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A COMPREHENSIVE REVIEW OF WIRELESS ELECTRIC VEHICLE CHARGING SYSTEMS: TECHNOLOGIES, APPLICATIONS, AND HEALTH AND SAFETY CONCERNS.

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Abstract - This review paper provides an overview of wireless charging systems for electric vehicles (EVs). It explains the basic operating principle of a wireless charging system for EVs and the three key elements involved: the power source, the transmitter coil, and the receiver coil. The paper discusses different wireless power transfer methods, including inductive power transfer, capacitive power transfer, conductive power transfer, and hybrid systems. The focus is on the coils used in dynamic wireless charging of EVs, and the advantages and limitations of different coil shapes, including circular, rectangular, "double D," hexagonal, and oval shapes. The paper also covers commercial and non-commercial wireless power transfer projects, health and safety concerns, health and safety standards, application of wireless electric vehicle charging systems, and costs of WEVCs. Overall, the paper provides a comprehensive review of wireless charging systems for EVs and highlights the need for further research to improve the efficiency and convenience of wireless charging for EVs.

I. INTRODUCTION

The increasing concern over climate change and the depletion of fossil fuels has led to a significant shift towards the use of electric vehicles (EVs) in recent years. However, the limited range and the need for frequent charging have been identified as significant obstacles to the widespread adoption of EVs. Thus, the development of efficient and convenient charging systems is crucial for promoting the use of EVs.
The traditional charging systems, including plug-in charging and battery swapping, have some limitations, such as the inconvenience of locating charging stations and the limited battery life. Wireless charging technology has emerged as a promising solution to overcome these limitations by providing convenient and efficient charging for EVs.
Dynamic wireless charging (DWC) is a relatively new concept that allows EVs to charge while driving on the road. DWC is particularly useful for long-distance travel as it eliminates the need for frequent stops to charge the battery. The concept of DWC involves embedding charging infrastructure, such as charging pads or cables, into the road surface, enabling EVs to charge while driving over them.
The DWC system is composed of three main components: the roadway infrastructure, the power conversion system, and the EVs themselves. The roadway infrastructure consists of the charging pads, cables, or coils embedded in the road surface, which transmit power wirelessly to the EVs. The power conversion system changes the grid's AC electricity into DC power so that the EV batteries can be charged. The EVs have a receiver coil that captures the electromagnetic waves transmitted by the charging infrastructure and converts them back into electrical energy to charge the battery.
Several research studies have been conducted to optimize the DWC system's performance, reliability, and safety. [1] proposed a multi-paralleled LCC reactive power compensation network and its tuning method for EV dynamic wireless charging, which enhances the system's power transfer efficiency. [2] developed a highly efficient analysis and design for a wireless power transmission system with an intermediate

coil.[3]presented a new coil structure and optimization design for EV dynamic wireless charging with constant output voltage and current.
Furthermore, DWC systems can be combined with other renewable energy sources, such as photovoltaic power [4] and hybrid fast charging stations [5], to minimize greenhouse gas emissions and enhance energy efficiency.
However, there are still some challenges associated with DWC systems, including the optimal positioning of charging infrastructure [6], battery degradation due to frequent charging [7], and the necessity for integrated planning of the infrastructure for static and dynamic charging [8]. Also, the dynamic charging mode of electric buses is taken into account in the dependability assessment of power distribution grids. [9] and the deployment of dynamic charging infrastructure for plug-in hybrid electric trucks [10] are still topics of active research.
In summary, DWC technology has great potential to revolutionize the way we charge EVs, enabling EVs to travel long distances without pulling over frequently to recharge their batteries. However, further research is needed to overcome the current challenges and optimize the DWC system's performance, reliability, and safety to promote the widespread adoption of EVs.

II. Basic Principle of Wireless Electric Vehicle Charging Systems (WEVCS)

Wireless charging technology involves charging an electric vehicle battery wirelessly by transmitting power from a charging pad or ground-based transmitter to a receiver coil mounted on the electric vehicle’s undercarriage. The basic operating principle of an electric vehicle wireless charging technology involves three key elements: the power source, the transmitter coil, and the receiver coil. The power source is connected to the transmitter coil, which generates a magnetic field. The receiver coil, located on the electric vehicle’s undercarriage, picks up the magnetic field and converts it into electrical energy to charge the electric vehicle battery.

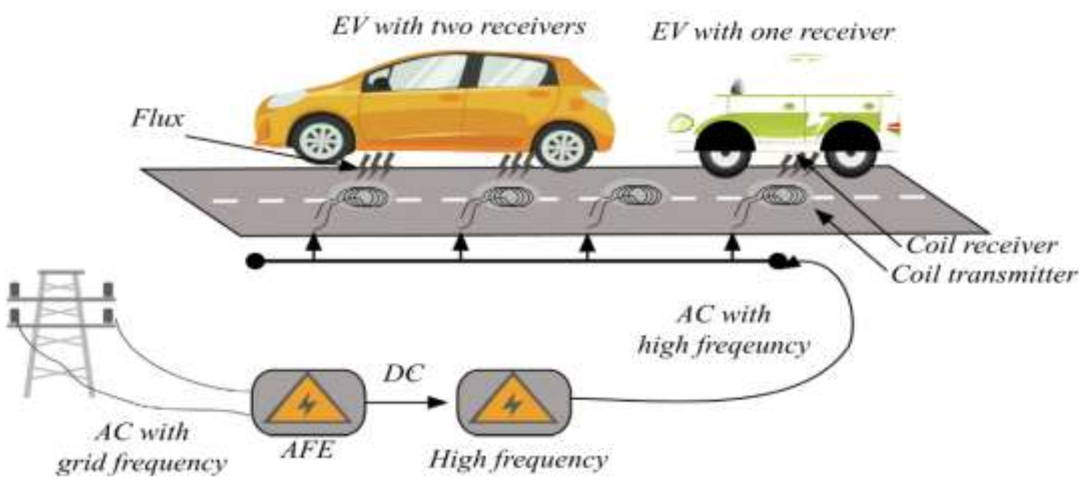

Fig. 1. Wireless transmitter system composition[11]

III. Wireless Power Transfer Methods

Dynamic wireless charging (DWC) systems enable electric vehicles (EVs) to charge their batteries while driving on the road, overcoming the limitations of traditional charging methods. Dynamic charging methods come in three primary categories: inductive power transfer, capacitive power transfer, and

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conductive power transfer. Each system has its unique characteristics, advantages, and challenges, which we will discuss in detail below.

A. Inductive Power Transfer (IPT)

Inductive Power Transfer (IPT) is a technology that enables wireless power transfer through electromagnetic fields between two coils, one on the ground and another on the vehicle. It is a highly efficient and safe way to charge electric vehicles (EVs) without the need for cables or plugs. IPT is appropriate for applications involving static and dynamic charging. In this article, we examine the most recent advancements in IPT technology and how they apply to the charging of electric vehicles.

In recent years, the demand for EVs has increased due to environmental concerns and the need to reduce carbon emissions. However, the charging infrastructure for EVs is still developing, and the traditional plug-in method for charging EVs may not be convenient for all situations. IPT technology has emerged as a promising alternative to traditional charging methods, enabling wireless charging for EVs.

One significant advantage of IPT is its efficiency. [1] proposed a multi-paralleled LCC reactive power compensation network for EV dynamic wireless charging. This network can provide high power transfer efficiency, reduce the size and cost of the power converter, and simplify the system design. [3] developed a coil structure that offers steady output voltage and current for EV dynamic wireless charging, increasing the efficiency of power transmission.

In addition to high efficiency, IPT is also safe and reliable. [12] researched, improved, and demonstrated a vehicle detection system for applications involving dynamic wireless charging.. The system can detect the position and orientation of the EV accurately and provide safe and reliable charging. [13] conducted a system research and operation analysis of wireless EV charging systems, demonstrating that IPT can provide EVs with dependable and secure charging.

IPT technology is also suitable for various applications, including static and dynamic charging. Static charging refers to charging an EV while it is parked or stationary. [2] investigated and created a high-efficiency static charging wireless power transfer system using an intermediary coil. They suggested a better circuit layout to raise system effectiveness and scale back the power converter. [5] presented a dynamic charging method for EVs using a hybrid fast charging station, which can shorten charging times and increase charging station use.

Dynamic charging refers to charging an EV while it is moving, which requires IPT technology to provide a continuous power supply. [4] proposed a dynamic energy management system for an EV charging station using photovoltaic power. The system can adjust the charging power and ensure continuous charging for the EV. [14] presented a dynamic charging method for EVs using a hybrid fast charging station, which can shorten charging times and increase charging station use.

The deployment of IPT technology also requires proper planning and optimization. [8] proposed an integrated planning method for static and dynamic charging infrastructure for EVs. The method considers the demand and spatial distribution of charging stations and aims to maximize the charging efficiency and minimize the investment cost. [10] presented a technique of deploying dynamic charging infrastructure for plug-in hybrid electric vehicles that takes into account the volume of traffic and the trucks' travel patterns. [15] EVs have a fixed and dynamic charging infrastructure that has been proposed for deployment along traffic corridors, taking into account the demand for charging and the accessibility of charging stations..

B. Capacitive Power Transfer (CPT)

Capacitive power transfer (CPT) is a type of wireless power transfer technology that uses an electric field to transfer power between two resonant circuits. It has gained increasing attention as a potential solution for dynamic wireless charging of electric vehicles (EVs) due to its high efficiency and simplicity. In CPT, power is transferred between two parallel plates or electrodes, where one is the power source and the other is the load. The energy is transferred by means of electric fields, and the amount of power transferred depends on the capacitance between the two plates and the frequency of the electric field.

CPT has been the subject of numerous investigations looking towards EV dynamic wireless charging. For EV dynamic wireless charging, [1] suggested a multi-parallel LCC reactive power compensation network and associated tuning approach. For EV dynamic wireless charging using CPT, [3] suggested a new coil construction and optimization design with constant output voltage and constant output current. [2] performed an analysis and constructed a high efficiency wireless power transmission system with an intermediate coil. A wireless charging technology for EVs employing two receiver coils was proposed by [11].

CPT has also been investigated in the context of energy management and planning for EV charging infrastructure. [4] proposed a dynamic energy management system for an EV charging station using photovoltaic power. [5] For EVs, a hybrid rapid charging station has been suggested as a dynamic charging technique. [14] looked into methods for EV freight delivery that could dynamically charge while driving. Furthermore, several studies have investigated the deployment and optimization of CPT-based EV charging infrastructure. [10] For plug-in hybrid electric trucks, it was suggested that a dynamic charging infrastructure be deployed. [15] suggested placing EV charging stations along major thoroughfares that are both stationary and dynamic. [6] investigated the optimal positioning of dynamic wireless charging infrastructure in a road network for battery electric vehicles. [16] For EV in-motion wireless charging, a strategic network design and analysis have been recommended.

C. Conductive Power Transfer

Conductive power transfer refers to the transfer of electrical power from a power source to an electric vehicle via a physical connection, such as a conductive charging cable. Conductive charging has been widely used in public charging infrastructure due to its high efficiency, reliability, and lower cost compared to other charging methods [2].

The conductive power transfer technique has also been used in dynamic wireless charging, where the electric vehicle receives power wirelessly from an inductive charger while moving. [1] In order to reduce power loss and improve the effectiveness of the wireless power transmission system, a multi-parallel LCC reactive power compensation network has been proposed..

Another application of conductive power transfer is in photovoltaic (PV) powered charging stations. [4] created a dynamic energy management system for a solar-powered electric vehicle charging station. The technology combines static and dynamic charging, using dynamic wireless charging for slow charging and conductive charging for quick charging.

Vehicle detecting systems designed for dynamic wireless charging applications can also use conductive power transmission. [12] proposed an optimal detection range for vehicular detection systems that uses a magnetic field generated by a conductive charging cable for wireless power transfer.

[3] proposed a new coil structure for electric vehicle dynamic wireless charging that uses a conductive charging cable. The design optimizes the output voltage and current, resulting in a more efficient wireless power transfer system.

D. Hybrid Systems

Hybrid systems are gaining popularity as an effective approach for electric vehicle charging due to their ability to combine multiple charging methods for optimal performance. The integration of static and dynamic charging methods can provide a flexible charging infrastructure that meets the needs of various

EVs and their owners. Hybrid charging systems have been studied extensively by researchers, and a review of some of these studies is presented below.
[1] For dynamic wireless charging of EVs, a multi-parallel LCC reactive power compensation network has been proposed. This method utilized an LCC resonant network that compensated for the reactive power of the EV, allowing for efficient wireless charging. The system was optimized using a tuning method that minimized the power loss of the system.

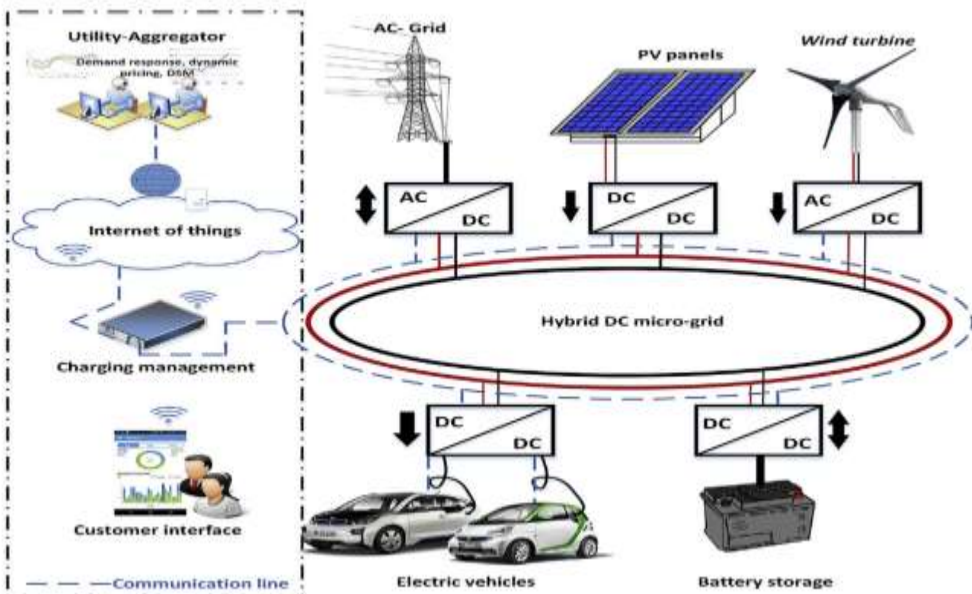

Fig. 2. Proposed hybrid DC fast charging system.[5]

[4] presented a dynamic energy management system for an EV charging station that combined photovoltaic (PV) power with grid power. This hybrid system allowed for sustainable and cost-effective charging of EVs, while reducing the load on the grid during peak demand.
[12] evaluated and improved a vehicle-detecting system for applications involving dynamic wireless charging. The proposed system used an inductive loop sensor and a magnetic sensor to detect the presence of EVs and adjust the charging power accordingly. The system was optimized to achieve high accuracy in vehicle detection and charging power adjustment.

IV. Coils Used in Dynamic Wireless Charging EVs

A potential remedy for the range anxiety issue with electric cars (EVs) is dynamic wireless charging. This technology involves transferring power wirelessly from an infrastructure-based source to the EV while it is in motion. The wireless charging process requires two sets of coils, a transmitter coil embedded in the infrastructure and a receiver coil installed on the vehicle. The efficiency of wireless power transfer is primarily affected by the shape and size of the coils. The magnetic field's uniformity, the coils' alignment, and their coupling can all be impacted by the coils' shape.
[17] presented a wireless power transfer method for EV dynamic charging that uses transmitter coils embedded in the road.. The system uses circular coils that are vertically embedded in the road surface. The transmitter coils are arranged in parallel rows and spaced apart by a distance equal to the width of the receiver coil. The receiver coil is a circular coil that is placed at the bottom of the EV. The circular shape of the receiver coil ensures uniform coupling with the transmitter coils, resulting in higher efficiency.

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[18] analyzed the economic feasibility of dynamic charging for EVs. They considered different coil shapes, including circular, rectangular, and square. They found that the circular coil shape is the most efficient and cost-effective for dynamic wireless charging.
[19] proposed a systematic design of a wireless charging transportation network. They used rectangular coils for the wireless charging system. The transmitter coils are arranged in a staggered pattern, and the receiver coils are placed at the bottom of the EV. The rectangular shape of the coils allows for a larger coupling area and higher efficiency.
[20]proposed a wireless power transfer system that uses electric field resonance for dynamic charging. The system uses a rectangular-shaped transmitter coil that is mounted on the ground. The receiver coil is a circular-shaped coil that is placed at the bottom of the EV. The rectangular shape of the transmitter coil provides a larger magnetic field, which enhances the coupling between the coils and improves the charging efficiency.
[21]Zhang et al. (2016) designed and analyzed different coil shapes for a dynamic wireless charging system for EVs. They considered circular, square, and rectangular shapes for the transmitter coil and circular and rectangular shapes for the receiver coil. They found that the circular-shaped transmitter coil with a rectangular-shaped receiver coil is the most efficient for dynamic wireless charging.
[22] For dynamic wireless charging of EVs, a lumped track layout design was suggested. The technology employs a grid of square-shaped transmitter coils arranged in a linear array along the route. Located at the bottom of the EV, the receiver coil is a rectangular coil. A more uniform magnetic field is created by the transmitter coils' square shape, which boosts charging effectiveness.

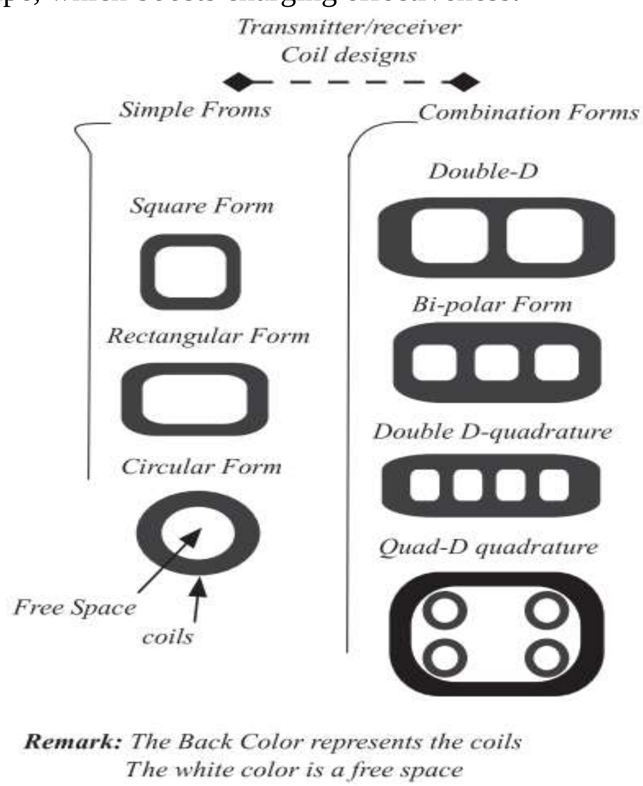

Fig. 3. Coil shapes.[11]

[23] designed and demonstrated a 25-kW dynamic charging system for roadway EVs. The system uses a circular-shaped transmitter coil that is mounted on the ground. The receiver coil is a circular-shaped coil

that is placed at the bottom of the EV. The circular shape of the coils provides uniform magnetic fields and coupling between the coils, resulting in higher charging efficiency.
[24] reviewed different wireless charging systems for EVs. They discussed different coil shapes, including circular, rectangular, and square. They found that circular coils are the most commonly used shape for wireless charging of EVs.

V. Commercial And Non-Commercial WPT Projects

Wireless Power Transfer (WPT) is a promising technology for charging electric vehicles (EVs) without the need for physical contact between the vehicle and the charging infrastructure. WPT projects can be divided into commercial and non-commercial projects. Commercial projects are typically developed by companies or organizations with the goal of commercializing the technology, while non-commercial projects are often developed by academic or research institutions to explore the feasibility and limitations of the technology.
One example of a commercial WPT project is the dynamic wireless charging (DWC) system developed by ElectReon Wireless. The system uses magnetic resonance technology to transfer power wirelessly from the road to a receiving coil on the EV. The company has successfully demonstrated the system in several pilot projects, including a project in Sweden where a bus was equipped with the technology and operated on a designated route. The company is currently working on commercializing the technology for mass adoption [25].
Another commercial WPT project is the virtual power plant architecture developed by [26]. The architecture is designed to support dynamic charging of automated guided vehicles (AGVs) using OpenADR 2.0b. The project aims to reduce the energy consumption of AGVs and increase their efficiency by optimizing their charging schedules.
WPT system optimization research includes non-commercial WPT projects, such as the work on a novel coil structure and its optimization design for EV dynamic wireless charging done by [3]. The researchers proposed a new coil structure that improves the efficiency of the WPT system by achieving constant output voltage and constant output current.
Another example of a non-commercial WPT project is the study conducted by [1] on the multi-paralleled LCC reactive power compensation networks and their tuning method for EV dynamic wireless charging. For the compensation network's tuning, the researchers suggested a strategy to raise the WPT system's power factor.
For example, [8] developed an integrated planning model for static and dynamic charging infrastructure for EVs. The model aims to optimize the location and capacity of the charging stations to minimize the total cost while meeting the demand for charging services.
In a similar vein, [6] put forth a model for the optimal positioning of dynamic wireless charging stations in a network of roads for battery electric vehicles. The model aims to minimize the total cost of infrastructure installation while meeting the charging demand of EVs.
[27] presented the design of a WPT system for dynamic charging of EVs. The system is designed to overcome the range anxiety problem of EVs by enabling on-the-go charging. This commercial project focuses on using magnetic resonance coupling technology for the transfer of power from the infrastructure to the EV.
[28] discussed the potential of dynamic charging of EVs. This non-commercial project concentrates on the feasibility of using Wireless Power Transfer for charging EVs while they are in motion. The authors discussed the advantages and challenges of implementing this technology in practical applications.

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[29] reviewed the most recent WPT technology for EV charging. This non-commercial project focuses on the principles, standards, and core technologies of WPT. The authors discussed various technologies, including magnetic induction and magnetic resonance coupling, and their advantages and disadvantages.
[30] proposed a state-of-charge estimation method for lithium-ion batteries using gated recurrent neural networks. This non-commercial project aims to improve the accuracy of battery state-of-charge estimation, which is crucial for WPT systems. The authors demonstrated the effectiveness of their proposed method through experiments.
[31] proposed a lithium-ion battery charging management system that considers the economic costs of electrical energy loss and battery degradation. This non-commercial project aims to optimize the charging process of batteries, which is essential for WPT systems. The authors showed that their proposed method can reduce the total cost of battery charging.
[32] proposed a fast EV charging station integration with the grid, ensuring optimal and quality power exchange. This commercial project focuses on designing an efficient and reliable EV charging station. The authors considered various factors, including the charging rate, energy management, and grid integration.
[33] reviewed the charging technologies, infrastructure, and charging station recommendation schemes for EVs. This non-commercial project provides a comprehensive overview of the latest developments in WPT technology for EV charging. The authors discussed various topics, including charging infrastructure, charging technologies, and charging station management.
[34] proposed the design of an electric vehicle fast-charging station with the integration of renewable energy and storage systems. This commercial project focuses on designing an efficient and sustainable EV charging station. The authors considered various factors, including energy management, power quality, and environmental impact.
[35] proposed a fast-charging station deployment for battery electric bus systems, considering electricity demand charges. This non-commercial project focuses on designing an efficient and cost-effective EV charging system for bus fleets. The authors showed that their proposed method can reduce the electricity demand charges and improve the efficiency of the charging process.
[36] reviewed the technologies, energy trading, and cybersecurity issues related to EVs. This non-commercial project provides a comprehensive overview of the latest developments in EV technology. The authors discussed various topics, including battery technology, energy trading, and cybersecurity issues.
[37] presented a technological review of EV standards, charging infrastructure, and their impact on grid integration. This non-commercial project provides a comprehensive overview of the challenges and opportunities associated with EV charging infrastructure.In addition, several studies have focused on the deployment and optimization of the WPT infrastructure.
Overall commercial and non-commercial WPT projects are being developed to explore and commercialize the technology of dynamic wireless charging for EVs. Commercial projects focus on developing the technology for mass adoption, while non-commercial projects focus on optimizing and improving the efficiency of the WPT system. These projects are essential for the development and implementation of WPT technology for EVs

VI. Health And Safety Concerns

WPT is a promising technology for electric vehicle charging that eliminates the need for physical connection between the charging station and the EV. However, there are several health and safety concerns associated with WPT systems that need to be addressed for widespread adoption of this technology. In this review paper, we will discuss some of the major health and safety concerns related to WPT systems for EV charging, along with recent advancements in this field.

One of the primary concerns with WPT systems is the exposure to electromagnetic fields (EMFs). EMFs are generated by the WPT system and can potentially harm human health. Several studies have investigated the exposure to EMFs in WPT systems and have found that the exposure levels are well below the safety limits set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [38][39]. Nevertheless, it is important to monitor the exposure levels and ensure that they remain within the safety limits.

Another concern is the potential for electric shock when the EV is being charged wirelessly. In order to prevent electric shock, WPT systems should be designed with adequate insulation and grounding mechanisms. [40] proposed a wireless charging system that utilizes an isolation transformer to prevent electric shock.

In addition to these concerns, there are also safety concerns related to the design and operation of WPT systems. For example, the location of the charging stations can affect the safety of the system. [41] developed a flow-capturing location model to determine the optimal location of wireless charging facilities for EVs based on the stochastic user equilibrium. Similarly, [42] proposed an optimal location model for dynamic wireless charging links of EVs based on electricity prices.

Furthermore, the design of the coil structure is also critical for ensuring the safety and efficiency of the WPT system. [3] presented a new coil layout for EV dynamic wireless charging that has constant output voltage and constant output current.[43] proposed a resonant wireless charging scheme that achieves high efficiency and safety.

In conclusion, WPT systems for EV charging have several health and safety concerns that need to be addressed. While recent advancements have addressed many of these concerns, it is important to continue research in this field to ensure the safety and efficiency of WPT systems for widespread adoption.

VII. Health And Safety Standards

Health and safety standards are important in the design and implementation of dynamic wireless charging systems for electric vehicles (EVs) to ensure the safety of operators and users. Many studies have looked at the development of charging infrastructure as well as the design, optimization, and assessment of dynamic wireless charging systems for EVs.

The safety of the charging process is critical to the success of dynamic wireless charging systems. [3] To maintain a consistent output voltage and current to guarantee safe charging, a new coil structure and optimization design have been presented for dynamic wireless charging systems.[1] In order to decrease power loss and improve the safety of dynamic wireless charging systems, multi-parallel LCC reactive power compensation networks were developed, along with a method for calibrating them.

[4] examined the use of photovoltaic energy for the dynamic energy management of an EV charging station, which can enhance the process' sustainability and safety. [12] evaluated and improved a vehicle detecting system for applications requiring dynamic wireless charging, which can improve the efficiency and security of the charging procedure.

[2] proposed a wireless power transfer system for high efficiency, which can lower power loss and improve the security of dynamic wireless charging systems. [13] completed a system research and operation survey of wireless EV charging systems, which can offer direction on how to design and deploy secure charging systems.

[5] proposed a dynamic charging strategy with a hybrid fast charging station for EVs, which can enhance the safety and efficiency of the charging process. [26] In order to improve the dependability and safety of the charging process, a virtual power plant design based on Open ADR 2.0b has been developed.
[9] examined the dependability of power distribution grids while taking electric bus dynamic charging into account, which can offer recommendations for the secure and reliable operation of dynamic wireless charging systems. [11] presented a new, more secure and effective wireless charging solution for EVs that makes use of two receiver coils.
[14] analysed and created traffic and energy models to assess the effectiveness and safety of dynamic charging while driving systems for EV-based freight transportation services.[25] investigated wireless charging in California and assessed EV range, recharge, and electrification, which can offer suggestions for the secure and efficient development of dynamic wireless charging infrastructure.
[7] examined various lead-acid battery conditioning and testing procedures to gauge how well they tolerate dynamic charging, which could improve the security and effectiveness of dynamic wireless charging systems. [8] To increase the efficiency and safety of electric vehicles, the planning of their static and dynamic charging infrastructure was combined.
[10] recommended installing dynamic charging infrastructure for plug-in hybrid electric trucks, which might enhance the efficiency and safety of the charging process. [15] EVs can be charged more safely and efficiently if stationary and dynamic charging infrastructure is deployed along traffic routes, as has been investigated.
[6] enhanced the placement of dynamic wireless charging infrastructure for battery electric vehicles on a road network, which can improve the efficiency and safety of the charging process. [16] carried out a strategic network design and analysis for in-movement wireless charging of EVs to assess their effectiveness and safety.
[44] conducted an assessment of wireless charging for electric cars that was critical, emphasising the significance of safety in WPT system design. The authors emphasized the need for compliance with international standards, such as the International Electrotechnical Commission (IEC) standard for electromagnetic compatibility (EMC) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines for human exposure to electromagnetic fields.
[45] highlighted the significance of safety precautions to prevent electrical risks in their work on compensation topologies of high-power WPT systems. They advised using shielding and isolation transformers to minimise electromagnetic interference (EMI) and lower the possibility of electric shock.
[46] proposed an efficient WPT system for electric vehicles and discussed the safety issues related to the design of the system. The authors highlighted the importance of minimizing EMI and ensuring the safety of the charging process, including the prevention of electric shock and fire hazards.
[39] presented a coreless hybrid coil design for WPT systems and discussed the safety issues related to the design. The authors emphasized the importance of ensuring that the system operates within safe limits of voltage and current, to prevent electrical hazards such as electric shock and fire.
[47] conducted a review of static and dynamic WPT systems and emphasized the importance of safety in the design and deployment of these systems. The authors recommended compliance with international safety standards, such as the IEC standard for EMC and the ICNIRP guidelines for human exposure to electromagnetic fields.
[48] addressed the value of safety in the design of these systems and examined and contrasted resonance topologies in 6.6 kW inductive WPT systems for electric vehicle batteries. The authors advocated adhering to global safety norms, such as the IEC standard for EMC and the ICNIRP recommendations for human

exposure to electromagnetic fields, and they underlined how crucial it is to make sure the system functions within acceptable voltage and current limitations.

VIII. Application Of Wireless Electric Vehicle Charging Systems (WEVCS)

Wireless Electric Vehicle Charging Systems (WEVCS) have been gaining popularity as a convenient and efficient way of charging electric vehicles (EVs). This technology allows for the transfer of electrical power wirelessly between a transmitting pad installed on the ground and a receiving pad attached to the EV. WEVCS has many potential applications in transportation, from personal EVs to public transportation. In this text, we will explore some of the current applications of WEVCS with references to research in this field.

Dynamic charging of EVs while in motion is one of the main uses of WEVCS. With this technique, EVs may be charged while they are in motion, doing away with the requirement for frequent stops to charge the battery. [1] proposed a multi-paralleled LCC reactive power compensation network for dynamic wireless charging and a tuning method to maximize the power transfer efficiency. [12] demonstrated a vehicular detection system intended for dynamic wireless charging applications, which used a computer vision algorithm and machine learning techniques to identify the location of EVs on the road.

Another application of WEVCS is in static charging infrastructure. [4] presented an EV charging station with a dynamic energy management system that harnesses photovoltaic energy to generate electricity for EV charging. [3] introduced a novel coil design and its optimization design with constant output voltage and constant output current for wireless dynamic charging of electric vehicles. [2] investigated and created a high efficiency wireless power transmission system with an intermediary coil.

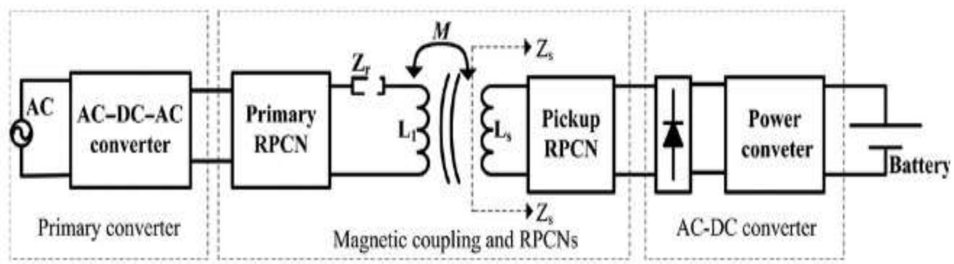

Fig. 4. Typical structure of WPT system.[1]

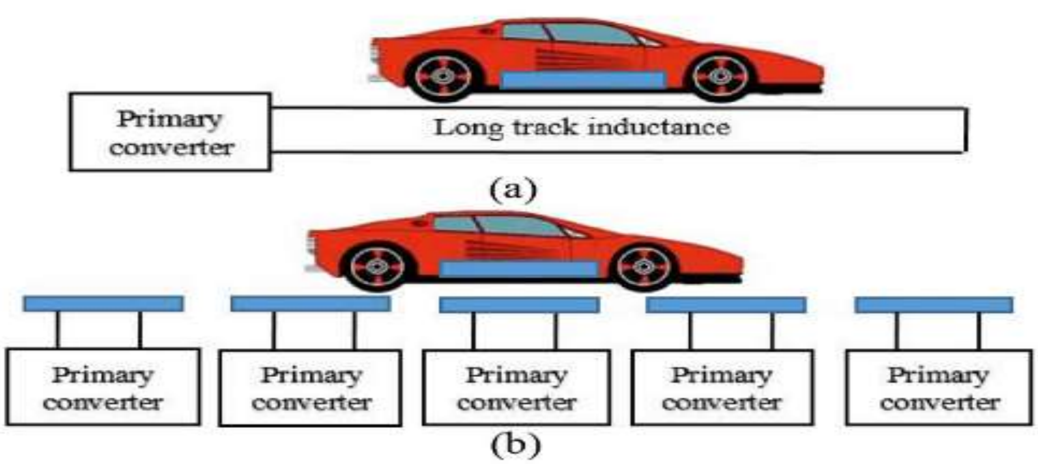

Fig. 5. Two kinds of primary magnetic couplers in a dynamic WPT system.
(a) Long track couplers. (b) Segmental couplers

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WEVCS is also being used in the optimization of power distribution grids. [26] presented a virtual power plant design utilizing Open ADR 2.0b for dynamic charging of self-guided vehicles. [9] evaluated the reliability of power distribution grids considering the dynamic charging mode of electric buses.

The deployment of WEVCS infrastructure is also being studied. [25] explored the deployment of WEVCS in California, while [10] analyzed the implementation of dynamic charging infrastructure for plug-in hybrid electric trucks. [15] investigated the placement of EV charging infrastructure, both static and mobile, along traffic corridors. [8] proposed an integrated planning method for static and dynamic charging infrastructure for EVs.

The placement of dynamic wireless charging infrastructure in road networks is also being studied in order to maximize its effectiveness.[6] proposed an optimal positioning method for dynamic wireless charging infrastructure in a road network for battery electric vehicles. [16] designed and analyzed a strategic network for electric vehicle in-motion wireless charging.

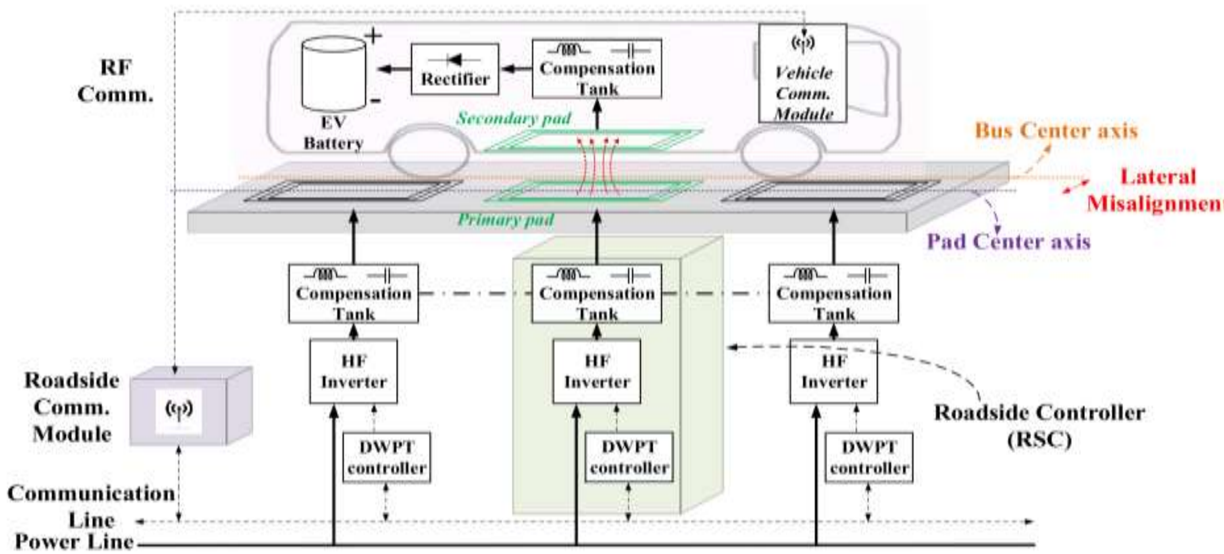

Fig. 6. Structure of a DWPT system.[12]

IX. Costs Of Wireless Electric Vehicle Charging Systems (WEVCS)

Wireless charging systems for electric vehicles (EVs) offer several advantages over traditional wired charging systems, including convenience, safety, and the elimination of the need for cables and connectors. However, the costs of implementing wireless charging systems for EVs can be significant, which can be attributed to several factors.

One significant cost driver is the need for additional infrastructure to be installed, such as charging pads or coils, that can transmit the electricity wirelessly to the vehicle. This requires investment in the installation of charging infrastructure and equipment, including power electronics, communication systems, and software control systems. Moreover, the cost of the infrastructure will depend on the capacity of the charging system, the charging speed, and the location of the charging station.

Another cost factor is the cost of the wireless charging system's components. These include the charging pads or coils, power electronics, communication systems, and software control systems. The cost of these components depends on the technology used, the system capacity, and the number of vehicles that can be charged simultaneously. For example, [1] proposed a multi-paralleled LCC reactive power compensation

network that could be used to tune the wireless charging system's components for optimal performance, which could potentially reduce costs.
In addition, the cost of the wireless charging system will depend on the battery technology used in the EV. [3] proposed a new coil structure for wireless charging systems that can provide constant output voltage and current, which could help reduce costs by optimizing the battery's charging efficiency.

Deployment costs are also important in evaluating the feasibility of wireless charging systems for EVs. This includesthe cost of planning, designing, and installing the charging infrastructure, as well as the cost of maintaining and operating the system. [13] noted that the costs of deployment could vary significantly depending on the location, type of infrastructure, and charging speed.
The cost of wireless charging systems can be a significant barrier to their adoption. However, recent research has focused on optimizing the design and performance of wireless charging systems to reduce costs. For example, [11] presented a new, more effective, and less expensive wireless charging technology that makes use of two receiver coils. Furthermore, strategic network design and analysis can help optimize the deployment of wireless charging systems to minimize costs [16]
Overall, the costs of implementing wireless charging systems for EVs are significant, but ongoing research and development can help to reduce these costs and improve the viability of wireless charging systems as a practical solution for charging EVs.

X. Conclusion

Wireless electric vehicle charging systems (WEVCS) have become an essential research area due to the increasing demand for electric vehicles. This review paper has provided an overview of the operating principles and power transfer methods used in WEVCS. Inductive power transfer (IPT), capacitive power transfer (CPT), conductive power transfer (CMT), and hybrid systems were discussed as the primary wireless power transfer methods used for WEVCS. Moreover, different coil structures such as circular, rectangular, and double-D were explained. The review also discussed various commercial and non-commercial projects, safety concerns, health and safety standards, and applications of WEVCS. The cost of WEVCS was also considered in this review paper.
Moreover, the applications of WEVCS are diverse, ranging from public transportation to personal vehicles. However, one of the major obstacles for the widespread adoption of WEVCS is the cost. Despite the cost, the benefits of WEVCS are significant, including increased efficiency, convenience, and environmental friendliness. In summary, WEVCS is a promising technology that has the potential to revolutionize the way we charge electric vehicles.

XI. References

[1] Zhou, S., and Chris Mi, C., 2016, “Multi-Paralleled LCC Reactive Power Compensation Networks and Their Tuning Method for Electric Vehicle Dynamic Wireless Charging,” IEEE Transactions on Industrial Electronics, **63**(10), pp. 6546–6556.
[2] Moon, S., Kim, B. C., Cho, S. Y., Ahn, C. H., and Moon, G. W., 2014, “Analysis and Design of a Wireless Power Transfer System with an Intermediate Coil for High Efficiency,” IEEE Transactions on Industrial Electronics, **61**(11), pp. 5861–5870.
[3] Li, Y., Hu, J., Lin, T., Li, X., Chen, F., He, Z., and Mai, R., 2019, “A New Coil Structure and Its Optimization Design With Constant Output Voltage and Constant Output Current for Electric Vehicle Dynamic Wireless Charging,” IEEE Trans Industr Inform, **15**(9), pp. 5244–5256.
[4] Kouka, K., Masmoudi, A., Abdelkafi, A., and Krichen, L., 2020, “Dynamic Energy Management of an Electric Vehicle Charging Station Using Photovoltaic Power,” Sustainable Energy, Grids and Networks, **24**.

[5] Elma, O., 2020, "A Dynamic Charging Strategy with Hybrid Fast Charging Station for Electric Vehicles," Energy, **202**.

[6] Ngo, H., Kumar, A., and Mishra, S., 2020, "Optimal Positioning of Dynamic Wireless Charging Infrastructure in a Road Network for Battery Electric Vehicles," Transp Res D Transp Environ, **85**.

[7] Budde-Meiwes, H., Schulte, D., Kowal, J., Sauer, D. U., Hecke, R., and Karden, E., 2012, "Dynamic Charge Acceptance of Lead-Acid Batteries: Comparison of Methods for Conditioning and Testing," J Power Sources, **207**, pp. 30–36.

[8] Sun, X., Chen, Z., and Yin, Y., 2020, "Integrated Planning of Static and Dynamic Charging Infrastructure for Electric Vehicles," Transp Res D Transp Environ, **83**.

[9] Qiu, K., Naim, W., Shayesteh, E., and Hilber, P., 2021, "Reliability Evaluation of Power Distribution Grids Considering the Dynamic Charging Mode of Electric Buses," Energy Reports, **7**, pp. 134–140.

[10] Liu, Z., and Song, Z., 2018, "Dynamic Charging Infrastructure Deployment for Plug-in Hybrid Electric Trucks," Transp Res Part C Emerg Technol, **95**, pp. 748–772.

[11] Mohamed, N., Aymen, F., Alqarni, M., Turky, R. A., Alamri, B., Ali, Z. M., and Abdel Aleem, S. H. E., 2022, "A New Wireless Charging System for Electric Vehicles Using Two Receiver Coils," Ain Shams Engineering Journal, **13**(2), p. 101569.

[12] Azad, A. N., Echols, A., Kulyukin, V. A., Zane, R., and Pantic, Z., 2019, "Analysis, Optimization, and Demonstration of a Vehicular Detection System Intended for Dynamic Wireless Charging Applications," IEEE Transactions on Transportation Electrification, **5**(1), pp. 147–161.

[13] Jang, Y. J., 2018, "Survey of the Operation and System Study on Wireless Charging Electric Vehicle Systems," Transp Res Part C Emerg Technol, **95**(March), pp. 844–866.

[14] Deflorio, F., and Castello, L., 2017, "Dynamic Charging-While-Driving Systems for Freight Delivery Services with Electric Vehicles: Traffic and Energy Modelling," Transp Res Part C Emerg Technol, **81**, pp. 342–362.

[15] Chen, Z., Liu, W., and Yin, Y., 2017, "Deployment of Stationary and Dynamic Charging Infrastructure for Electric Vehicles along Traffic Corridors," Transp Res Part C Emerg Technol, **77**, pp. 185–206.

[16] Mubarak, M., Üster, H., Abdelghany, K., and Khodayar, M., 2021, "Strategic Network Design and Analysis for In-Motion Wireless Charging of Electric Vehicles," Transp Res E Logist Transp Rev, **145**.

[17] Throngnumchai, K., Hanamura, A., Naruse, Y., and Takeda, K., 2013, "Design and Evaluation of a Wireless Power Transfer System with Road Embedded Transmitter Coils for Dynamic Charging of Electric Vehicles," World Electric Vehicle Journal, **6**(4), pp. 848–857.

[18] Jeong, S., Jang, Y. J., and Kum, D., 2015, "Economic Analysis of the Dynamic Charging Electric Vehicle," IEEE Trans Power Electron, **30**(11), pp. 6368–6377.

[19] Correa, D., Jakub, G., and Moyano, C., 2021, "Systematic Design of Wireless Charging Transportation Network," Transportation Research Procedia, **58**(2019), pp. 527–534.

[20] Li, S., Liu, Z., Zhao, H., Zhu, L., Shuai, C., and Chen, Z., 2016, "Wireless Power Transfer by Electric Field Resonance and Its Application in Dynamic Charging," IEEE Transactions on Industrial Electronics, **63**(10), pp. 6602–6612.

[21] Zhang, X., Yuan, Z., Yang, Q., Li, Y. Y., Zhu, J., and Li, Y. Y., 2016, "Coil Design and Efficiency Analysis for Dynamic Wireless Charging System for Electric Vehicles," IEEE Trans Magn, **52**(7), pp. 7–10.

[22] Buja, G., Bertoluzzo, M., and Dashora, H. K., 2016, "Lumped Track Layout Design for Dynamic Wireless Charging of Electric Vehicles," IEEE Transactions on Industrial Electronics, **63**(10), pp. 6631–6640.

[23] Tavakoli, R., and Pantic, Z., 2018, "Analysis, Design, and Demonstration of a 25-KW Dynamic Wireless Charging System for Roadway Electric Vehicles," IEEE J Emerg Sel Top Power Electron, **6**(3), pp. 1379–1393.

[24] Amjad, M., Farooq-i-Azam, M., Ni, Q., Dong, M., and Ansari, E. A., 2022, "Wireless Charging Systems for Electric Vehicles," Renewable and Sustainable Energy Reviews, **167**(October).

[25] Fuller, M., 2016, "Wireless Charging in California: Range, Recharge, and Vehicle Electrification," Transp Res Part C Emerg Technol, **67**, pp. 343–356.

[26] Kolenc, M., Ihle, N., Gutschi, C., Nemček, P., Breitkreuz, T., Gödderz, K., Suljanović, N., and Zajc, M., 2019, "Virtual Power Plant Architecture Using OpenADR 2.0b for Dynamic Charging of Automated Guided Vehicles," International Journal of Electrical Power and Energy Systems, **104**, pp. 370–382.

[27] Diep, N. T., Trung, N. K., and Minh, T. T., 2020, "Wireless Power Transfer System Design for Electric Vehicle Dynamic Charging Application," International Journal of Power Electronics and Drive Systems, **11**(3), pp. 1468–1480.

[28] Hutchinson, L., Waterson, B., Anvari, B., and Naberezhnykh, D., 2019, "Potential of Wireless Power Transfer for Dynamic Charging of Electric Vehicles," IET Intelligent Transport Systems, **13**(1), pp. 3–12.

[29] Niu, S., Xu, H., Sun, Z., Shao, Z. Y., and Jian, L., 2019, "The State-of-the-Arts of Wireless Electric Vehicle Charging via Magnetic Resonance: Principles, Standards and Core Technologies," Renewable and Sustainable Energy Reviews, **114**(February), p. 109302.

[30] Yang, F., Li, W., Li, C., and Miao, Q., 2019, "State-of-Charge Estimation of Lithium-Ion Batteries Based on Gated Recurrent Neural Network," Energy, **175**, pp. 66–75.

[31] Liu, K., Hu, X., Yang, Z., Xie, Y., and Feng, S., 2019, "Lithium-Ion Battery Charging Management Considering Economic Costs of Electrical Energy Loss and Battery Degradation," Energy Convers Manag, **195**(February), pp. 167–179.

[32] Khan, W., Ahmad, F., and Alam, M. S., 2019, "Fast EV Charging Station Integration with Grid Ensuring Optimal and Quality Power Exchange," Engineering Science and Technology, an International Journal, **22**(1), pp. 143–152.

[33] Savari, G. F., Sathik, M. J., Raman, L. A., El-Shahat, A., Hasanien, H. M., Almakhles, D., Abdel Aleem, S. H. E., and Omar, A. I., 2023, "Assessment of Charging Technologies, Infrastructure and Charging Station Recommendation Schemes of Electric Vehicles: A Review," Ain Shams Engineering Journal, **14**(4), p. 101938.

[34] Domínguez-Navarro, J. A., Dufo-López, R., Yusta-Loyo, J. M., Artal-Sevil, J. S., and Bernal-Agustín, J. L., 2019, "Design of an Electric Vehicle Fast-Charging Station with Integration of Renewable Energy and Storage Systems," International Journal of Electrical Power and Energy Systems, **105**(March 2018), pp. 46–58.

[35] He, Y., Song, Z., and Liu, Z., 2019, "Fast-Charging Station Deployment for Battery Electric Bus Systems Considering Electricity Demand Charges," Sustain Cities Soc, **48**(February).

[36] Bharathidasan, M., Indragandhi, V., Suresh, V., Jasiński, M., and Leonowicz, Z., 2022, "A Review on Electric Vehicle: Technologies, Energy Trading, and Cyber Security," Energy Reports, **8**, pp. 9662–9685.

[37] Das, H. S., Rahman, M. M., Li, S., and Tan, C. W., 2020, "Electric Vehicles Standards, Charging Infrastructure, and Impact on Grid Integration: A Technological Review," Renewable and Sustainable Energy Reviews, **120**

[38] El-Shahat, A., Ayisire, E., Wu, Y., Rahman, M., and Nelms, D., 2019, "Electric Vehicles Wireless Power Transfer State-of-the-Art," *Energy Procedia*, Elsevier Ltd, pp. 24–37.

[39] Wang, Z., Chen, X., Ye, T., and Chen, K., 2021, "A Coreless Hybrid Coil Design for the Wireless Power Charging System," Energy Reports, **7**, pp. 436–442.

[40] Khutwad, S. R., and Gaur, S., 2017, "Wireless Charging System for Electric Vehicle," International Conference on Signal Processing, Communication, Power and Embedded System, SCOPES 2016 - Proceedings, pp. 441–445.

[41] Riemann, R., Wang, D. Z. W., and Busch, F., 2015, "Optimal Location of Wireless Charging Facilities for Electric Vehicles: Flow Capturing Location Model with Stochastic User Equilibrium," Transp Res Part C Emerg Technol, **58**(Part A), pp. 1–12.

[42] Liu, H., Zou, Y., Chen, Y., and Long, J., 2021, "Optimal Locations and Electricity Prices for Dynamic Wireless Charging Links of Electric Vehicles for Sustainable Transportation," Transp Res E Logist Transp Rev, **152**.

[43] Guo, X., Qi, Y., Liu, L., Jia, S., and Mi, L., 2023, "Resonant Wireless Charging Scheme," Energy Reports, **9**, pp. 612–621.

[44] Machura, P., and Li, Q., 2019, "A Critical Review on Wireless Charging for Electric Vehicles," Renewable and Sustainable Energy Reviews, **104**, pp. 209–234.

[45] Zhang, W., and Mi, C. C., 2016, "Compensation Topologies of High-Power Wireless Power Transfer Systems," IEEE Trans Veh Technol, **65**(6), pp. 4768–4778.

[46] Chatterjee, S., Iyer, A., Bharatiraja, C., Vaghasia, I., and Rajesh, V., 2017, "Design Optimisation for an Efficient Wireless Power Transfer System for Electric Vehicles," Energy Procedia, **117**, pp. 1015–1023.

[47] Panchal, C., Stegen, S., and Lu, J., 2018, "Review of Static and Dynamic Wireless Electric Vehicle Charging System," Engineering Science and Technology, an International Journal, **21**(5), pp. 922–937.

[48] Al-Saadi, M., Ibrahim, A., Al-Omari, A., Al-Gizi, A., and Craciunescu, A., 2019, "Analysis and Comparison of Resonance Topologies in 6.6kW Inductive Wireless Charging for Electric Vehicles Batteries," *Procedia Manufacturing*, Elsevier B.V., pp. 426–433.