A Comparative Study on Dynamic and Static Wireless Charging Technologies for Electric Vehicles

Haoyu Kong[1], Zhuorong Li[2*], Ziheng Zhao[3]

[1] College of Computer and Information Engineering (College of Artificial Intelligence), Nanjing Tech University, Nanjing, 210000, China
[2] School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, 212013, China
[3] School of Electrical Engineering, University of Jinan, Jinan, 250000, China

3230501042@stmail.ujs.edu.cn

Abstract. This paper presents a systematic comparative study of static and dynamic wireless charging technologies for electric vehicles. It outlines their fundamental principles: static wireless charging, which relies on magnetic field coupling, and dynamic wireless charging, which is divided into rail-type and segmented-type configurations. The study further examines their technical differences in terms of system structure, coupling mechanisms, compensation topologies, stability, and safety. The findings suggest that while static wireless charging technology is relatively mature, it is constrained by its limited transmission distance and efficiency. In contrast, dynamic wireless charging holds significant potential for development but faces challenges such as large air gaps and coil misalignment. Additionally, the paper discusses the future challenges and optimization directions for both technologies, considering the integration of smart grids, policy support, and market promotion. The research indicates that static wireless charging is well-suited for fixed-location applications, whereas dynamic wireless charging has the potential to significantly extend the driving range of electric vehicles. However, both technologies require further improvements in efficiency, safety, and cost to facilitate the widespread adoption of wireless charging for electric vehicles.

Keywords: Electric Vehicles; Static/Dynamic Wireless Charging Technology; Coupling Mechanism; Compensation Topology; Safety of Wireless Power Transfer

1 Introduction

Amid growing global concerns over energy and environmental issues and the rapid expansion of the electric vehicle (EV) market, there is increasing public interest in EVs that offer zero emissions, low noise, and high energy efficiency. However, limited driving range and inconvenient charging remain key barriers to their widespread adoption. As a promising emerging technology, wireless charging has

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garnered significant attention from academia and industry due to its convenience, safety, and intelligent control advantages. The integration of wireless charging technology into the EV industry is anticipated to help alleviate issues such as "range anxiety."

Wireless charging for EVs can be broadly categorized into two types: conventional static wireless charging and the more innovative dynamic wireless charging. Each approach presents distinct advantages and disadvantages in practical applications. Although static wireless charging is relatively mature, it still faces limitations in electromagnetic compatibility, transmission range, and energy efficiency. Dynamic wireless charging, while offering greater potential to address range limitations, involves significant technical challenges such as large air gaps and relative coil misalignment due to vehicle movement. A comparative analysis of these two technologies is essential for identifying their respective development pathways and offers a valuable theoretical foundation for optimizing and promoting future wireless charging systems for EVs.

While existing research has made notable progress in both static and dynamic wireless charging, comprehensive comparative studies remain limited, and there is a lack of systematic analysis and synthesis. This paper aims to fill that gap by summarizing the fundamental principles of static and dynamic wireless charging, and by comparing the two in terms of system architecture, coupling mechanisms, compensation topologies, and operational stability. Additionally, it reviews representative domestic and international case studies of static and dynamic wireless charging technologies. Finally, the study explores the future challenges and optimization strategies for both charging methods, particularly in the context of smart grid integration and supportive policy environments.

2 Principle of Static-Dynamic Wireless Charging for Electric Vehicles

2.1 Principles of static wireless charging technology

Main Technical Programs and Status of Implementation. The static wireless charging technology for electric vehicles is mainly a magnetic coupled field technology, which is divided into electromagnetic induction and electromagnetic resonance, and the comparison of the two is shown in Table 1.

Table 1. Comparison of electromagnetic induction and electromagnetic resonance technologies

	Electromagnetic Induction	Electromagnetic Resonance
Transmission Distance	Short (centimeter scale)	Medium (meters)
Volume Weight	Medium	Medium
Power Rating	Large (kilowatt scale)	Small (hundred-watt class)
Transmission Efficiency	High (70%-90%)	Medium (40%-60%)

Electromagnetic induction wireless charging technology has the advantages of high power carrying capacity and high near-field transmission efficiency, however, its working mechanism is limited by the sensitivity of the coupling coefficient in the law of electromagnetic induction, which results in the effective transmission distance being confined to the centimeter range. On the contrary, the electromagnetic resonance type, based on the magnetic resonance coupling principle, realizes mid-range energy transmission, and in typical application scenarios, its transmission distance can be extended to 3-4 times the diameter of the transmitting coil. What is more noteworthy is that the electric field distribution characteristics of this technology enable it to penetrate non-magnetic obstacles for energy transmission, thus showing significant technical advantages in the field of static charging of electric vehicles, especially in terms of spatial adaptability and electromagnetic compatibility [1].

Magnetic Field Coupling Technology.

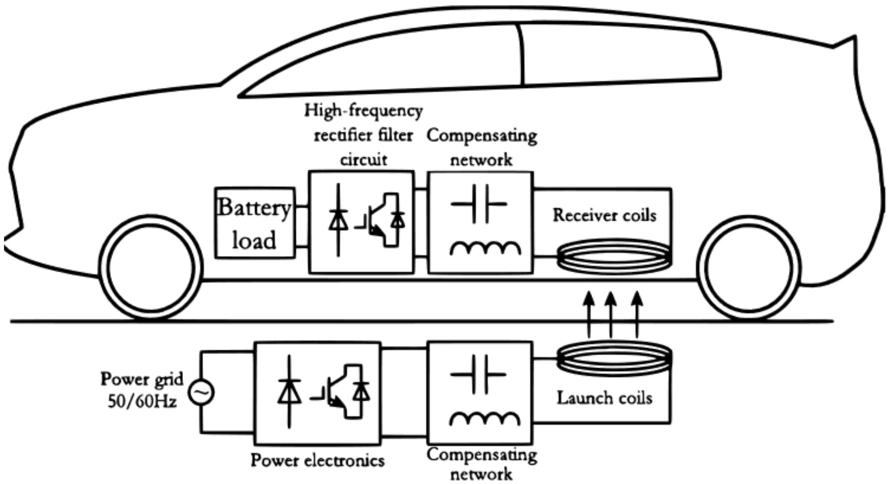

Fig. 1. Schematic structure of electromagnetic resonance type [2]

As shown in Fig. 1, the electromagnetic resonance type usually consists of a power electronic converter, a primary and secondary compensation network, a transmitter-receiver coil, a high-frequency rectifier-filter circuit and a battery load. It utilizes the principle of energy resonant coupling to transfer energy through a high-frequency electromagnetic field. The AC power transmitted from the power supply side (grid) is converted to high frequency AC by the power electronic converter. In order to cope with the small coupling between the transmission coils, a compensation network, also known as a resonance network, is added to improve the system characteristics and thus resonate the circuit, which then transmits the power through a pair of coils [3]. One of the coils is the transmitting coil and can be considered as an antenna for transmitting power. The other coil can be considered as the receiving coil and is used as the receiving antenna. The time-varying voltage applied to the transmitter side coil generates a magnetic field in the near field of that coil. Due to this magnetic flux, a voltage is induced in the receiver side coil which is present in the near field of the first coil. This is due to mutual induction between the coils. Electromagnetic resonance type system is enhanced by a magnetic resonance network between the primary and secondary sides. At the resonant frequency, the coupled wave reaches its maximum value, thus, producing an effective power transfer [4]. Finally, the transmitted electromagnetic energy charges the battery through the vehicle energy conditioning circuit. This magnetic field resonant charging method has high energy conversion efficiency and stability [3].

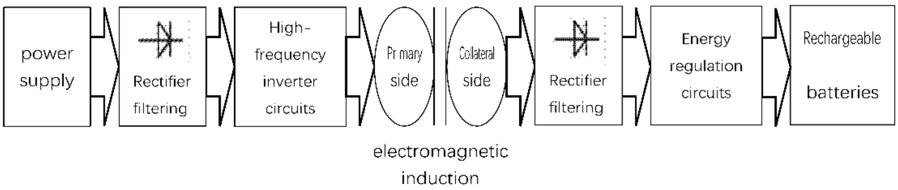

Fig. 2. Schematic of electromagnetic induction type structure [3]

Electromagnetic induction wireless charging is a new technology based on Faraday's law of electromagnetic induction. It transmits radio energy to the rechargeable battery by separating the primary and secondary transformers. Rectifier and filter circuits convert the current at the power side of the system to DC. The DC reaches the primary side of the induction coil through a high frequency inverter circuit to produce an induction current, which is then filtered and the energy regulation circuit regulates the power inside the electric vehicle and then charges the battery in fig 2 [3].

Base Station and On-board Receiver Equipment Design. The static wireless charging device for electric vehicles consists of two parts (Fig. 1). The transmitting end is installed under the charging space and the receiving end is installed in the electric vehicle. When the electric vehicle is parked in the charging space, the electromagnetic field is generated and changed to wirelessly transmit electric energy to the battery of the electric vehicle for charging.

2.2 Principles of Dynamic Wireless Charging Technology

Main Technical Programs and Status of Implementation. The principle of dynamic wireless charging system (DWCS) is similar to that of static wireless charging, and the dynamic wireless charging technology can be categorized into rail type and segmented type according to the division of energy transmitter. Both technologies have attracted many scholars at home and abroad to study them. For example, in August 2018, the State Grid's key scientific and technological special project "engineering research on dynamic wireless charging system for mobile electric vehicles" made breakthrough progress. The China Electric Power Research Institute and Harbin Institute of Technology jointly built China's first full-size (total length of 142 meters) test platform with 50kW dynamic replenishment capacity at

60km/h cruising speed, marking the entry of China's electric vehicle wireless charging technology into a new stage of engineering application verification.

Collaboration Between On-Road Charging Facilities And On-Board Receiving Systems.

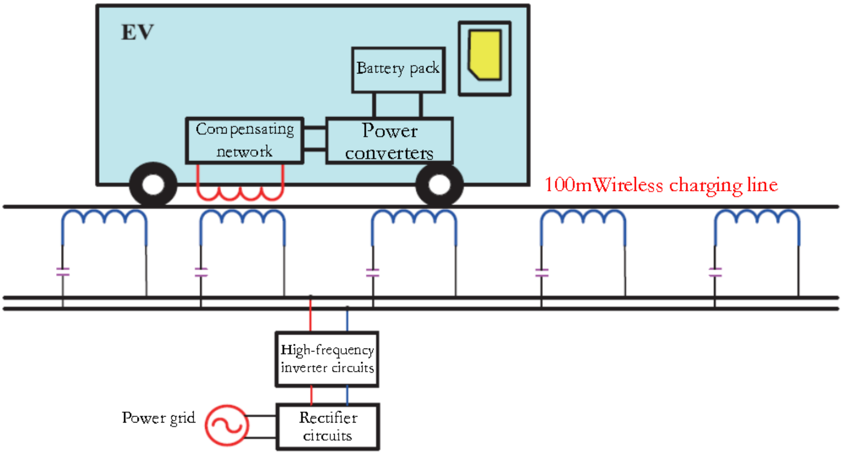

Fig. 3. Schematic diagram of rail type DWCS structure [5]

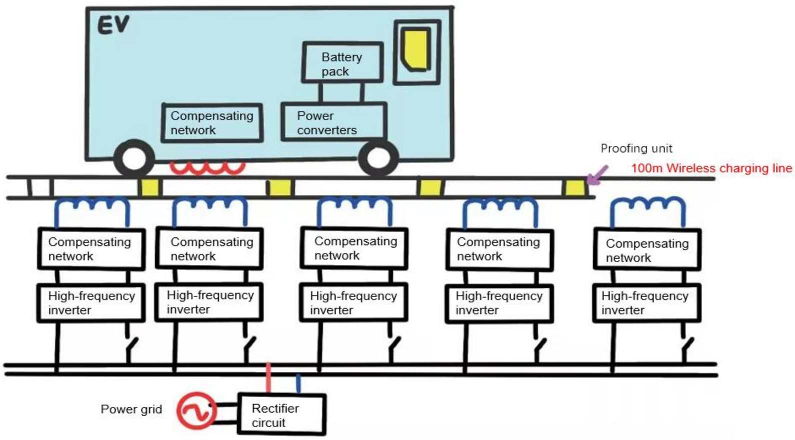

Fig. 4. Schematic diagram of segmented type DWCS structure [5]

The power supply rails/segmented coils (transmitter coils) for wireless charging need to be laid below ground level and connected to the power grid. The vehicle then needs to be fitted with power receiving equipment at the receiving end. Rail type DWCS are relatively simple in structure, and the charging rails at the energy-transmitting end are typically tens of meters long, allowing for simultaneous charging of multiple EVs (e.g., Fig. 3).

The segmented type DWCS power supply rail model, on the other hand, divides the power supply rail into multiple sections (e.g., Fig. 4), each of which has a transmitting coil and a compensation network. When a car passes through the segmented supply rail, only its transmitting coil is energized and the other coils are not energized. This enables the car to utilize the energy rationally [5].

Stability and security of power transmission . Rail type DWCS enables continuous power transfer while the vehicle is in motion, without the need for frequent starts and stops. However, the rail type DWCS still has drawbacks: the receiving coil can only be coupled to part of its relative power supply area, and when there is only one electric vehicle on the rail type DWCS, full energization of the rail type DWCS will lead to a great loss of energy, which means a low transmission efficiency, and the inductance of the transmitting coil is too large resulting in a very small coupling coefficient, which leads to a high parasitic resistance, and thus leads to instability of the power supply. In addition, when the system fails, the whole power supply rail needs to be de-energized for maintenance, which increases the difficulty of maintenance [6].

Compared with the rail type DWCS, the segmented type DWCS reduces the power loss of the system, after the coil self-inductance is reduced, the sensitivity of the system to the change of coil parameters is reduced, so its stability is improved; in addition, due to its higher independence fault repair also becomes easier. In the future with the development and maturity of vehicle location detection technology, the vehicle communication is connected to the ground communication, and the start and shutdown of the ground coil is controlled by analyzing the power of the vehicle battery, so as to achieve the goal of improving the system's energy transfer efficiency and energy utilization [5]. However, segmented type DWCS still has some shortcomings, such as higher difficulty in system integration, expensive cost, and unavoidable problem of frequent starting and stopping.

3 Comparison of Static and Dynamic Wireless Charging Methods

3.1 Coupling Mechanism

From the perspective of transmission mechanism, static wireless charging technology can be categorized into electromagnetic radiation type, electric field coupling type and magnetic field coupling type. The main types of electromagnetic radiation type are radio wave type and laser type, the advantage is that the transmission distance is very far, but its shortcomings are also very obvious, charging efficiency is low, the transmission power is small, the technical development is not mature and other issues make the electromagnetic radiation type has not gained widespread attention. Similarly, the electric field coupling type mainly utilizes the electric field of the capacitor for energy transmission. However, due to the significant harm of the electric field to human health, the electric field coupling type has not been widely studied either. Relatively speaking, the magnetic field coupling type has received more attention. The magnetic field coupling technology can be further divided into inductive and resonant types. From the perspectives of transmission power and transmission distance, the resonant type has more advantages in static wireless charging.

Compared with static wireless charging technology, dynamic wireless charging technology adopts the working mode of inductive coupling and electromagnetic resonance in coordination. Therefore, there are significant differences in the electromagnetic coupling mechanism. For static wireless charging systems, due to the advantage of non-radiative energy in the near-field magnetic field, energy can be transferred between bilateral coupled coils with the same resonant frequency, and it has high efficiency and good stability. On the contrary, for dynamic wireless charging, the horizontal relative positions of the transmitting coil and the receiving coil are constantly changing during charging, which can lead to problems such as excessive magnetic leakage and reduced coupling degree, and is not conducive to efficient charging. It can be seen from this that the coupling mechanism of dynamic wireless charging requires a more perfect design to solve problems such as energy loss. According to the different structural combinations of the magnetic coupling transceiver coils, they can be classified into four types: round-round type, round-square type, square-round type and square-square type. The square-square coupling mechanism has better anti-offset ability and is therefore more suitable for dynamic wireless charging [7].

In addition to choosing the coupling mechanism based on different combinations of transceiver coil structures and different magnetic field distribution characteristics, the size relationship between the transmitting track and the receiving coil can also be used as a selection basis. Currently, there are mainly two options: one is the array type, and the other is the rail type. Through simulation comparison, it is found that under the premise of choosing the array structure at the transmitting end, compared with the single receiving coil, the double receiving coil can not only reduce the energy loss of the coil, increase the input power at the vehicle end, but also reduce the change of mutual inductance of the coupling mechanism during the dynamic wireless charging process, in fig 5 [7]. Meanwhile, research institutions such as KAIST proposed an embedded coil array design scheme. By arranging multiple sets of coupling coils beneath the road surface, it ensures that the vehicle can still maintain stable energy reception when traveling at high speed. Studies show that when the vehicle speed reaches 60km/h, the optimized coil system can achieve continuous and stable power transmission, with the transmission efficiency remaining above 85%. These innovative designs not only verify the feasibility of dynamic charging technology, but also lay an important foundation for the construction of future intelligent transportation systems [8].

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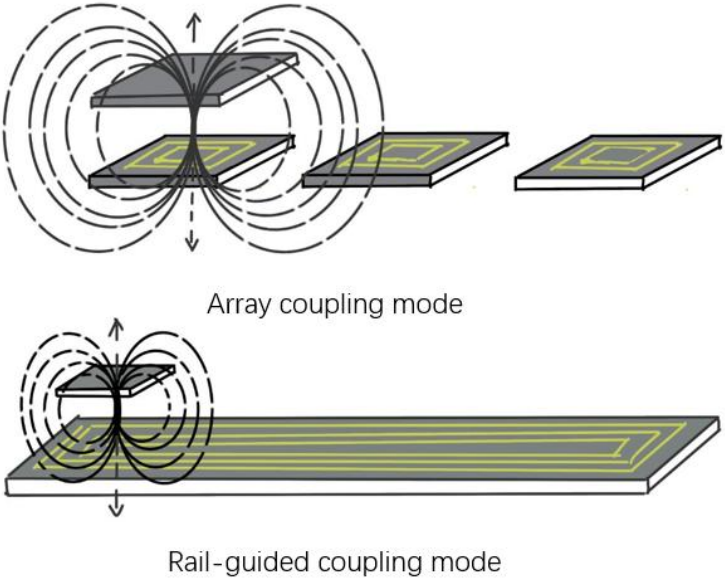

Fig. 5. Schematic diagram of Different Coupling modes [7]

In addition, by improving material selection and resonant parameter configuration, or by using some special coil structures, the energy transmission efficiency can also be significantly enhanced and the effective transmission distance can be extended. For instance, the research team at KAIST successfully increased the transmission efficiency by 15% by using high-permeability ferrite materials as the core of the coil, and simultaneously extended the effective transmission distance from 10 centimeters to 25 centimeters. The Oak Ridge National Laboratory (ORNL) achieved a transmission efficiency of over 90% under a power transmission condition of 6.6kW by precisely adjusting the resonant frequency of the coil and the parameters of the resonant circuit, and extended the maximum transmission distance to 40 centimeters. Utah State University proposed a double-layer helical coil structure. By using the design of irregular coils, the alignment tolerance problem was significantly improved. Even if the offset at the receiving end reached 30% of the coil diameter, the system could still maintain a transmission efficiency of more than 80%. These specific cases fully demonstrate the key role of coupling coil optimization in improving the performance of wireless charging systems, providing important support for its commercial application [8].

3.2 Compensation Topology

Whether it is a static wireless charging system or a static wireless charging system, the offset of the vehicle position will cause problems such as drastic changes in the mutual inductance coefficient, thereby leading to an imbalance in system performance. Therefore, improving the anti-offset performance of the charging system is crucial for both charging systems, and the design of the compensation topology is one of the important methods to enhance the anti-offset performance of the system. Meanwhile, the compensation topology can also effectively reduce the reactive power loss of the system and decrease the system's dependence on reactive power.

Compensation topologies are mainly divided into two categories: basic compensation and compound compensation. According to the connection mode of resonant capacitors and resonant inductors, basic compensation mainly includes series compensation, parallel compensation, series-parallel compensation, as well as the derived series-series, series-parallel, parallel-series and parallel-parallel. The above four basic compensation networks are relatively simple, use fewer components and are easier to analyze. However, at the same time, due to the difference in anti-offset performance and the significant influence of coupling coefficients, they are not suitable for dynamic wireless charging systems.

Since a single compensation topology cannot achieve system stability when both the coupling coefficient and the load change simultaneously, a composite topology emerged. This structure is based on the principle that the output characteristics of different topologies are opposite during offset, ensuring that the current and voltage remain stable after offset. Tong Zhou's team calculated and obtained the output current expression of the LCC-LCC compensation topology, thereby proving that the LCC-LCC compensation topology has the good characteristic of constant current output [7]. Moreover, through calculation, it was concluded that when the system operates at the resonant frequency point, the equivalent resistance of the system is purely resistive, which can achieve normal operation per unit power factor. That is, LCC-LCC has a higher degree of freedom, which is conducive to the subsequent optimization design. Liu xu's team proposed and studied a parameter optimization design of a hybrid topology based on a four-rectangular orthogonal magnetic coupling mechanism. The compensation topology was optimized by using the poor coupling of the QRQP coil, which effectively suppressed the fluctuation of the system output voltage when the load changed over a wide range and the coil moved freely [9].

3.3 Infrastructure Construction and Maintenance Costs

Static wireless charging technology is mostly applicable to parking lots, shopping malls, residential areas and other places. The initial construction mainly involves installing high-power high-frequency power supplies and installing transmitting coils at specific locations. Dynamic wireless charging is mostly applicable to the construction of smart highways, smart buses and other fields. The initial cost investment is relatively large, and it requires manual transformation of designated sections. Moreover, it also needs more manual maintenance in the later stage. Therefore, compared with static wireless charging technology, dynamic wireless charging is more difficult to build and requires more investment.

At present, mainstream automakers (such as Nissan and Audi) have promoted the initial implementation of WPT technologies like magnetic resonance and induction through cooperation with technology suppliers. However, large-scale construction still faces the challenge of high costs. The manufacturing, installation and maintenance costs of ground components (GA) and on-board components (VA) are the main cost sources for large-scale deployment, especially in scenarios such as public parking lots. Although standardization (such as SAE J2954, ISO 19363) reduces long-term costs through compatibility, the investment in the research and development verification stage still needs to be shared. It is worth noting that the wireless charging system, with its high energy efficiency (> 90%) and contactless feature, can reduce cable loss and human maintenance costs, and has economic advantages in long-term operation. [10]

4 Challenges and Optimizations for Future Development

4.1 Challenges

To ensure the driving range of electric vehicles (EVs), it is essential to develop a well-planned charging infrastructure. Consequently, determining how to optimally allocate charging stations remains a critical challenge. Within budget constraints, mathematical models can be formulated to optimize the placement and number of charging facilities in order to meet user demand as effectively as possible. The layout optimization of charging infrastructure typically involves complex computational models, and the development of efficient solution algorithms is key to achieving practical and scalable results.

For dynamic wireless charging technology, major technical bottlenecks include the stability, efficiency, and safety of power transmission. In contrast, static wireless charging has made significant progress and is gradually entering the commercial market. It is already widely used in consumer electronics such as smartphones, smartwatches, and wireless earbuds. However, its application in electric vehicles is still limited, currently appearing only in certain high-end models.

By comparison, dynamic wireless charging remains in the experimental phase and has yet to achieve broad adoption, primarily due to its high technological costs, the complexity of infrastructure deployment, and limited user acceptance.

4.2 Optimizations

Smart grids enable efficient power dispatch and system management through digitalization, automation, and bidirectional communication technologies. At the same time, wireless charging offers a convenient and safe method for recharging electric vehicles (EVs). To address the uncertainties associated with EV users' charging preferences and behaviors, a Monte Carlo Simulation (MCS) approach is applied, providing a comprehensive analysis of user behavior patterns and their potential impact on charging infrastructure [11].

The optimized integration of smart grid systems and wireless charging technologies yields several key benefits, including improved overall efficiency of the power grid, enhanced utilization of renewable energy sources, increased grid stability, and an improved user experience. The synergy between these technologies not only enhances the reliability and performance of the power system but also supports the broader adoption and deployment of electric vehicles.

5 Conclusion

Static and dynamic wireless charging technologies each present distinct advantages and limitations, making them suitable for different application scenarios.

Static wireless charging primarily utilizes electromagnetic induction and resonant technologies. Among these, resonant charging has emerged as the dominant method due to its ability to support mid-range power transmission and operate through non-magnetic obstacles. However, it is confined to fixed-location applications. In contrast, dynamic wireless charging allows vehicles to be charged while in motion by means of rail-type or segmented transmitter coils embedded in the roadway. Despite its potential, this technology faces several challenges, including high implementation costs, energy losses, and concerns related to electromagnetic safety.

From a technical performance standpoint, dynamic wireless charging demonstrates slightly higher energy transfer efficiency compared to static systems. However, its coupling mechanisms remain less stable and require further optimization. In terms of safety, both technologies must adhere to international electromagnetic exposure standards; nonetheless, dynamic charging is more susceptible to magnetic field leakage due to its inherent mobility.

Overall, static wireless charging is more technologically mature, cost-effective, and user-friendly, but it is limited to stationary charging scenarios. On the other hand, dynamic wireless charging holds significant promise—particularly in extending the driving range of electric vehicles (EVs)—though its complexity and high infrastructure costs call for continued research and technical refinement.

With the adoption of advanced materials and technologies, both static and dynamic wireless charging systems are expected to improve in efficiency, transmission distance, and safety. At the same time, reductions in cost are anticipated to accelerate their adoption. The market for static wireless charging in the EV sector is likely to see steady growth, while dynamic wireless charging is expected to enter the market progressively as the technology matures.

While wireless charging has already achieved significant commercialization in the consumer electronics sector, its application in EVs and industrial settings is still in the early stages. Future research should prioritize enhancing the stability, efficiency, and safety of dynamic wireless charging systems, alongside exploring their integration with smart grid infrastructure. Policy support and market incentives will also play a crucial role in fostering the development and deployment of wireless charging technologies. With continuous technological advancements, wireless charging is poised to become one of the mainstream charging solutions for electric vehicles.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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