-material systems have demonstrated the ability to keep megawatt-level coil temperatures at 108 °C and heating-plate temperatures below 80 °C. Nevertheless, residual heat dissipation through air remains inefficient, while EMC performance, compact packaging, and dynamic responsiveness require further improvement [67]. Additional risks encompass electromagnetic field effects, thermal hazards, accelerated battery degradation, coil misalignment, and the long-term maintenance of embedded roadway electronics [68]. Future research must prioritise advanced thermal architectures that balance cooling performance with efficiency, including eddy-current cancellation techniques and EMI-optimised phase-change-material enclosures [67] [69].

7. Global Standards and Safety Regulations

7.1. International Standards

For consumer WPT applications, the IEC and WPC set international standards for low- and medium-power WPT applications, respectively. Their work complements the power level and operational frequency spectrum.

7.1.1. WPC Qi2: 25 W (v2.2.1) and IEC 63563 Adoption

Still dominating the consumer wireless power market is the Wireless Power Consortium (WPC) with its Qi standard. In July 2025, the WPC unveiled Qi version 2.2.1 under the branding Qi2 25 W, nearly doubling the original Qi2 power output of 15 W and addressing the growing demand for faster, more efficient wireless charging [70]. Fourteen devices, including receivers, transmitters, and complete systems, from multiple manufacturers have already completed Qi2 25 W certification in a limited pilot, with full certification testing for several hundred additional products underway [70]. Beyond the higher power rating, the standard incorporates several technical improvements. The Magnetic Power Profile (MPP) optimizes coil alignment to improve transfer efficiency and reduce losses caused by misalignment [71]. Strict thermal management protocols ensure surface temperatures remain below 40 °C during normal use, while enhanced Foreign Object Detection (FOD) prevents inadvertent heating of metallic objects [71]. Updated Magnetic Power Level Agreement 2 (MPLA2) and Mated Q specifications further increase efficiency and optimize performance for wireless power accessories [71].

In addition, the Qi specification has been formally adopted as an international standard through IEC 63563-1:2025, covering flat-surface devices such as mobile phones and tablets [72]. Within one year of launch, more than 1.5 billion certified Qi2 devices, transmitters, and receivers had entered the global market [70], reflecting widespread adoption by major Android manufacturers alongside Apple. Complementing near-field Qi technology, IEC TR 63239:2025 (second edition) addresses RF beam wireless power transfer for mobile devices [73]. This technical report surveys candidate technologies, product trends, international standards, and regulatory developments. Compared with the 2020 edition, subclause 4.4 provides expanded guidance on candidate frequencies, including industrial, scientific, and medical (ISM) bands, while a new clause 6 identifies emerging applications such as IoT devices, in-car sensors, nursing-home sensors, medical implants, electronic price tags, and lighting [73]. RF beam WPT enables continuous power delivery to devices where physical contact or precise alignment is impractical, eliminating battery replacement in smart-home IoT systems, implantable and wearable medical devices, and retail electronic shelf labels [74]. The availability of an IEC technical report supplies designers and manufacturers with a recognized reference for frequency selection, system design, and certification, thereby accelerating product commercialization.

7.1.2. IEC TR 63239:2025 (RF Beam WPT for IoT, Medical, Retail)

In contrast to inductive WPT, which requires close-range alignment and prioritizes higher power and efficiency (as in Qi standards), RF beam WPT provides spatial freedom for far-field power delivery, typically at lower power levels. It is particularly suitable for IoT devices, medical implants, retail sensors, and ultra-small electronics where physical connections are impractical. In 2025, the IEC published the second edition of Technical Report 63239, "Radio frequency beam WPT for mobile devices" [73]. This edition surveys existing technologies, product trends, international standards, and regulatory developments. Compared with the 2020 version, it expands guidance on candidate frequencies, especially ISM bands (subclause 4.4), and broadens application coverage in clause 6 to include IoT devices, vehicle-mounted sensors, home-care sensors, medical implants, electronic price tags, and wireless lighting [73]. RF beam WPT enables continuous low-power delivery, for example, sustaining 1-watt supplies for always-on smart-home devices [74], powering implantable and wearable medical systems without surgical battery replacement, and supporting lifelong operation of retail sensors without manual battery changes. The IEC technical report thus provides manufacturers with a clear reference for design, certification, and commercialization.

7.2. Regional Initiatives

7.2.1. China: 50 W Fast Charging Group standard and EV Interoperability

Norms: China has led global WPT standardization in both the consumer electronics fast charging and EV segments. The country boasts a mature standardization framework across three technical routes for wireless, conductive, and battery-swapping charging technology, covering 21 domains including terminology, electrical systems, metrology, and safety [75]. In consumer electronics, the China Communications Standards Association (CCSA) and the Telecommunication Terminal Industry Forum Association (TAF) developed the joint group standard T/CCSA 708-2025 (T/TAF 313-2025) titled "Technical requirements for mobile terminal fusion fast charge wireless charge," released in November 2025 [76]. The standard mandates the electromagnetic induction method for mobile terminal fusion wireless fast charging and sets specifications for the general physical, protocol, and application layers, including the function of detecting foreign objects [76].

This standard has been a game changer, as before its adoption, various high-power wireless fast charging schemes adopted by different device manufacturers could not interoperate, and consumers were forced to use slow charging or accept charging delays if they did not have chargers compatible with their devices [76]. As such, the Chinese standard increases the efficient utilization of resources and eliminates the redundant purchase of chargers and the production of electronic waste. In the electric vehicle domain, China has been active in formulating its electric vehicle wireless power transfer standards. Currently, seven documents comprising the national standard GB/T 38775 are published to regulate wireless power transfer in electric vehicles, including technical aspects related to general requirements, communication protocols, electromagnetic compatibility (EMC), and interoperability [77].

7.2.2. Japan: Streamlined Certification for Near Field

Japan has focused on promoting swift market entry for near-field coupled WPT systems through the facilitation of quick certification procedures and designated spectrum usage. In September 2024, the Ministry of Internal Affairs and Communications (MIC) revised the Regulations for the Enforcement of Radio Law, stipulating a technical standard for capacitive coupled WPT systems operating in the 6.7 MHz band, primarily for use by transport robots in logistics centers [78]. The amended regulations came into force in December 2024, providing a straightforward regulatory framework for industrial WPT applications. Japanese regulatory authorities distinguish WPT systems according to coupling mechanisms and intended applications. Magnetic resonance-based WPT, with its power transfer capabilities ranging from tens of centimeters to meters, falls under the scope of the WPT Working Group of the Broadband Wireless Forum (BWF, Japan), where it develops technical standards using ARIB's drafting protocols [79]. To assess human exposure to electromagnetic radiation (EMR) from WPT systems, Japan utilizes the Radio Radiation Protection Guidelines (RRPG), which offer guidelines for evaluation when persons use radio waves and their bodies are exposed to EMFs [79]. Additionally, Japan has established technical requirements for near-field planar WPT systems, and its research institutions have proposed a partitioning scheme for enhanced power transfer efficiency [60].

7.3. Health and Safety

Ensuring the safe use of WPT technology is crucial, and human exposure to EMF generated by these systems is a key concern for manufacturers, regulators, and consumers. The joint IEC/IEEE 63184:2025 standard provides the definitive benchmark for assessing human exposure to EMFs associated with stationary WPT systems.

7.3.1. Joint IEC/IEEE 63184:2025 - EMF Exposure Assessment (1 kHz–30MHz)

The IEC/IEEE 63184:2025 standard establishes methods for assessing human exposure to EMF generated by stationary WPT systems. It evaluates exposure through SAR, internal electric field, current density, and contact current [80]. Covering the frequency range of 1 kHz to 30 MHz (3 kHz to 30 MHz in the IEC version), the standard applies to inductive WPT systems used in consumer devices, industrial equipment, and electric vehicle charging [80]. Published in February 2025, this first edition supersedes IEC PAS 63184:2021 and incorporates several technical revisions: the lower frequency limit was raised from 1 kHz to 3 kHz; contact currents were explicitly included as indirect effects; internal E-field and SAR formulas were integrated into measurement procedures; averaging methods for internal E-field and current density were refined; computational uncertainty guidance was updated; and requirements for test-report content were added [80]. The standard currently addresses only inductive WPT systems, which dominate mid- and high-power applications [80].

Compliance may be demonstrated through four alternative approaches: a general assessment procedure, measurement methods, computational methods, or a combined computational–measurement approach [80]. Assessment of immunity of cardiac implantable devices to WPT emissions falls outside the present scope [80]. Future editions, including a second edition planned for July 2029, are expected to incorporate guidelines for capacitive WPT systems [81–82].

7.4. Implications for Industry and Product Certification

Standards continue to shape the WPT ecosystem. Consumer demand for seamless charging is driving rapidly adoption of Qi2 25 W and IEC 63563-1:2025 devices, leveraging the existing network of more than 1.5 billion Qi-certified units already shipped worldwide [70]. Proprietary systems risk reduced market acceptance as interoperability becomes expected. IEC TR 63239:2025 supplies medical and IoT developers with a design baseline for RF beam WPT, although its status as a technical report indicates that formal standardization remains ongoing. Developers are advised to monitor IEC TC 100 progress toward converting the report to an international standard. For electric-vehicle applications, SAE J2954 provides a mature framework for light-duty static charging up to 11 kW, yet higher-power and dynamic charging systems remain undefined [83-84]. Complementary standards IEC 61980 and ISO 15118 address safety and communications but are not yet fully integrated [85]. Regionally, the EU Radio Equipment Directive relies on harmonized international standards for EMF and EMC compliance, with IEC/IEEE 63184:2025 positioned for reference in the Official Journal. In the United States, FCC Parts 15 and 18 apply according to frequency, while China’s GB/T and group standards form the basis for type approval.

7.5. Gaps and Future Standardization Needs (Dynamic Charging, Topological Systems)

A significant standardization gap remains and should be addressed in the next cycle by IEC, IEEE, SAE, ISO, regional bodies, and other standards-development organizations. The most urgent priority is DWPT, in which vehicles charge while moving over roadway-embedded transmitter segments. Although pilot systems employing segmented or selectively energized coils have demonstrated technical feasibility, comprehensive standards covering system architecture, operation, and verification do not yet exist [51]. Broader corridor-scale deployment is constrained by reliability under varied climatic conditions, high infrastructure costs per kilometre, vehicle alignment tolerances, site-specific installation variations, and foreign-object detection on moving platforms, particularly regarding electromagnetic-compatibility margins [86–87]. Standardized strategies for dynamic coil control, seamless segment-to-segment power hand-off, and verification under realistic operating conditions are therefore required.

Equally pressing is the need for high-power static WPT standards covering commercial and heavy-duty vehicles. SAE J2954 currently addresses only light-duty applications up to 11 kW, whereas depot charging of buses and trucks typically requires 50 kW or higher [84], [87]. Future standards must define coil geometries, operating frequencies, control protocols, and associated safety measures suitable for these higher-power use cases. Interoperability among manufacturers remains incomplete. Divergences among SAE J2954, IEC 61980, and ISO 15118 create scope for incompatible implementations [85]. Critical parameters requiring harmonization include frequency alignment, coil compatibility, power-level matching, communication-protocol compliance, and integration of safety features [85]. The absence of a universal global certification scheme further limits consumer confidence and infrastructure investment. A technical interoperability assessment framework spanning the full WPT application space has been proposed for consideration by standards bodies and regulators [85]. [88]

Topological diversity presents additional challenges. Current standards focus predominantly on inductive WPT, while capacitive, magnetic-gear, and resonant inductive systems possess different operating principles and safety profiles [51]. IEC/IEEE 63184:2025 explicitly defers exposure-assessment guidance for capacitive systems to future editions [80]. Interference with implantable medical devices likewise remains outside the present scope of that standard [80]. Environmental and sustainability criteria are largely absent. Energy efficiency under partial-load conditions, life-cycle assessment of copper coils, ferrite shielding and power electronics, and end-of-life management require harmonized treatment. Although conductive charging systems are already subject to efficiency regulations, equivalent WPT-system standards have yet to be established.

Spectrum allocation for beam WPT remains fragmented across ISM bands (2.4 GHz, 5.8 GHz, 24 GHz, 61 GHz), with IEC TR 63239:2025 offering only non-binding suggestions [73] and ITU guidance remaining recommendatory [81]. The European Commission has called for accelerated WPT standardization with a target deadline of December 2026 [82]. Sustained collaboration among standards organizations, industry, and policymakers is essential to close these gaps and prevent the emergence of isolated, non-interoperable systems.

8. Comparative Discussion and Future Outlook

8.1. Synthesis: Topological Robustness vs. Beamforming Flexibility vs. Standardization Readiness

After considering specific applications and their WPT requirements, the principal technologies for consumer devices, electric vehicles, and drones/IoT systems can be evaluated against three core parameters: topological robustness, beamforming flexibility, and standardization readiness. Inductive WPT (Qi2, SAE J2954) scores highest on both topological robustness and standardization readiness, explaining its market dominance. It delivers high power and efficiency (85–95 % under optimal alignment) after decades of iterative refinement [51] and benefits from an established ecosystem exceeding 1.5 billion certified devices [75], [89]. Nevertheless, dependence on costly ferrites, sensitivity to misalignment (despite Qi2 improvements), and spatial inefficiency limit its suitability for dynamic applications [89–90].

Capacitive WPT offers an alternative topology that eliminates ferrites and operates at higher frequencies, yielding smaller and lower-cost devices with inherently better electromagnetic compatibility [91]. Hybrid structures have improved misalignment tolerance, yet power and efficiency remain below inductive levels, and standardization continues to lag [83]. IEC/IEEE 63184:2025 explicitly anticipates future exposure-assessment guidance for capacitive systems [80]. Magnetic-gear wireless power transfer (MGWPT) employs synchronous permanent-magnet interaction to achieve higher efficiency than inductive systems at comparable distances without complex compensation networks [84]. The technology, however, remains largely confined to laboratory research and lacks commercial deployment or standardization [51].

RF beamforming WPT provides the greatest spatial freedom, enabling power delivery over metres to tens of metres for IoT sensors, medical implants, and retail applications [73]. Transmission efficiencies typically range from 10–40 %, with power limited to watts or sub-watts by radiation regulations. IEC TR 63239:2025 is a technical report rather than a full international standard, reflecting the relative immaturity of the approach [73]. No single topology currently dominates all performance dimensions (Table 4).

8.2. Road Map for 2026–2030

During the next 5 years of development for WPT, the following three transformative trends are expected to mature in tandem: hybrid topological MIMO architectures, AI-based real-time control, and EV wireless charging global roaming interoperability. Each one addresses an intrinsic system-level bottleneck of WPT.

8.2.1. Hybrid Topological MIMO Architectures

To overcome the inherent limitations of SISO wireless power transfer, restricted spatial freedom, sensitivity to misalignment, and single-device charging, MIMO architectures have attracted increasing attention [92]. MIMO WPT employs multiple transmitting coils to deliver power to one or more receivers, thereby enhancing spatial coverage, total power capacity, and beamforming capability. Research on a three-coil electric-resonant system arranged in a stacked MISO hexagonal array has demonstrated a combined transmission coefficient of up to 0.90 at three representative receiver positions [86]. Full-wave simulations and experimental measurements showed a maximum deviation of only 0.09, confirming stable resonance near 6.78 MHz and scalability to larger transmitter arrays. For dynamic WPT, modular coil arrays designed with low in-plane mutual inductance, yet strong inter-plane coupling, have reduced crosstalk relative to conventional square layouts [87]. Three-dimensional finite-element analysis verified improved performance on flat surfaces and robust scalability.

A hybrid relay topology further enhances mutual inductance and misalignment tolerance. Experimental results at 3.3 kW achieved DC–DC efficiency exceeding 93.05 % across a 100 mm horizontal displacement, with mutual-inductance fluctuation limited to 4.89 % [93] (Table 5). By integrating a receiver-side relay coil and dual adjustment factors, the approach maintains high efficiency under practical misalignment conditions relevant to electric-vehicle charging. In the far-field domain, a 16×16 transmitter and 8×8 receiver RF MIMO array simultaneously optimized both the air-propagation and rectification stages, yielding a 65.6 % improvement in end-to-end conversion efficiency over prior work and establishing a performance benchmark for future real-time systems.

8.2.2. AI-Driven Real-Time Control for Dynamic Environments

Transitioning from static to dynamic WPT for electric vehicles, autonomous drones, and mobile robots introduces environmental uncertainties that conventional control strategies cannot adequately address. Coil alignment, coupling coefficients, load conditions, and external disturbances such as thermal effects, electromagnetic interference, and foreign objects vary continuously. Artificial intelligence, particularly reinforcement learning, has therefore emerged as a promising approach for intelligent power management in dynamic wireless charging systems (Table 6).

Researchers have developed a unified AI-powered optimization and control framework that integrates genetic-algorithm-based static optimization, artificial neural network predictive models for rapid performance evaluation, and proximal-policy-optimization reinforcement learning for real-time dynamic control. Earlier solutions were typically limited to static optimization, neglected real-time dynamics, or lacked comprehensive robustness testing. Twin-delayed deep-deterministic-policy-gradient (TD3) algorithms have been applied to regulate inverter switching frequency and duty cycle in real time, enabling offline-trained controllers to operate reliably under parameter variability, changing trajectories, and noisy measurements. Deep reinforcement learning has also been used to tune the frequency of LCC-S converters, compensating for coil or coupling variations that would degrade conventional controllers.

A more advanced architecture employs a hyper-adaptive, chaos-aware asynchronous twin soft-actor-critic controller for a 100 kW dynamic WPT system, combining real-time hyper-fuzzy PID control with dual-objective reinforcement learning to manage abrupt coupling changes, electromagnetic-interference bursts, and thermal fluctuations. In drone applications, soft-actor-critic optimization of multi-transmitter, single-receiver arrays enables efficient charging despite imperfect landing accuracy by redistributing power according to actual receiver position. Looking ahead, the integration of AI with sensing technologies is enabling real-time detection of foreign, living, and metallic objects together with adaptive beamforming. The trajectory is toward predictive rather than reactive systems that simultaneously improve efficiency, spatial freedom, and operational safety.

8.2.3. Global Roaming for EV Wireless Charging (Interoperability)

For electric-vehicle wireless charging to achieve the convenience of wired systems, allowing any vehicle to use any charging station regardless of brand or network, universal roaming interoperability is essential. At present, divergent international standards such as SAE J2954, IEC 61980 and ISO 15118 hinder widespread adoption [85]. EV-WPT interoperability has been defined as the capability of power-supply equipment and vehicles to achieve safe and efficient magnetic-field power transmission in compliance with applicable standards [94]. Realising this capability requires harmonisation across five dimensions: frequency matching, coil compatibility, power-level matching, communication-protocol consistency and integration of safety functions [85]. Current implementations exhibit insufficient overlap in these areas, resulting in a fragmented ecosystem in which vehicles cannot reliably charge on infrastructure from different manufacturers.

A technical interoperability evaluation framework based on these five dimensions has been proposed to guide designers, manufacturers and regulators [85] (Table 7). Key shortcomings identified in the literature include the absence of a unified global certification programme, incomplete standardization of higher-power (>50 kW) and dynamic charging systems, and inconsistent application of communication protocols and safety functions [85]. Progress has been made: SAE J2954:2024 integrates dynamic-charging requirements (SAE J2954/3) with static-charging specifications, while ISO 5474-4:2025 will standardize the wireless-power-transfer interface [95]. Nevertheless, deployment of dynamic WPT beyond pilot corridors remains constrained by maintenance challenges, climatic variability, high costs per kilometre and the need for site-specific verification of safety, exposure and electromagnetic-compatibility margins [91]. Roadmaps envisage progressive global interoperability between 2026 and 2030 through three stages: convergence of static standards (2026–2027), integration of quasi-dynamic charging (2027–2028) and full dynamic-WPT roaming (2029–2030). Success will require coordinated action by standards bodies (IEC, IEEE, SAE, ISO), industry consortia (WPC, CharIN), and governments.

8.3.1. Economic impact: the wireless charging market has exploded globally.

The total market was valued at USD 27.2 billion in 2025, and is expected to reach USD 96.3 billion by 2030, representing a CAGR of 28.7% [96]. Among this value, the wireless charging IC market, the most representative of the underlying technology adopted in other products, will grow from USD 5.0 billion in 2025 to USD 12.1 billion in 2030 at a CAGR of 19.3% [18]. Although the absolute value is much lower (USD 1.36 billion in 2025), wireless EV charging has the fastest growth rate (80.3% CAGR for 2024-2030), indicating a shift from emerging to a mainstream technology [97].

For commercial applications, such as fleets, delivery vehicles, taxis, and public transport, static wireless EV charging makes sense today because of opportunity charging (e.g., while loading or unloading goods), reducing battery size and the need for a person to plug. Even though the premium on customer convenience still needs to be evaluated for personal-use cars, the data (83% of EV charging occurs at home [47]) shows that residential wireless charging can be a significant selling point. For Dynamic WPT, the calculation is much harder. The installation costs of DWPT infrastructure (e.g., roadway digging, coil embedding, power supply houses, roadside management equipment) are much more expensive than wired charging infrastructure [66]. The costs of installing each kilometer, plus reduced efficiency (40%-55% in a real system as compared to 85%-95% in static WPT), make DWPT only viable for heavy utilization corridors; however, the benefits of using DWPT for vehicles- reduced vehicle size (therefore decreased price), eliminated downtime, lower TCO of a vehicle working on an electrified road are undeniable [91]. Techno-economic analysis needs to be performed for such projects by including the whole-picture benefits of the system.

8.3.2. Environmental Impact

The environmental effects of wireless charging systems are more complicated than they might first appear. Based on life cycle assessments (LCAs) of systems, there is a major carbon trade-off: The manufacturing of wireless chargers involves greater carbon emissions than plug-in charging, taking between ten and fifteen years of operation on a low-carbon grid to break even [98]. This upfront carbon debt is attributed to the additional components that need to be fabricated: The additional ferrite shielding plates and coils, the extra components needed for the power electronics that transfer the power inductively. This burden can be particularly high for the large shielding plates needed in EV wireless receivers (the EV-side charging receiver of a 11 kW EV wireless charging system can weigh over 20 kg and requires plates around 80 cm in diameter to mitigate vehicular EMI).

However, when supplied from renewable sources, this upfront debt can be recouped during the operational phase of a system. In a life-cycle comparison that integrated PV generation and grid-interactive power electronics for WPT in a grid that is expected to be heavily influenced by renewable sources, the life-cycle GHGs of the wireless charging can be less than that of a plug-in system, consuming 0.3% less electricity and resulting in 0.5% fewer GHGs across the entire life cycle [99]. In fact, for DWPT systems, the actual power consumption of the systems during the use phase is slightly higher (due to a decrease in efficiency), but other factors such as the ability to use smaller batteries, to lower vehicle weight, or shift charging load to periods with higher renewable energy availability might outweigh this penalty [100], [101]. More comprehensive studies of wireless power transfer and, in particular, the resonance mode of WPT have detailed LCA assessments covering the issues of power loss, interference, and material selection [101].

8.3.3. Societal Impact

WPT implementation will have social consequences related to equity, accessibility, and labor. Equity and infrastructure access: The risk that private implementation of wireless charging in predominantly higher-income neighborhoods (where private garages and driveway pads are more common and able to support higher upfront infrastructure costs) will further drive EV equity will be limited if public wireless charging is also made available at curbsides, in community charging locations, and in multi-unit dwellings, though market incentives will likely dictate location. The inclusion of policies in the policy framework such as infrastructure bond securitization, dynamic right-of-way leasing, and renewable energy co-location mandates would help assure that deployment does not exacerbate social inequities [98].

The risk of exposure to RF EM fields has been shown to have no ill effects when WPT is operated in accordance with limits in IEC/IEEE 63184:2025 standards. Nevertheless, some people in a neighborhood or near a DWPT system will be sensitive to and potentially concerned about RF EM field exposure, especially from DWPT roadways where people, including children, live, work, and go to school. This will require clear communication, transparent independent monitoring, and public involvement in deployment planning. The publication of a harmonious international standard by IEC/IEEE 63184:2025 offers a clear technical foundation to such communication, but only if the results of independent monitoring and the principles of community planning can allay these social concerns.

8.3.4. Policy and Regulatory Issues

A review of the socio-economic and environmental impacts of wireless charging suggests the need for an integrated policy response. Building upon earlier proposals, five policy measures can be put forward:

- Infrastructure bond securitization enabling the funding of the capital investment required for static and dynamic WPT infrastructure via public-private partnerships and repayment tied to the economic life of the infrastructure.
- Dynamic right-of-way leasing through the granting of licenses to private operators, under which private companies are allowed to lease road segments for DWPT installation through competitive tenders tied to a range of performance standards (up-time, energy efficiency, safety).

9. Limitations and Future Scope

9.1. Limitations of This Study

Several limitations warrant acknowledgment. First, the review focuses exclusively on near-field (non-radiative) WPT systems, excluding far-field technologies such as microwave and laser WPT where comparison was not meaningful. Second, the temporal scope (2020-2026) may not capture foundational work predating this period or very recent developments beyond the search cutoff. Third, while extensive, the review relies on published data that may reflect publication bias toward positive results. Fourth, experimental validation for many emerging topological and MIMO systems remains limited to laboratory-scale demonstrations, with scalability to commercial applications requiring further investigation. Fifth, the economic and environmental analyses are based on market forecasts and life-cycle assessments that may not fully account for regional variations or unforeseen technological breakthroughs.

9.2. Future Research Directions

Priority research areas for 2026-2030 include: (1) hybrid topological-MIMO architectures combining robustness with beamforming flexibility through reconfigurable structures using varactors or tunable metamaterials; (2) AI-native control systems employing reinforcement learning for real-time foreign object detection, adaptive beamforming, and thermal management;

(3) accelerated DWPT standardization completing by 2028, encompassing system architecture, safety verification, and interoperability protocols; (4) comprehensive life-cycle assessments addressing carbon footprint, material resource depletion, and end-of-life management; (5) advanced thermal management strategies balancing efficiency and cost through hybrid cooling systems; (6) global roaming interoperability across SAE J2954, IEC 61980, and ISO 15118 with universal certification schemes; and (7) policy frameworks including infrastructure bond securitization and renewable energy co-location mandates.

10. Conclusion

This comprehensive review has examined the transformative evolution of near-field wireless power transfer over the past five years, spanning topological innovations, dynamic applications, and standardization frameworks. The analysis reveals that inductive WPT technology has achieved technical maturity, delivering 85-95% efficiency across power ranges from watts to 11 kW, supported by over 1.5 billion Qi2-certified devices globally. However, dynamic wireless charging (DWPT) systems, while demonstrating technical feasibility through successful field trials in France (300 kW), the United States, Italy, and Germany, remain constrained by the absence of comprehensive interoperability standards. Topological WPT and MIMO-based beamforming techniques offer promising solutions for misalignment tolerance and multi-device charging, though scalability challenges persist. Standardization progress has been substantial, with IEC 63563-1:2025 and IEC/IEEE 63184:2025 providing formal frameworks for consumer devices and EMF safety, yet significant gaps remain for dynamic charging, high-power applications, and capacitive/RF beam technologies.

DECLARATIONS

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Use of AI and AI-Assisted Technologies: AI-assisted tools, specifically Grammarly, were used solely for grammar correction and language polishing; no generative AI contributed to content creation.

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Authors' Contribution: Belay Sitotaw Goshu: designed the study, formulated the research problem, performed data analysis, interpreted results, and prepared the complete manuscript.

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Figures

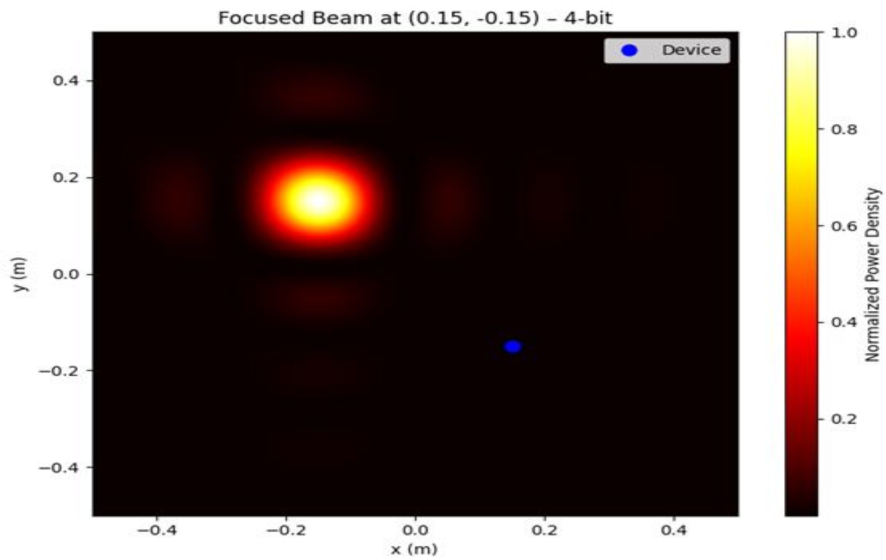

Figure 1: Normalized power density of a Fresnel zone-focused beam at (0.15, 0.15) using 4-bit DMA. The blue dot indicates the position of the device.

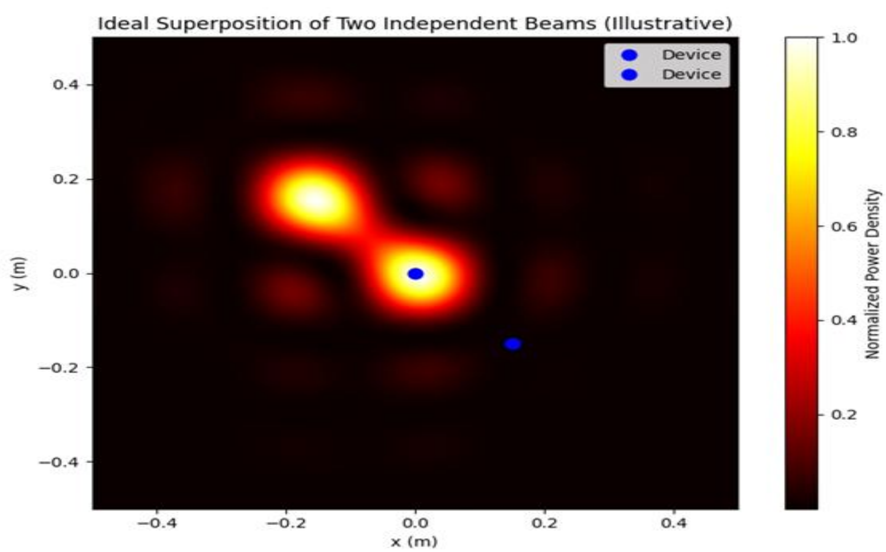

Figure 2: Ideal superposition of two independent Fresnel zone beams at two device locations (blue dots) using DMA.

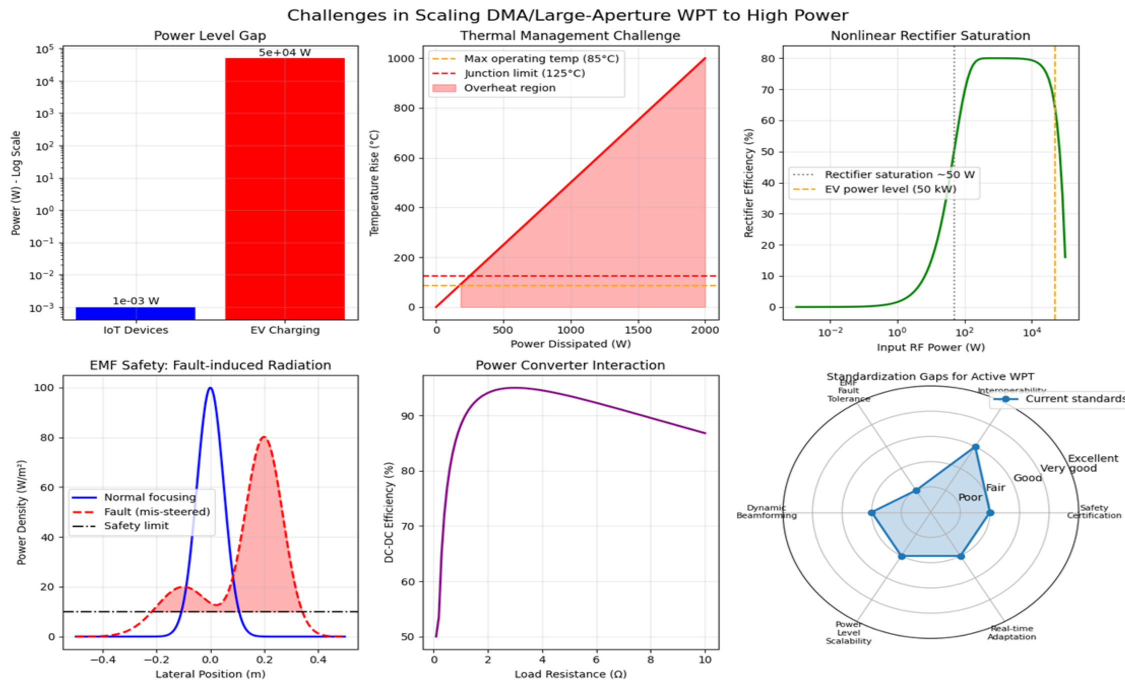

Figure 3: Technical barriers limiting large-aperture wireless power transfer scalability, including thermal effects, rectifier saturation, safety, efficiency, and standardization.

Tables

Period	Breakthrough Domain	Key Contribution	References
2015-2017	Resonant compensation networks	High-order compensation topologies (LCL, LCC, SP, S/SP) for EV charging	[102][103]
2018-2019	Multi-coil architectures	3-coil and 4-coil systems for extended distance	[33]
2020-2021	Metamaterial and metasurface integration	Negative permeability metamaterials to enhance coupling and shield EMF	[29][104]
2021-2022	Topological WPT (TWPT)	First demonstration of edge-state protected power transfer using SSH chains	[35]
2022-2023	Parity–time (PT) symmetric systems	Exceptional point operation for distance-insensitive efficiency	[105]
2023-2024	MIMO-WPT	Multi-transmitter, multi-receiver architectures with adaptive beamforming	[106]
2024-2025	Dynamic metasurface antennas	Near-field beam focusing in Fresnel zone for multi-device charging	[107]
2025-2026	Large-aperture near-field focusing	Distance-independent power budget using physically large apertures	[26]
2025-2026	AI-enhanced adaptive matching	Single-step P&O and machine learning–based impedance optimization	[30][108]

Table 1: Roadmap of breakthroughs in near-field WPT (2015–2026).

System Architecture	Peak Efficiency	Efficiency at 10% Misalignment	Efficiency at 20% Misalignment	References
Conventional uniform chain	85%	52%	28%	[35]
SSH topological chain (1D)	82%	79%	74%	[35]
Conventional multi-relay (3-coil)	78%	45%	22%	[3]
LADS (large-area defect state)	81%	77%	73%	[3]
Machine learning–optimised SSH chain	65% (long-distance)	57.9% under 30% structural perturbations	—	[4]

Table 2: Comparative performance of topological versus conventional WPT under misalignment.

Feature	Conventional (SISO)	Topological (SSH chain)	Large-Aperture/DMA	MIMO-Neld-Mead
Efficiency at ideal alignment	High (85–95%)	Moderate (65–82%)	Moderate (depends on aperture)	High (competitive)
Efficiency under misalignment	Low (falls rapidly)	High (maintains >70% under 20% coupling variation)	Moderate (beam steering can compensate)	High (optimised via S-parameters)
Distance capability	Short (< coil diameter)	Extended (multiple resonators)	Long (Fresnel region, > several wavelengths)	Short (near-field, < 1 m)
Number of devices supported	One	Multiple (corner states, defect states)	Multiple (simultaneous focusing)	One (per optimisation cycle)
Active/passive adaptation	Passive	Passive	Active (DMA weights)	Active (amplitude/phase)
Hardware complexity	Low	Moderate (precision fabrication)	Low (DMA with single RF chain)	High (multiple Tx RF chains)
Regulatory EMF compliance	Poor (power density near infrastructure)	Not specifically addressed	Good (focusing reduces leakage)	Not specifically addressed
Key strength	Simplicity, low cost	Robustness, defect tolerance	Long range, multi-device, low hardware complexity	Misalignment tolerance, adaptive
Key limitation	Sensitive to distance and misalignment	Limited range, static design	Requires physically large aperture	Many active elements, complex control

Table 3. Comparative analysis of advanced WPT paradigms.

Parameter	Inductive (Qi2 / SAE J2954)	Inductive (DWCS)	Capacitive (CPT)	Magnetic Gear (MGWPT)	RF Beamforming
Power level (typical)	5 W-11 kW	50 Kw-300 kW	100 W-3 kW	1 kW-10 kW	1 μW-1 W
Efficiency (optimal)	85-95%	40-55% (experimental)	75-88%	90-95%	10-40%
Spatial freedom	Low (mm-cm alignment required)	Moderate (segmented tracks)	Low (similar to inductive)	Moderate	High (metres)
Ferrite requirement	Heavy, expensive ferrites	Heavy ferrites	None	None (permanent magnets)	None
EMF shielding	Complex, heavy shielding plates	Very heavy (> 80 cm for EVs)	Lower inherent emissions	Moderate	Low (subject to RF exposure)
Standardisation status	Mature (Qi2, SAE J2954, IEC 63563)	Emerging (DWPT gaps identified)	Developing (IEC 63184 future)	None	TR level (IEC TR 63239)
Commercial maturity	High (>1.5 B devices)	Pilot-ready (pilot highways)	Low	Very low	Low
Primary applications	Mobile devices, wearables, EVs	Heavy-duty EVs, buses, trucks	Mid-power industrial, EVs	Future EV charging	IoT sensors, medical, retail

Table 4: Comparative synthesis of WPT topological architectures (2025–2026).

Sources: [70], [51], [91], [83], [84]

Architecture	Power	Efficiency/Transmission	Key advantage	Readiness	References
Hexagonal-stacked MISO ER-WPT coupler	≤500 W	Trans. coeff. ≤0.90	Stable resonance near 6.78 MHz, reduced freq. shift	Prototype validated	[86]
Modular MIMO coil array for DWPT	N/A	Outperforms square coil	Reduced cross-coupling, flat surface, robust scalability	FEM simulation	[87]
Hybrid topology relay WPT	3.3 kW	DC-DC >93.05%	4.89% MI fluctuation over 100 mm misalignment	Experimental verif.	[93]
16×8 MIMO RF WPT	≤100 W	65.6% TCE improvement	Joint RF-RF and RF-DC optimisation, ISAC compatible	Simulation validated	[109]

Table 5: Comparative summary of advanced MIMO/MISO architectures.

Control method	Application	Key feature	References
GA + ANN + RL (PPO) unified framework	EV DWPT	Hybrid static + dynamic optimisation	[110]
TD3-based RL controller	EV static WPT	Simultaneous freq. + duty cycle regulation	[89]
DRL for LCC-S resonant converter	EV WPT	Output voltage regulation under parameter drift	[90]
HAC-SAC² (hyper-adaptive twin SAC²)	100 kW DWPT	Three-layer hybrid: fuzzy PID + twin RL	[111]
Soft Actor-Critic (SAC)	Drone WPT	Multi-transmitter power opt. under landing error	[112]

Table 6: AI-driven WPT control systems (2025–2026).

Timeframe	Milestone	Key enablers
2026-2027	Harmonized static charging standards (≤22 kW)	Convergence of SAE J2954, IEC 61980, ISO 15118; unified test specs
2027-2028	Cross-manufacturer static WPT interoperability	Adoption of common communication protocol; certification schemes
2027-2028	Quasi-dynamic WPT standardisation	Stop-and-go charging specifications for buses, taxis, delivery
2028-2029	DWPT pilot corridor standards	Segment energisation, handover, safety at 50–150 kW
2029-2030	Full DWPT interoperability + cross-network roaming	Unified RF, coil, power, comms, safety; global certification

Table 7: Interoperability roadmap for EV wireless charging (2026–2030).