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Review

Wireless Chargers for Electric Vehicle: A Systematic Review on Converter Topologies, Environmental Assessment, and Review Policy

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Abstract: The delivery of electricity employing an electromagnetic field that extends across an intervening region is called a wireless power transfer (WPT). This approach paves the way for electric vehicles (EVs) to use newly available options to reduce their environmental impact. This article is a review that examines the WPT technology for use in electric vehicle applications from both the technical aspect and the environmental impact. This review will attempt to accomplish the following objectives: (1) describe the present state of the technology behind the development and application of a WPT across the transportation industry; (2) substantiate the actual implementation of WPT EV systems; and (3) estimate the functioning of the autonomous system, as well as detect the potential stumbling blocks and openings for enhancement. The most recent advancements and implementation in compensating topologies, power electronics converters, and control techniques are dissected and debated scientifically to improve the system's performance. To evaluate the performance from a sustainable perspective, energy, environmental, and economic factors are utilized, and at the same time, policy drivers and health and safety problems are researched.

Keywords: electric vehicle; wireless charging; inductive pad; converter topology; control techniques

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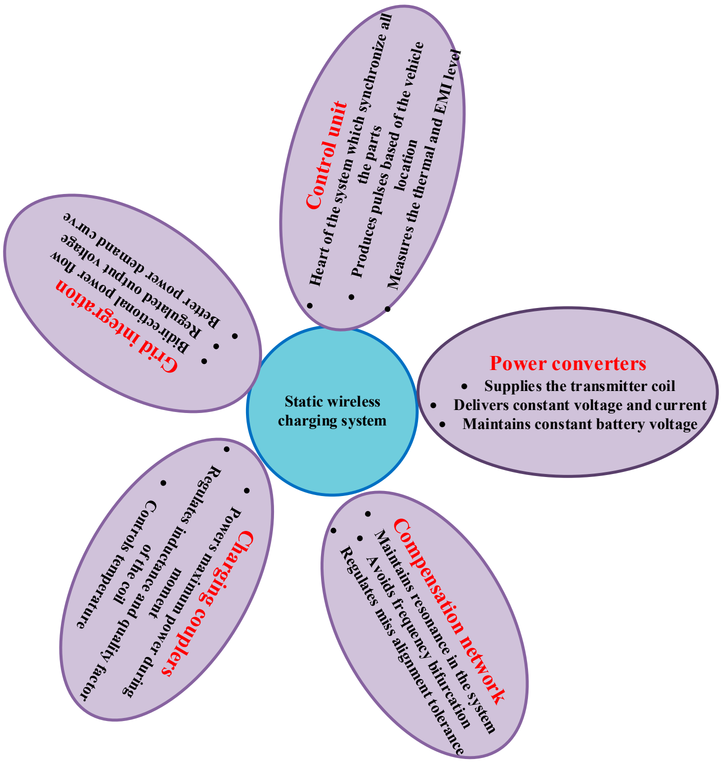
1. Introduction

Nicola Tesla performed efforts to transfer power a century ago wirelessly [1,2]. WPT has been the subject of extensive study in recent decades to speed up the widespread adoption of electric devices. Examples include EVs, cell phones, implanted medical devices, robots, and household electronics. In most cases, an electromagnetic field is used to transmit energy. The WPT is becoming increasingly popular for several reasons, the most important of which is the inherent simplicity of the technology and the possibility of a continuous operation with no interruptions for recharging.

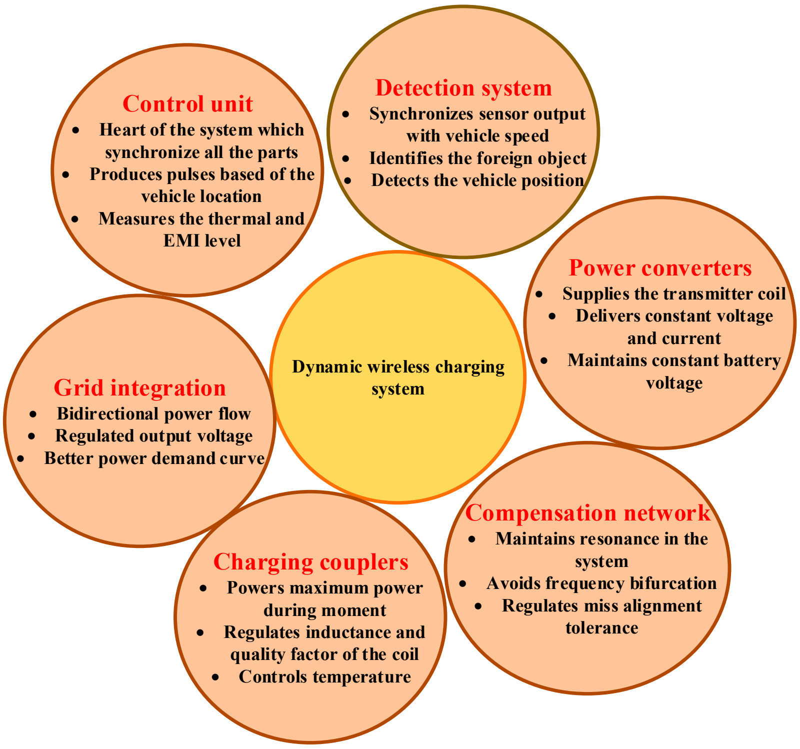
However, magnetic coupling WPT, whether inductive-based or resonant-based, is the method of choice for near-field transmission since it causes significantly less damage to the surrounding environment. In addition, power transmission for any long distance between the Earth and solar power satellites can be accomplished using a wireless power transfer that uses electromagnetic radiation. This radiation can take the form of microwaves or lasers. This study focuses on the magnetically coupled WPT for any electric vehicle charging application and has made the subject of a significant amount of research [3–8]. In terms of its operational modes, a WPT can be of two categories: (1) static WPT, which involves charging the battery while the vehicle is parked, and (2) dynamic WPT, which involves the battery being charged while the vehicle is moving down a roadway that is enabled for WPT. The WPT for electric vehicles has the potential to remove some of the barriers that prevent vehicle electrification and achieve sustainable mobility [9]. This would mean that wired chargers would no longer be necessary. A WPT can significantly reduce the size of the onboard battery in an electric vehicle, meaning it offers much more convenience. In the case of electric transit buses with a stationary WPT, for instance, the onboard [10,11] charging station can be reduced by approximately two-thirds of the size due to the many situation charges made while waiting for and unloading the passengers at bus stops. It is acceptable to bear a significantly small onboard battery because these charges en route still meet the vehicle route requirements. There is a considerable reduction in the vehicle weight because the weight of the battery pack can be as much as one-fourth of the total weight of an electric bus which is built for continuous operation during the daytime [12]. Reducing the size of the battery has substantial ramifications in terms of lowering the overall weight of the vehicle and raising the economical operation of the car [10]. Theoretically, in the case of passenger cars on significant highways based on a dynamic WPT, widespread charging stations could make it possible for EVs to have an unlimited range with a small battery capacity [13,14].

Nonetheless, the WPT for EVs raises new questions and trade-offs about the environment, which have sparked debate in academic and business communities. The benefits of a reduced battery size and enhanced fuel economy must be weighed against the costs of deploying widespread WPT infrastructure. A lowered charging efficiency at high speeds is a significant cause for concern, as is the question of whether or not a dynamic WPT is technically and financially feasible. Various parts of static and dynamic charging are illustrated in Figure 1.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Wireless charging: (**a**) static and (**b**) dynamic.

The course of the paper is organized as follows: Section 2 deals with compensation topologies, and the power converter topologies and control structures are briefed in Sections 3 and 4, respectively. In Section 5, the frequency and power level determination are explained. The environmental and energy assessment and policy and economic forecasting are detailed in Sections 6 and 7, respectively. In Section 8, the safety and health of using EVs are explained. The recent trends in the EV WPT and the paper's conclusion are explained in Sections 9 and 10, respectively.

2. Compensation Topologies

To generate RIPT in the static inductive charging systems for electric vehicles, compensating capacitors are introduced in parallel and series combinations, as shown in Figure 2. This is done on both the receiver and transmitter sides of the system. In Figure 3, there are four distinct topologies for compensation networks. These topologies are stated as series–series (SS), parallel–parallel (PP), parallel–series (PS) and series–parallel (SP). It is necessary to have the source compensated to eliminate the phase difference between the current and the voltage and to cut down on the amount of reactive power produced by the source [15,16].

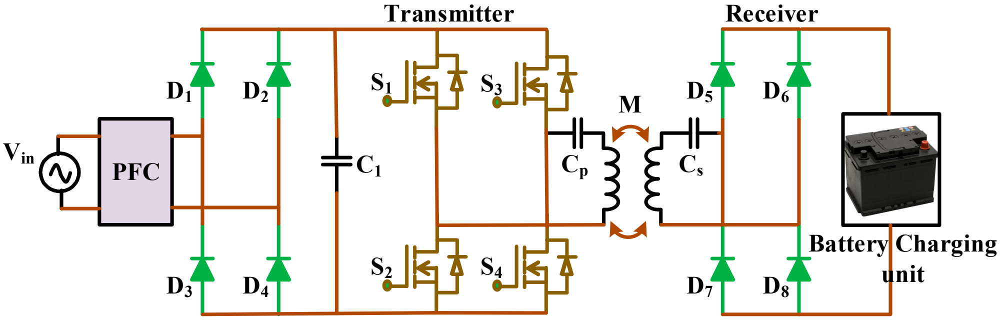


Figure 2. Resonant power inductive transfer topology.

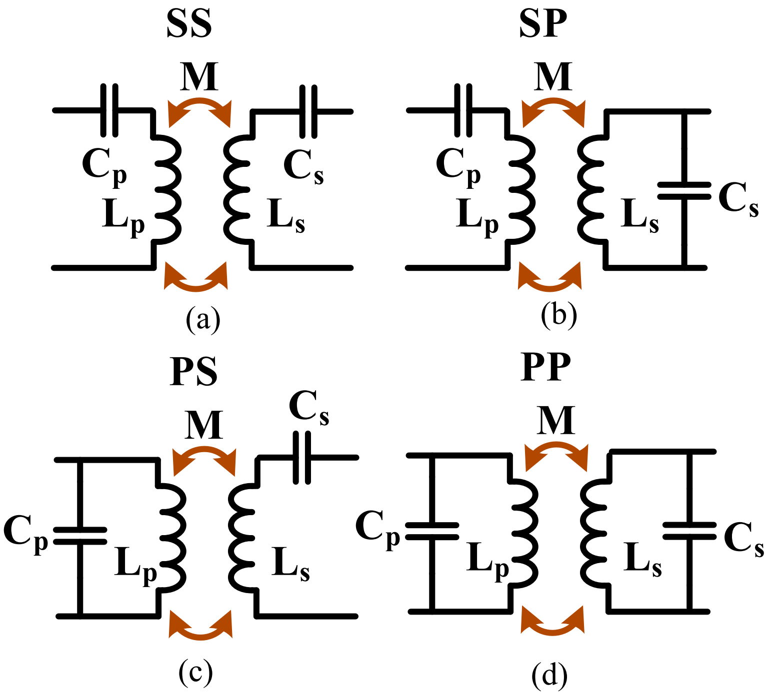


Figure 3. Compensation networks (**a**) SS; (**b**) SP; (**c**) PS; (**d**) PP.

The system load transfer capacity and efficiency can be maximized to their full potential by implementing a secondary compensating network [17]. In addition, the particular application requirements contained in the WPT are taken into consideration when choosing the network topologies to implement. The PS- and PP-compensated wireless charging station (WCS) has safeguards to ensure that the source coil will not function if the receiver coil is not there. Even though it provides a risk-free setting, the system cannot transfer adequate power when the transmitter and receiver are not appropriately positioned [18].

Additionally, extra series inductors are needed to manage the source current to flow parallel within the resonating circuit. A capacitor's rating depends on the magnetic resonance and its Q factor [19]. This is how the capacitor achieves its value. In an SP-based compensated WCS, the primary compensating capacitor's value is independent of the mutual inductance. As a result, this system can provide more power-transferring capacity when compared to the graded system.

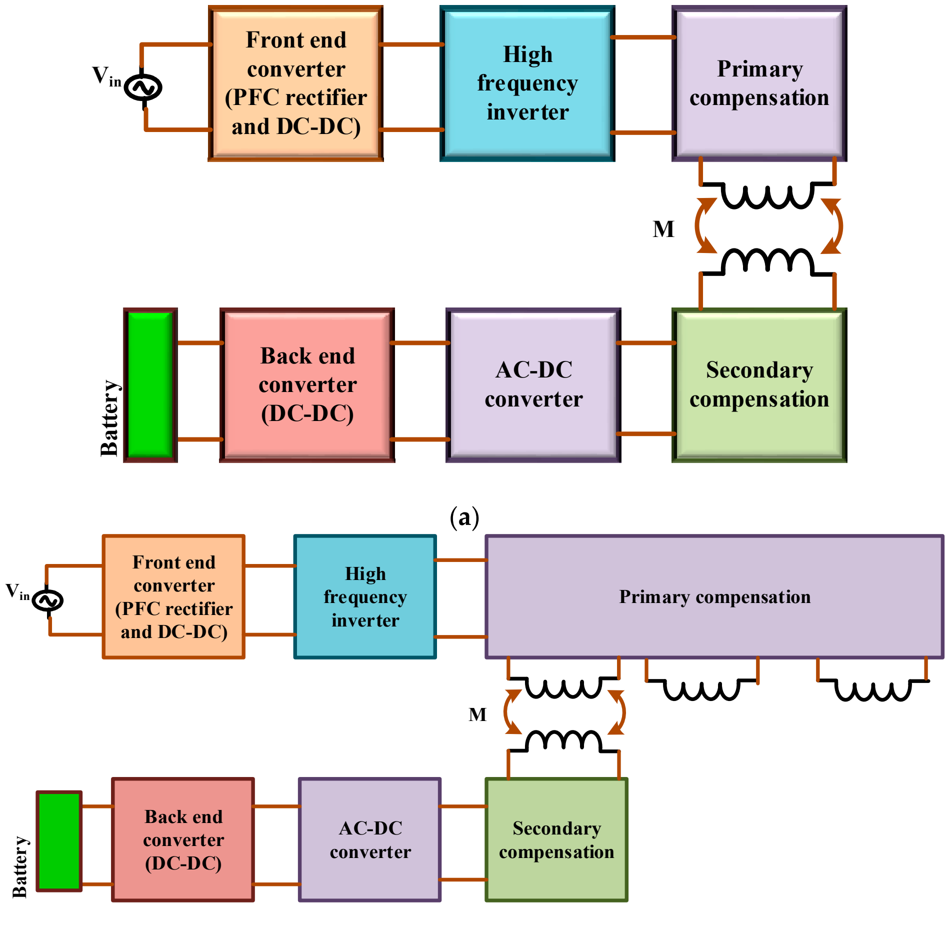
Nevertheless, it is pretty sensitive to changes in the load [20]. Because it has two significant benefits also considering cybersecurity [21,22], the SS-compensating topology is the one that is best suited for EV applications. The first benefit is that the enhanced current and mutual inductance do not affect the values of the capacitor on either of the sides. As a result, the mutual coupling and loads do not affect the sources' or receivers' resonance frequencies; instead, they depend on the secondary and main coils' self-inductance [16]. Such systems can retain a unity power factor by drawing active power at the resonance frequencies because the reflecting resistance from the reception does not contribute an imaginary component in the transmitter coil [20]. This is the second advantage of such systems. The suggested SS topology based on the WCS may provide a more reliable method for charging batteries since it may supply the cell with a consistent voltage and current [18]. Table 1 [17,18,23,24] outlines the supplementary benefits and characteristics of various compensation networks, all of which are utilized in the WPT for electric vehicles (EVs).

Table 1. Advantages and features of the compensation network.

Features	**SS**	**SP**	**PS**	**PP**
Ability of power transfer	Good	Good	Poor	Poor
PF	Less	Less	Moderate	Moderate
Displacement tolerance	High	High	Moderate	Moderate
Value of Z at resonant time	High	High	Moderate	Low
Tolerance of frequency	Low	Low	High	High
Application on EV	Low	High	Low	High
Primary capacitor	$\frac{1}{\omega^2 L_p}$	$\frac{1}{\omega^2 (L_p - \frac{M^2}{L_s})}$	$\frac{1}{\omega^2 (L_p + \frac{\omega^2 M^4}{L_p R})}$	$\frac{1}{\omega^2 (L_p - \frac{M^2}{L_s}) + \frac{\frac{M^4}{i^4} R^2}{\omega^2 (L_p - \frac{M^2}{L_s})}}$
Secondary capacitor	$\frac{1}{\omega^2 L_s}$	$\frac{1}{\omega^2 L_s}$	$\frac{1}{\omega^2 L_s}$	$\frac{1}{\omega^2 L_s}$
Load	$\frac{\omega L_s}{Q_s}$	$\omega L_s \; Q_s$	$\frac{\omega L_s}{Q_s}$	$\omega L_s \; Q_s$

3. Power Converter Topologies

Figure 4 shows that a typical grid-to-vehicle static and dynamic wireless power transfer (DWPT) system needs power electronic converters that work in four stages. On the primary side, these are front-end converters and HF inverters; on the secondary side, there are rectifiers and the back-end DC-DC converters are connected. Table 2 shows the transfer stages, the topologies used at each stage, and the control handles they offer.



(**a**)

(**b**)

Figure 4. Block diagram of typical grid-to-vehicle WPT: (**a**) static WPT and (**b**) dynamic WPT.

3.1. Source Side Converter

Front-end primary converters typically consist of rectifiers on the grid side, a power factor correction (PFC) converter, and a DC-DC converter on the other stages. Front-end primary converters are also known as buck converters. The buck converter is the most common form of the several types of DC-DC converters, which can also take the form of boost or buck-boost converters. The controls from DC-DC converters at the front-end assist in running the WPT stages at a specific operating point, which aids in their soft switching [25–29].

The WPTs primary inverter configurations consist of being voltage-fed from a single-phase, three-phase, or multistage inverter [27,30,31], current-fed push–pull [25], and class EF structures [32]. These inverters are depicted in Figure 5 and convert voltages from one phase. The inverters suggested in DWPT systems may drive a single or several coils that offer various control options for activating and deactivating the appropriate charger. They can come with varying degrees of complexity of the actual implementation.

Table 2. At various stages of the converter.

Stage of the Converter	Topology	Control Action
Front end converter	• Rectifier/PFC [33] • PFC added with buck or boost converter [30]	• The duty ratio of PFC • The duty ratio of the buck-boost converter
Inverter	• Single phase [34] • Multiphase [35] • Class EF [32]	• The duty ratio of switches • Phase shift among half bridge legs • Switching frequency
Rectifier	• Full bridge diode rectifier [30] • Full bridge synchronous rectifier [36]	• No controls
Back-end converter	• Buck converter [37] • Boost converter [38] • Buck-boost converter [39]	• Duty ratio

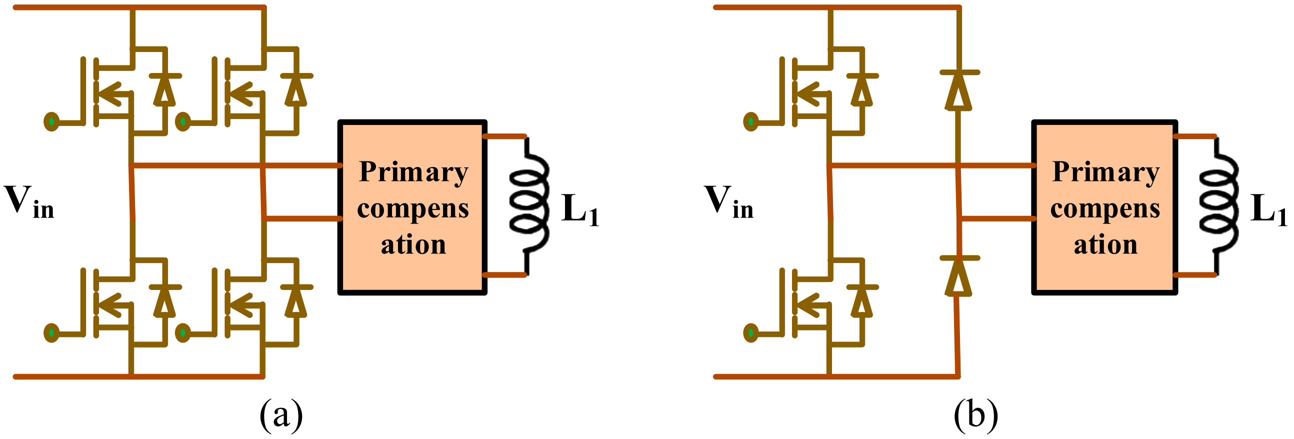


Figure 5. Static WPT high-frequency converter topologies: (**a**) full bridge type and (**b**) half bridge type.

3.2. Static WPT Source Side Converter

The static type WPT systems are commonly energized using a high frequency inverter at the preprimary side using full bridge topology. The other alternative method is to reduce the number of switches the half bridge inverters are proposed. In both methods, the inverters are designed to operate at the high frequency operation using square PWM techniques. Figure 5 shows the two types of static WPT primary side inverter topologies. In order to minimize the harmonics distortion in both the techniques, the compensator capacitors are designed at the primary and secondary side of the coil.

3.3. Dynamic WPT Source Side Converter

Generally, the DWPT systems are designed to operate using a high-power, high-frequency inverter. Figure 6 shows the various topologies adapted in the DWPT primary side inverter. For the cost-effective solutions, single high-power inverters are designed to power multiple coils connected in series with the primary compensators. However, these methods are able to power only one EV running in the lane at a time. Multiple inverters connected at discrete locations can switch ON and OFF the individual modules based on the vehicle's position. It is also suitable for the simultaneous power transfer to multiple vehicles in the same dynamic charging lane. Moreover, a fault in any inverter will not hamper the entire charging lane. However, the investment cost on the multiple inverter modules is higher compared with the single inverter DWPT system.

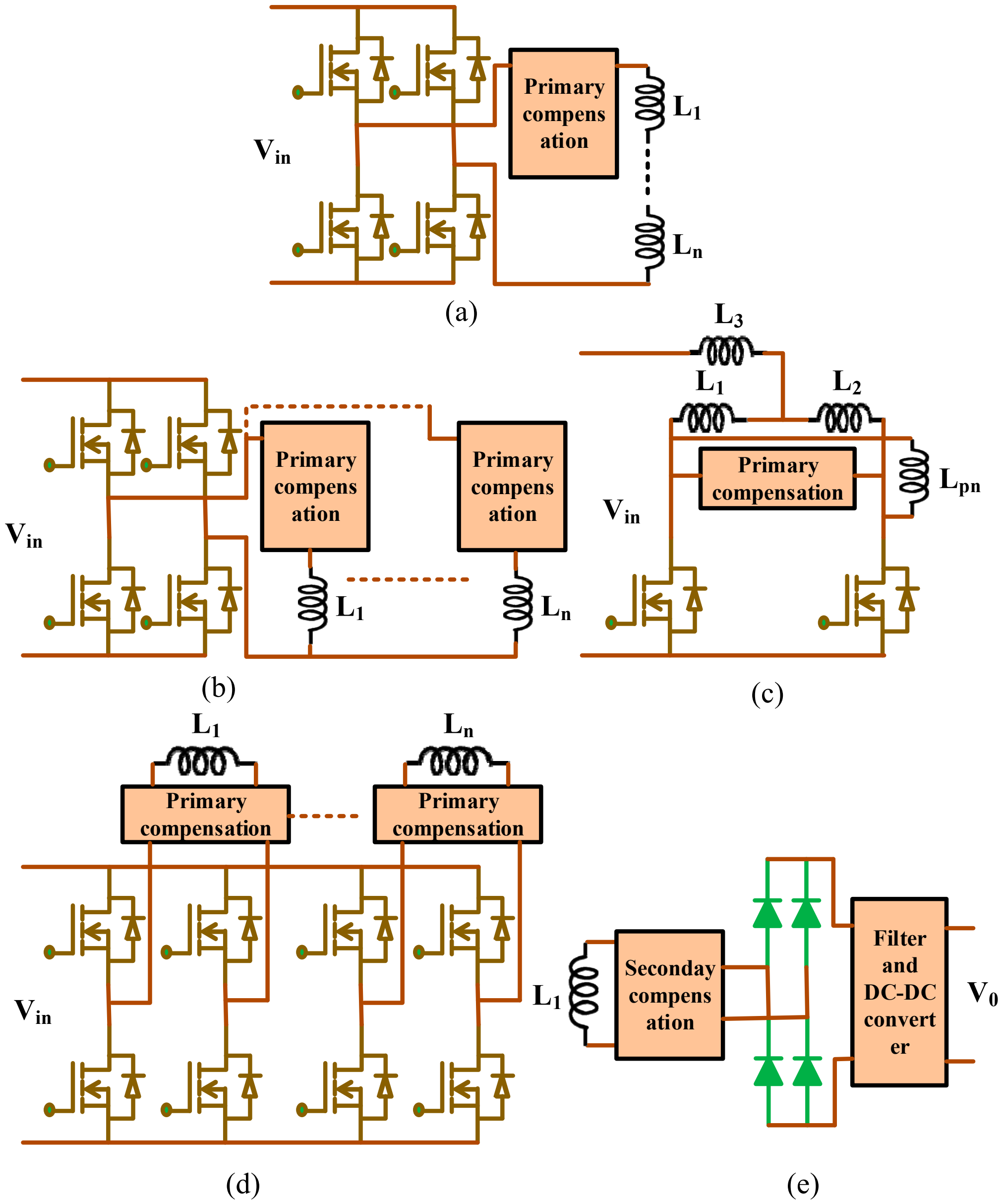


Figure 6. Various high-frequency converter topologies for DWPT feeding; (**a**) multiple coils connected in series; (**b**) multiple coils connected in parallel; (**c**) push–pull converter; (**d**) multi-phase converter; (**e**) secondary compensation topologies.

3.4. Load-Side Converter

Diode rectifiers are the most common solution for secondary-side converters, and many researchers have worked to make the secondary side as straightforward and uncomplicated as possible [39]. The use of a synchronous rectification mode is restricted since it simply enhances the efficiency [40,41] without offering any additional advantages in terms of the control. Most secondary-side-controlled DWPT systems use an extra DC-DC converter after the rectifier [24,42]. With DDQ-type coils or many secondary pads, several rectifying stages are used; however, this is not popular because it increases the vehicle's overall size [25,39,43].

The converters determine the extent to which the DPWT system may be controlled. Table 3 lists the formulas describing the effects of adjusting the various control handles on the tank's parameters. Since buck converters are so ubiquitous, they will be used to convert DC-DC at the front end of the circuit. Front-end and back-end converters frequently use duty ratio controls (D_i and D_o), while DWPT systems lack these stages and typically rely on inverter phase shift controls. An increased electromagnetic interference can be caused by adjusting the inverter's duty ratio or frequency. The inverter phase control can increase losses and EMI by preventing soft switching at particular load levels. Therefore, an excellent efficiency and low EMI can be maintained by controlling the front-back-end converters. However, inverters must be able to activate or deactivate the appropriate coils based on the vehicle's location.

Table 3. Various converter topologies.

Topology	Control Techniques	Control Formula
VSI	Phase shift control	$V_0 = \frac{2\sqrt{2}V_{in}}{\pi}\sin(\frac{\phi}{2})$
	Front end converter	$V_0 = \frac{2\sqrt{2}V_{in}}{\pi}\mathrm{D}$
CSI	Phase shift control	$V_0 = \frac{\pi V_{in}}{2\sqrt{2}\pi\ \sin(\frac{\phi}{2})}$
	Front end converter	$V_0 = \frac{\pi V_{in}}{2\sqrt{2}}\mathrm{D}$

4. Control Techniques

Three different ways of control can be made in WPT: primary-, secondary-, and dual-side control [44]. The control technique on the primary side can be made at the main winding and utilizes a full primary bridge controlled by a regulated transmitter current. PFC was also responsible for the regulation of some instances.

The information from the secondary side helps control the primary side, such as the state of charge, the voltage at the battery's terminals, the state of health, and its state of charge information for regulating the central pad based on the load.

Under this strategy, the necessity for interaction with the secondary side is kept to a minimum. As a result, the amount of onboard electronics has been cut down, lowering both the cost and the vehicle's overall weight [45]. The control on the secondary side can be done by an active rectifier and a converter which are used to charge the battery. However, because more electronics are on the secondary side, the vehicle becomes heavier and more expensive.

Control on both sides of the WPT system is required for this method, referred to as the dual-sided control. In this method, there is a requirement for a link to communicate on both sides. It depends on the operation whether both sides were controlled independently or not looking also at cybersecurity issues [46]. Whenever it comes to dynamical charging that has challenges in application [44], they applied the static wireless charging method of dual-side control. The preferred and ideally independent control on both sides is suitable for dynamic wireless charging applications. However, stability issues must be meticulously examined when utilizing two independent controllers [44]. The following are some of the fundamental methods of control.

4.1. Frequency Adjustment

The switching frequencies were adjusted in this approach to regulate the input power. The rated power deviation produces a rise in the reactive power of the system, which leads to a decrease in the efficiency and increases the risk of being out of its control [47,48]. This technology does not require any moving component, resulting in a reduced physical footprint, decreased complexity levels, and increased dependability.

4.2. Phase Shift Control

Under this controlling method, the voltage supplied to the magnetic coil is controlled by appropriately adjusting the angles of the switches, which is accomplished by controlling the switching ON time. This helps in maintaining a steady frequency. With this method, you do not have to worry about the frequency at which the control works, and it also helps to remove of specific harmonic frequencies. However, due to the pole-splitting process, the selection of the switching frequency plays the most crucial function [47,48].

4.3. Phase-Locked Loop Control

PWM pulses are adjusted to manage the power transmission in this method, which incorporates PLL for achieving soft switching. It first analyses the differences in the zero-crossing point of both voltage and current signals to produce a delicate switching operation. Then, it changes the switching frequency of the converter [49]. It will not be easy to put this plan into action. In [50], resonant circuits' real and reactive power was a measure to control the two-way power fled. It is located on the side of the receiver and decreases the reactive power of the resonant circuit.

The author in [51] proposed cutting down on the cost and volume of a semi-bridgeless active rectifier (SBAR) by providing it with variable frequency control and because of its extensive aluminum shielding and the wide range of misalignments, merely using the fixed frequency adjustment in an EV application. This is due to the high impedance mismatch caused by combining these two factors. Even though the frequency is fixed, the control must be made with a large margin to guarantee zero voltage switching, provided that there is a big difference. The DC-DC converter of [52] was the DWPT operated by both PI and fuzzy controllers compared their respective performances.

On the contrary, the fuzzy controller quickly finds its equilibrium with the reference parameters. The proportional-integral (PI) controller is the most typically employed control system controller. In several of the WPT applications, the sliding mode control (SMC) and the perturbation and observation (P&O) algorithm were utilized [53,54]. A disconnected controlling system is suggested in the literature [54]. According to this method, only the DC-to-DC converter on the receiver side regulates the output voltage, whereas the rectifier on the secondary side is responsible for impedance matching [54].

5. Frequency and Power Level

When designing WPT systems, the choice of the frequency, power, and desired system efficiency are three of the essential design elements. When a frequency value is selected, the coil sizes can be decreased; nevertheless, this results in increased losses, particularly in the switching. The various frequency ranges used for operations are condensed into two bands. A frequency of 20 kHz was selected as the operating frequency for the majority of the investigations. Since the revival of interest in a high-frequency resonance WPT more than a decade ago, the goal has been to avoid the audible noise region as much as possible while adhering to the limitations imposed by the capabilities of the electronic power switches and the losses they incur. It has been reported that WPT systems can run at a frequency of several kilohertz when the appropriate switches are used. The WPT frequency range later became standard, and 85 kHz became the typical resonant frequency for uniform charging power levels in the automobile EV industry. The windings' sizes and numbers of turns are selected based on the desired frequencies. The proportion of turns in the primary to the number of turns in the secondary falls as the frequency rises. However, it is also important to consider things such as increased switching losses, power electronics' use of semiconductors, and how they interact with other car parts. Additionally, when the frequency is high, the current flows from the surface instead of through the conductor's cross-section. This is called the "skin effect". The usage of litz wire is recommended, especially for high-frequency research. As a result, the skin effect is mitigated thanks to the conductor's uniform current distribution over its cross-section. The proximity effect is another variable that changes with the frequency. The system's efficiency drops as the frequency value rises because of the rising winding resistance. Litz wire is used because of its low resistance and loss while winding.

To improve both its efficiency and air gap, the wireless charging of EV requires considerable changes to be made to two different aspects. Changing the system's operational frequency could result in a reduction in the system size and an increase in its overall efficiency. However, there is a ceiling to each power level, and the efficiency of the WPT grows along with the frequency of the transmissions. Both of these aspects are connected. As of the most recent phenomenon, there is no standard capable of reaching the optimum efficiency. The model's various businesses and educational institutions developed are presented in Table 4, along with the highest power levels at which they can charge a vehicle.

There is a wide range of achievement levels across the many enterprises, research institutions, and academic institutions engaged in developing diverse wireless charging initiatives. Every institute has the intention of developing such a system that is capable of becoming standardized. Increasing the frequency by around 1 MHz in a WPT system makes it possible to achieve a high efficiency [55]. A system with a frequency that falls between 200 and 100 kHz was suggested by Yvkoff [56]. They have developed their idiom as a transfer quality factor $T_0 = \omega M / R_0$. The mutual inductance between the transmitter and receiver, denoted by M, the resonant frequency (ω), and the equivalent resistance, denoted by Ro. T_0 must be massive to achieve its maximum potential. There are three different approaches to achieving a maximum T_0: (1) increasing the driving frequency to its maximum, (2) boosting the amount of mutual inductance, and (3) decreasing the amount of equivalent resistance. It is possible to lower the resonant frequency in two ways: by increasing the amount of inductance or the amount of capacitance. When we raise the frequency to an extremely high level, we cause a switching problem throughout the conversion process. The WPT system is limited in its ability to function at high frequencies because of its low coupling coefficient [57]. The WPT system is limited in its ability to function at high frequencies because of its low coupling coefficient [57]. The following table outlines several different WPT applications that operate at various frequencies. Each frequency has a predetermined value for its use. When a system is standardized, the frequencies on which it operates are also standardized so that it can function at its highest level of efficiency [58].

Table 4. Specification of various EV model.

Refs.	Industry/Institute Name	Power (kW)	Frequency (kHz)	WPT Distance (cm)	Efficiency (%)	Vehicle
[59]	ORNL	20	-	25.4	90	Car
[60]	Qualcomm halo	7	20	-	-	car
[61]	WiTricity EV	0.06	13.56	5–200	-	car
[62]	ETH Zurich	5	1000	0.052	96.5	car
[63]	WAVE	50	23.4	17.8	92	-
[64]	PATH	60	20	7.5	60	Car
[65]	INTIS	30	35	15	90	Bike

Table 4. *Cont.*

Refs.	Industry/Institute Name	Power (kW)	Frequency (kHz)	WPT Distance (cm)	Efficiency (%)	Vehicle
[66,67]	NYC	25	85	21	91	Car
[64]	Showa aircraft	30	22	15	92	van
[68]	University of Auckland	11	85	10	95.3	car
[69]	Utah State University	25–50	-	15	>90	bus
[70]	Saitama University	1.5–3	50	7	94	car
[71]	Tokohu University	0.015–0.018	360	20	75	car

6. Environmental and Energy Assessments

Recent environmental and energy studies have compared traditional engines with plug-in EVs and wireless charging vehicles. It was discovered that electric buses that used wireless charging performed better than conventional diesel in their carbon emissions. Within the scope of the CARTA project, a comparison was made between the use phases performance of an electric transit with wireless charging and a diesel bus that offered the same range of service. It is suggested that operating electric buses results in a 38% reduction in CO_2 emissions [72]. However, these findings only consider the use phase of the product. They lack the holistic perspective provided by a life cycle evaluation that also considers the burden of production, network deployment, and end-of-life disposal.

According to a life cycle analysis, it was discovered that the performance of plug-in recharging electric buses and wirelessly charging electric buses had similar results in terms of the amount of energy used and the emissions of greenhouse gases (GHG). The demand for a smaller battery, which results in a significant decrease in the vehicle's weight and contributes to an improvement in the fuel economy, is the favorable implication that wireless charging has in terms of the energy and environmental achievement it delivers. The catch is that the widespread installation of charging stations is needed. The University of Michigan researchers modelled the regular bus service in Ann Arbor, MI, over 12 years to illustrate the trade-off between the infrastructure burdens and the battery-related savings associated with wireless charging [10]. This allowed them to better understand inductive charging technology's environmental and energy trade-offs. The study drew two major conclusions: (1) although the wireless charging infrastructure for transit buses adds energy and greenhouse gas (GHG) emission loads, these costs can be mitigated through battery reduction, making a wireless charging all-electric bus system beneficial from an energy and environmental perspective. (2) Improving the efficiency of charging from the grid to the battery is the key obstacle to making wireless charging more sustainable. It was discovered that a battery that could be charged wirelessly was between 27 and 44% smaller than a battery that needed to be plugged in. Although the corresponding decrease of 13–17% in bus mass for the wireless bus routes can decrease 5.3–6.9% in battery usage, the relatively lower inductive charging efficiency could potentially cancel the light weighting advantage from the primary energy point of view.

Consequently, the cumulative energy consumption and impact on warming the planet were comparable in the use [10] of phases for both charging methodologies. In its current stage of development, wireless charging technology has an energy and climate impact comparable to that of plug-in charging technology when seen from the point of view of the product's entire life cycle. However, more improvements could be made in charging effectiveness and the use of renewable power in the power grid during the day or peak hours. This is performed by assuming that most wireless charging occurs during the day and most plug-in trying to charge takes place at night, making an inductive trying-to-charge bus system more environmentally friendly [10]. The coil pitch decides the space requirement between two adjacent coils. It provides an idea of the positioning of inductive chargers in the highway in order to obtain a high efficiency for passenger cars.

In the two-coil machine at ORNL, the winding pitch was set to 70%, so there was a space between the coils along the duration of the machine. When the receiver coil is positioned so that it is halfway between the transmitter coils, the least amount of power that may be sent is fifty percent [13] of the total power. Low-density and more separated energy transfer pads will decrease the amount of material consumed, reducing the burdens placed on the infrastructure. However, this could reduce the amount of energy conveyed to the moving vehicle and pose significant variations in the grid due to the fluctuating charging power requirements [73]. Therefore, the design of the coil pitch needs to be optimized to minimize the demands placed on the infrastructure while ensuring an adequate amount of power transfer.

7. Policy and Economic Forecasting

The charging infrastructure, the cost of the battery, and the energy cost will impact the degree to which wireless charging technologies can compete economically. Additionally, the magnetic couplers can bring an additional cost of around USD 400 even for low-power wireless charging [15] stations, creating a significant difference with the static WPT topology. The difference in cost is due to the magnetic couplers required for any wireless chargers. The increase in cost for WPT recharging hardware may be pretty reasonable when weighed against the benefits of wireless charging, which include reducing the battery's size and savings on long-term operational costs [74]. Compared to diesel buses, buses that are charged wirelessly can experience a reduction in fuel expenses that is greater than eighty per cent, equating to a savings of ninety thousand dollars [75]. It is important to note that the investment in infrastructure would be cost-viable for dynamic inductive charging on highways. This is significant because interstate highways in the United States make up only 1% of road miles and 22% of any miles driven [76].

On the other hand, because of the enormous number of cars that travel to the same destination, the investments in the infrastructure which has been created may be high [9]. Given more opportunities for charging during driving, vibrant wireless chargers could facilitate the increased cost of EVs by letting a substantially [9] reduced storage system size.

These light-weight vehicles can boost the overall usage of energy and economic operation as well [10,77]. In a life cycle scope, it was discovered that wirelessly charging electric buses were more price viable than diesel engines, diesel hybrid, and plug-ins trying-to-charge electric buses [77]. On the other hand, the life cycles financial outlook of dynamic wirelessly trying-to-charge cars is not yet well established.

The cost allotment of charging stations and the battery capacity calculation are two crucial factors that need to be considered in the context of an economic study of wireless charging technology. If more wireless charging points are installed, the onboard battery capacity will need to be reduced to accommodate them, and vice versa. Several optimization studies have investigated the trade-off between these two model parameters to reduce the amount of money needed for an investment in an inductive charging bus line in Korea [78,79]. The cost function that needs to be cut as much as possible is the cost of saving energy and batteries. Both fixed and dynamic costs are involved in the power transmitter's price. The two primary components that make up the fixed cost are the cost of the converter and the labor cost.

There is a correlation between the duration of the power transmitter and the variable cost [78]. This optimization framework needs to be extended to network routes with connected EV stations to increase the usage. More research is required to accomplish this goal. The cost function would also need to be updated to incorporate the costs associated with the investment phase and the expenses associated with replacing the battery, maintenance, and energy costs. It has not yet been determined how to maximize the deployment of charging equipment and battery capacity for passenger vehicles using highway variable wireless charging while maintaining the lowest possible total cost during the vehicle's lifetime.

8. Safety and Health

Even though the street WPT techniques would enhance the system's operational safety [74], a significant amount of research has been done [6,69,80] to investigate the EMF problems with human electromagnetic permissible levels. Exposure to magnetic and electric fields with a lower frequency is known to irritate the surface field effects, nervous system stimuli, and sometimes the formation of phosphines in the retina area [81]. The EMF can also cause high field strong points, creating heating effects in metals, small animals, and medical devices implanted in the body [82]. The human body is a good conductor of electric fields. The ICNIRP establishes a limitation on the interior electromagnetic current of all body cells, which states that these fields cannot be greater than 1.35×10^{-4} times the operating frequency.

In terms of magnetic fields, the permeability of the tissue is compared with the permeability of air, which is identical to that of the surrounding environment's field. In addition, the limit of 6.25 µT, which was established in 1998, is frequently utilized in the most recent investigations. The findings of a recent study indicate that EMF can be fully controlled within an acceptable range. Nevertheless, additional research has been required to guarantee the safety of individuals. In the case of public transportation buses, researchers analyzed the potential for a human exposure to the charging fields caused by a wireless charging system in electric buses.

During the charging process, they discovered that none of the electric or magnetic fields were detected either within or outside the bus [82]. Aluminum rings are placed at the pads to reduce stray fields [9,74], and aluminum panels at the reverse side of the second pad protect the inner part of the car from the EMF. When a magnetic flux travels through an aluminum shield, it induces eddy currents that, in turn, cause a new magnetism that moves in the reverse way of the initial magnetic flux. Aluminum shielding was utilized by scientists at ORNL [6] to manage the EMF at 22 kHz inside the permitted requirements at a large of 6.20 µT stated ICNIRP. This allowed for the dynamic inductive charging of moving passenger automobiles. More research must be done to ensure that vibrant charging is safe and healthy in open-traffic environments, which are more unpredictable than lab test environments. These environments include variable power required levels both for light-duty and heavy-duty vehicles operating at variable speeds and accidental leaks exposed to nearby pedestrians, cyclists, and patients.

9. Recent Trends in the EV WPT

One of the most significant new issues for the existing electricity grid is the rising demand for charging electric vehicles. V2G topologies offer a solution to this problem that needs to be solved. One well-known type of application is a V2G application, which involves EVs providing power to the power grid. In [83], Nguyen et al. thoroughly analyzed the V2G integrating technology with conductive charging for electric vehicles. Flexibility, automaticity, and bi-directionality in both the charging and discharging of batteries are essential prerequisites for V2G integration. The majority of the criteria mentioned above can be satisfied by wireless charging.

Transportation electrification presents a possible opportunity for renewable energy to displace fossil fuels. V2G can potentially benefit local microgrids and is simple to integrate with many forms of renewable energy [84]. Although the electricity generated by renewable sources cannot be used directly, batteries are nevertheless widely employed for energy storage. In the last ten years, numerous attempts have been made to enhance the conversion and consumption of energy to reduce the reliance on fossil fuels in the area of electrifying transportation and producing electric energy. Therefore, the generation of electricity in the future will see an increasing introduction of renewable energy, and electric vehicles (EVs) will be used more frequently [85]. However, the installation of renewable energy sources, particularly solar and wind systems, poses challenges [86] to the primary grid's reliability and power quality due to the unpredictable nature of the ambient conditions. In addition, the widespread adoption of electric vehicles, be they hybrids or battery-only vehicles, poses significant difficulties for the electrical grid [87]. A perfect option for the power system would be to incorporate RES to offset EVs' requirements [85]. In addition, RES, along with EVs, can be utilized to improve the power quality and stability of the power grid, which is commonly known today thanks to applications that include V2G. To achieve this level of coordination between RES, EVs, and the grid, EVs' charging and discharging infrastructure needs to be adaptable, automatic, straightforward, secure, and dependable.

For research, a great deal of emphasis is placed on the simplicity of design, high efficiency, low-cost adaptability, and automated charging and discharging methods. Due to the automation involved, wirelessly charging electric vehicles may very quickly provide a bidirectional flow of electricity between EVs and the grid. The research presented in the references [87–89] compares and contrasts the interactivity of wireless connections and those that are connected. According to the studies described above, wireless charging or wireless connectivity can provide a connectivity of up to 65 percent, but cable connectivity provides just 10 percent of instances where successful contact occurs [87]. It is possible to automate the wireless charging process by digitalization [90] and by using specific wireless communication equipment, which can automatically identify the situation and fulfil the requirements of V2G together with optimization techniques [91,92]. In the not-too-distant future, the advent of wireless charging will make it possible to expand the grid's connection with a car, allowing for the vehicle's excess energy to be used when necessary and vice versa.

10. Conclusions

This article aims to provide a clear idea for the researchers regarding the present scenario of the WPT application and developments required in the transportation industry. It also reveals the challenges and opportunities that have been faced in terms of achieving technical progress. The study of the technical features involved in any static and dynamic charging stations is explained in this article.

This review mainly focuses on some compensatory structures involved in the charging station and DC-DC converters and their controlling methodologies. The system's performance has been boosted due to technological developments. When considering the topic of sustainability, WPT electric vehicles present a trade-off between the advantages of a battery reduction and vehicle light-weighting and the need to deploy a significant amount of infrastructure. Compared to wired electric vehicles and traditional internal combustion engine vehicles, wireless charging technology provides the space for a reduced impact on the environment, reduced cost of life span, greater ease, increased energy saving, and an operational safety point of view. For fully exploiting the potential of WPT electric vehicles, the subsequent research gaps will need to be filled in: (1) the management of the energy grid that strikes a balance between the supply and demand of electricity for stationary as well as moving vehicles; (2) the optimization of large-scale charging stations can be focused on the life span of the battery used in transporting vehicles such as cars and busses; and (3) policies that integrate the advancement in WPT technology with the advancement in other upcoming EV technologies, such as automobiles, that are both linked and autonomous.

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