Optimized electric vehicle charging: solar-driven wireless power transfer system

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ABSTRACT

Wireless power transfer (WPT) is emerging as a transformative solution to overcome the limitations of conventional plug-in charging for electric vehicles (EVs). This study aims to design and implement an efficient and reliable wireless charging system using inductive coupling with low requirements on the primary circuit. The proposed system integrates an Arduino-controlled high-frequency converter along with sensors and relays to optimize power flow, ensure safety, and reduce energy wastage. The methodology involves experimental rearrangement of transformers and frequency elements to achieve maximum efficiency while maintaining compact circuit design. Results demonstrate that the system can achieve efficient energy transfer suitable for short charging intervals, particularly beneficial for shuttle buses at stations and rental taxis at parking hubs. The findings highlight that wireless charging not only reduces total charging time but also supports cost-effective battery sizing, enabling improved vehicle turnaround and operational efficiency. In conclusion, this work contributes a weather-resistant, safe, and economically viable charging approach that sets new standards for EV infrastructure. Its implications lie in redefining charging stations along predetermined routes and stops, ultimately advancing sustainable and user-friendly electric transportation.

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1. INTRODUCTION

Utilizing resonant magnetic coupling as the working principle, electrical power is transferred to the electric vehicles (EVs) through an inductive coil acting as a transformer. The setup consists of two inductive coils, i.e., the transmitter coil (primary coil) and the receiver coil (secondary coil), electromagnetic coupled together to generate flux and electromotive force (EMF). Thus, the wireless power transfer (WPT) method is used to charge the EV while power is transferred without any interconnecting wires. The wireless charging systems are also used in high-power scenarios, charging both EV and plug-in EV while stationary. The wireless charging system boasts simplicity, reliability, and user-friendliness, surpassing conventional plug-in charging systems. The stationary mode of operation enhances the range and storage capacity of the battery, enabling charging even when the vehicle is in a stationary state. Power transfer efficiency is determined by the alignment of coils and the air gap distance between the source and receiver. In smaller vehicles, the air gap typically ranges from 150 to 300 mm, with larger passenger vehicles requiring increased air gap distances. Our implemented system features a fully automatic, controllable system with a display and a sensor for enhanced control and data visualization. A controller is programmed as the EV identification device. Once detected by the controller, the sensor sends a signal to it for comparison. The IR data are then compared with input and output parameters, with all the data being displayed on an LCD. Once the comparison is successful, the relay sets itself on, energizing the charging transmitter coil. Afterwards, the receiver coils are energized, generating electromagnetic flux and initiating the charging process. The LED light on the receiver coil indicates the reception of the transmitted signal as a demonstration. This integrated system then guarantees a smooth and controlled wireless charging of EV. In a nutshell, a resonant magnetic coupling is the cornerstone of this novel technology-based system, which effortlessly transfers electric power to an EV through a tuned inductive coil serving as a transformer. Fundamentally, the system consists of two main components: the transmitter coil (primary coil) and the receiver coil (secondary coil). The electromagnetic coupling created with a very strong intensity gives rise to electromagnetic flux and EMF. The concept of wireless energy transfer presents a totally new approach to EV charging, thus implying a completely no-touch interface. The technology of wireless charging is high in power and novel in the sense that it can meet needs for high power charging of EV and plug-in EV, and under stationary conditions [1]. Not only does it claim simplicity of an extraordinary nature, with utmost reliance on capability and now user interaction with charging systems that surpass the commonly accepted plug-in system of charging. While in the parked mode, the luxury offered by such powering system is immense as it raises the range and storage capacities of EV batteries by allowing them to charge when the vehicle is idle. Power transfer efficiency varies with coil alignment and air gap distances, normally between 150 and 300 mm in the case of smaller vehicles and larger for higher ones. Our system is a representation of engineering excellence and technology perfection, delivering an efficient and seamless charging experience for EVs [2].

Latest studies have been on optimizing the coils, tuning the frequency, and designing compensation to enhance wireless charging: the tolerance to misalignment and on thermal management. Another avenue in the further studies is dynamic charging of moving vehicles, taking scalability and efficiency into consideration. However, intelligent control for safe and user-friendly operations has hardly been given any consideration. The distinguishing point of the study is combining resonant magnetic coupling with an Arduino-based sensor–relay system for real-time monitoring as a comparatively cheap, weather-resistant, and scalable counterpart to practical EV deployment.

2. LITERATURE SURVEY

This review will look into the new advances in wireless charging systems for EV as put forth by eminent research works. It begins with a detailed study of an innovative wireless charger for EVs, emphasizing the easy integration of the charger into the infrastructure so that it can be accessed and used by the general public with ease [3]. Next, it glides into cutting-edge WPT technologies for EVs, explaining their various applications as well as the problems that they are meant to overcome [4]. The integration of solar energy to charging strategy for EVs leads to the discussions, showing the work to integrate solar panels with charging stations to avoid grid use and ensure sustainability [5]. This survey brings about a novel wireless charging methodology for EVs that cleverly combines solar PV and wind energy, discussing its detailed design, implementation, and the various benefits it confers along with the challenges involved [6]. It further analyses the feasibility of implementing dynamic wireless charging on highways for EVs, dissecting technicalities like infrastructure design and implications on vehicle performance in detail [7]. The story continues with an extensive portrayal of the various nominal wireless charging systems for EVs, encompassing aspects of their design, implementation, and rigorous evaluation of their functioning The survey further views recent developments in wireless charging technology for EVs, predicting that these developments would have a tremendous effect on the rates of adoption and thus on the paradigm of sustainable mobility [8]. Furthermore, the paper considers challenges and opportunities inherent in establishing wireless charging infrastructure for EVs while providing a nuanced discussion of their potential implications for the widespread adoption of electric mobility solutions [9]. Complementing this discussion is a comparative analysis of the various wireless charging systems for EVs, focusing on their performance parameters, operational efficiency, and cost-effectiveness [10]. Arguably the most important contribution of Thompson brings the discourse to a zenith by offering an in-depth interpretation of the theoretical underpinnings, historical development, and practical applications of wireless charging systems for EVs. At the same time, it accounts for the intricate interplay of regulatory dynamics and economic imperatives to provide invaluable insights to shaping the contours of a sustainable transport paradigm, thereby resonating with scholars, practitioners, and policymakers alike [11], [12]. The design and implementation of a wireless charging system for EV based on resonant inductive coupling In the study, the system architecture, the control algorithm, and the experimental results were discussed to demonstrate the feasibility and operability of the proposed system [13]. Optimal sizing and placement of wireless charging stations for EV fleets in urban areas. A mathematical optimization model is proposed to determine the optimal number, capacity, and locations of charging stations so as to minimize cost and maximize coverage [14], [15].

3. METHOD

To construct and implement a resonant inductive wireless charging system for EV, it is important to take into account a number of significant steps. First, an extensive study is undertaken to thoroughly research the basics of resonant inductive charging with the emphasis on electromagnetic coupling behavior and resonance frequency. It is then followed by a lengthy component selection procedure for compatibility and reliability. An Arduino microcontroller placement is also given specific consideration for smooth operation of all systems. The transmitter and receiver coil fabrication and programming will be carried out, alongside the fabrication of the electronic circuitry. Also, a complete validation procedure benumbs the system's usability and functionality. The approach intends to engender a reliable charging solution that is effective and adapts to the special needs of EV.

Figure 1 shows the methodology adopted in the proposed work. Our novel wireless charging method is centered around dynamic charging, whereby the transmitter coil is physically moved in the direction of the EV's receiver coil. The initial studies review the fundamentals of dynamic wireless charging, focusing on resonant methods and inductive coupling. An extensive review highlights the special needs and challenges, guiding the design of a system architecture deliberately for dynamic charging. Specialized hardware parts are chosen and incorporated, such as moveable transmitter coils and control systems. Using Arduino-style microcontrollers, custom firmware allows for fine control and monitoring. Testing and prototyping ensure viability and maximize performance while taking alignment precision and charging speed into account. Validation in the real world ensures safety, dependability, and efficacy [16]. The goal of this technology is to provide EV owners with a novel and useful dynamic charging solution [17].

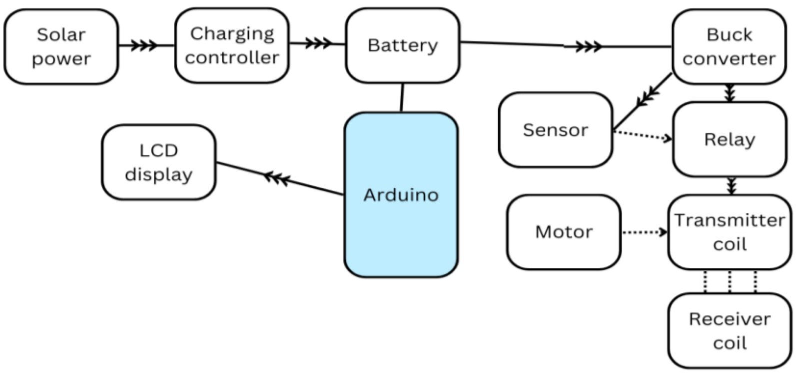


Figure 1. Methodology

3.1. Efficiency and input parameter

The solar panel produces DC voltage of 12 V to charge batteries with capacities somewhere between 12 and 15 volts. This correct matching of panel output with battery capacity keeps the battery well charged and from overloading. Energy efficiency shows what percentage of input energy is converted into useful output. Here, 70% of the energy supplied is put to effective use while 30% goes into heating, internal resistance, or losses within the system. Wireless charging transfers energy from a transmitter coil to a receiver coil without physical wires; hence, the said 70% efficiency implies energy loss. Though the transmitter operates at 5 V, the receiver somewhat effectively gets 3.5 V because of induction and coil resistance losses.

a. Power:
Solar panel output: P panel: 12 V
Battery capacity: C battery: 12-15 V

b. Energy efficiency:
Efficiency: η
The efficiency is calculated as:
Total_energyuseful_energy×100=70%

c. Wireless charging:
Charging efficiency: η charge: 70%
Charging power transfer: P transfer: 5 V (transmitter coil), 3.5 V (receiver coil)

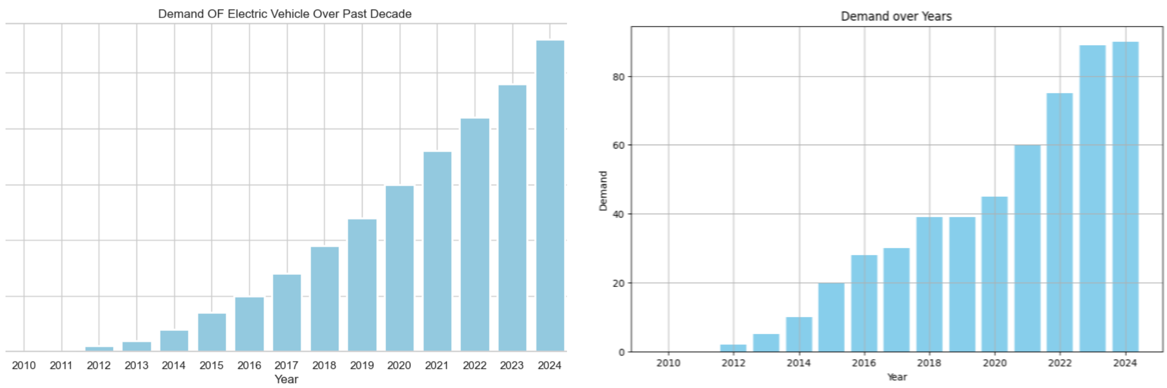
3.2. Scope of electric vehicles

The global rise of EV is transforming the auto sector, with over 10 million EVs sold in 2022 and a projected 35% growth in 2023, led by China (60% share), followed by the US and Europe, driven by policies like the Inflation Reduction Act and EU's Fit for 55. By 2030, EVs are expected to account for 60% of sales in major markets, reducing oil demand by 5 million barrels per day and boosting battery production, with China leading while the US and EU enhance supply chains via initiatives like the Net Zero Industry Act [18]. Rapid EV growth is emerging in markets like India and Thailand. Public charging infrastructure, essential for EV adoption, reached 2.7 million points globally in 2022, with China dominating slow chargers and Europe advancing through countries like Germany and Norway. Programs like the US NEVI initiative and Tesla's Supercharger network expansion are improving the EV-to-charger ratio, but sustained growth requires more accessible charging options [19], [20].

3.3. Challenges and current issues

The limitations and environmental impact of wired charging are a challenge, and the research aims to introduce sustainable wireless alternatives, reduce consumption and the goal is to overcome these problems by introducing an environmentally friendly approach to vehicle charging.

a. Limitations of wired charging systems: conventional wired EV charging faces limitations like manual handling, wear and tear, and safety risks, alongside significant environmental and infrastructure challenges. Wired systems increase carbon footprints through cable production, usage, and disposal while demanding costly installations and urban space. To address these issues, sustainable wireless charging offers a promising alternative by reducing environmental impact, enhancing durability, and aligning with global sustainability goals. This shift prioritizes eco-friendly, resource-efficient solutions to support the growing integration of EVs into transportation systems.
b. Research goals and scope: the objectives focus on developing durable wireless EV charging systems, enhancing user convenience and aesthetics, and enabling dynamic charging. Robust systems with reliable components aim to ensure long-term durability and minimal maintenance [21]. Figure 2 shows a steady rise in EV demand and charging infrastructure over the years. Figure 2(a) highlights the sharp increase in EV adoption from 2015 to 2023, while Figure 2(b) shows a similar upward trend in charging infrastructure from 2015 to 2024 [22]. This indicates a strong correlation between EV growth and the expansion of supporting infrastructure, essential for sustainable transportation.



(a) (b)

Figure 2. The growth of EV and supporting infrastructure; (a) demand for EV over the years and (b) trends in charging infrastructure

User-friendly interfaces and visually appealing designs enhance the charging experience, making it seamless and engaging. Dynamic charging explores a continuous power supply during vehicle operation, reducing wear and aligning with evolving EV needs. This innovative approach aims to redefine charging efficiency, adaptability, and sustainability, supporting the exponential growth of EV adoption in the coming decade. Figure 3 explains how widespread the scope of EV charging will be over the time of next decade and how it will affect our daily usage of EV charging.

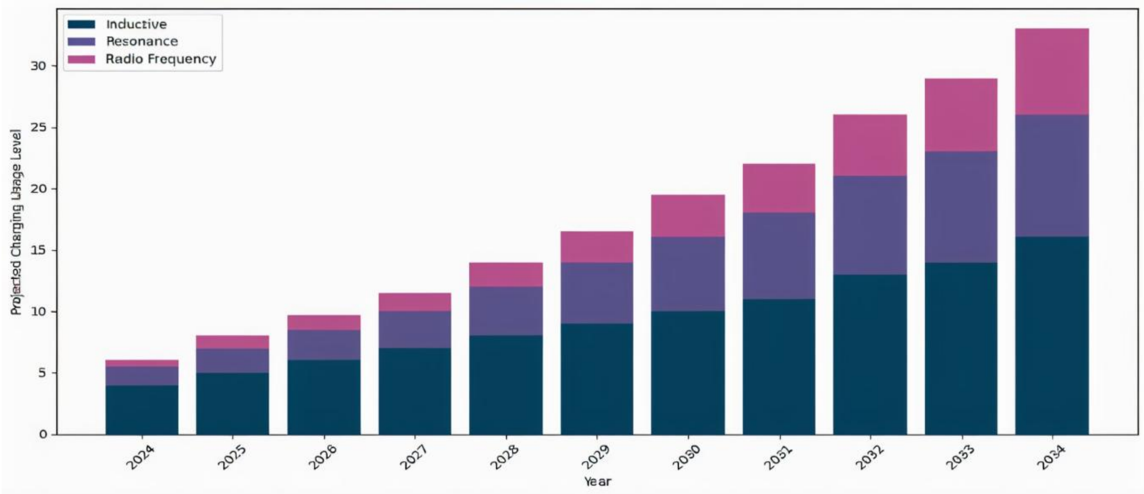


Figure 3. Scope of types of EV charging

4. WORKING

The wireless charging system uses a resonant inductive charging principle and uses two coils for power transfer. Circuit design, including reliable component selection and the role of Arduino, is central to this methodology. To put it simply, the working principle lies in maintaining the resonant frequency. Figure 4 illustrates a wireless EV charging system in which a sensor detects the vehicle, and an Arduino drives a lifting motor to raise and lower the transmitter and receiver coils, respectively. A relay is then used to allow power transfer from the transmitter to the receiver, while an LCD displays charging status for efficient contactless charging.

a. Overview of the wireless charging system: the resonance inductive charging is employed for the wireless charging system, where transmitter and receiver coils are involved in the transfer of power. A detailed block diagram is presented for better understanding of the complexities involved in the system [23].
b. Circuit design and components: the foundation of this prototype's success lies in the selection of sturdy and compatible components. An Arduino plays the central controlling function with which all other aspects are integrated and coordinated to operate together in harmony with maximized efficiency. The above considerations make the prototype very reliable, versatile, and efficient.
c. Operational principles and components: maximizing efficiency in wireless charging hinges on keeping the resonance frequency intact between transmitter and receiver coils. The compensation networks situated at the two terminals of the link participate in adjusting and tuning this resonance, thus enabling the smooth functioning and highest efficiency.
d. Paving the way for sustainability: this research strives to develop sustainable wireless charging solutions in order to mitigate environmental impacts, reduce wear and tear, and improve life span of this charging. It proffers an eco-friendly solution to green the long-term projection of charging EV.

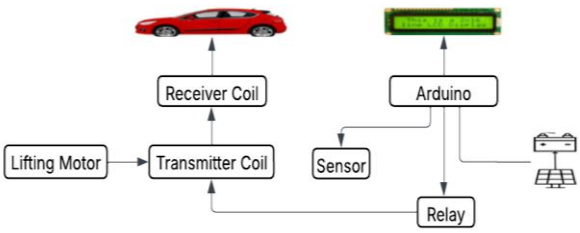


Figure 4. Working block

4.1. Resonant inductive charging

The nature of resonant inductive charging is a form of wireless power transfer where energy is transmitted between two coils (transmitter and receiver) having the same resonant frequency. This resonance, being able to create a more efficient energy transfer medium than regular inductive charging, does so at a slightly bigger distance.

a. Electromagnetic coupling dynamics: the phenomenon of resonant inductive charging, on the other hand, is witnessed in the intricate interplay of electromagnetic coupling between the transmitter and receiver coils. The moment the electric current flows inside the transmitter coil, the magnetic field comes to exist, eventually creating a pertinent EMF in the receiver coil. This section will go ahead to discuss in detail the physics of this coupling phenomenon, thus creating room to emphasize its importance in the transmission of wireless power from the transmitter coil to the receiver coil. By unravelling the complexities of electromagnetic coupling, we attempt to explain the basic principles on the effectiveness and efficiency of the resonant inductive charging technology as shown in Figure 5.

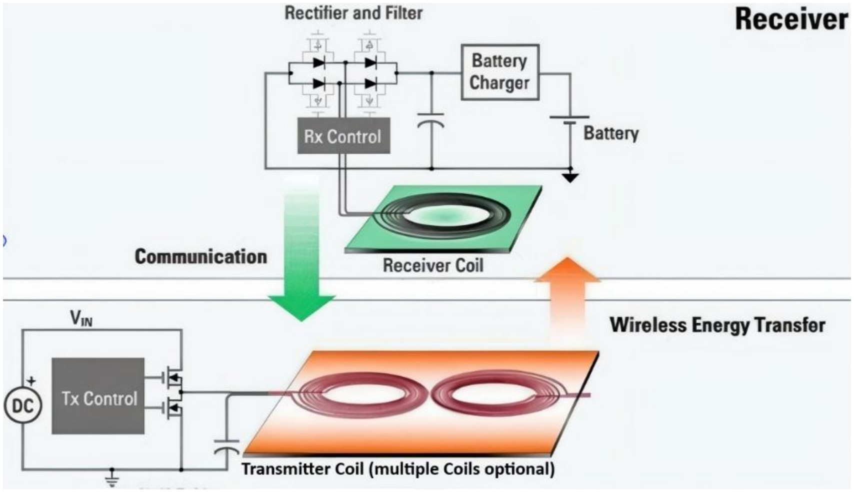


Figure 5. Resonant inductive charging

b. High-frequency alternating current (AC): the paramount significance of employing high-frequency AC unfolds as it intricately contributes to the creation of a dynamic and oscillating magnetic field. The AC current applied to the transmitter coil creates a magnetic field whose polarity changes alternately with time. From the perspective of WPT, this alternating magnetic field is extremely important as it enhances the efficiency and makes the energy transfer highly effective in absence of any physical connectors. The choice of high-frequency AC, therefore, is intentional and inevitably made in such a way to maximize the efficiency of WPT, hence emphasizing the need for technological precision that ensures smooth and effective energy transmission In delving into the intricacies of this deliberate design choice, one attains a thorough comprehension of the subtle engineering involved in fostering the generation of a dynamic oscillating magnetic field, which hence further leads toward the growth of wireless energy transmission [24].
c. Compensation networks for resonance frequency maintenance: the compensation networks play an important role in maintaining alignment of the resonance frequencies of the transmitter coils with those of the receiver coils to obtain the best WPT. These networks track and adjust resonance frequencies in real time to achieve maximum efficiency of energy transfer. Their particular design and working vastly improve the efficiency and reliability of wireless power systems [25].

5. EXPERIMENTAL SETUP AND TESTING

Proper selection of components, correct programming of Arduino, and making a full test procedure on the equipment guarantee its reliability and efficiency. This section explains the importance of each component toward the ultimate goal of proving seamless wireless charging.

a. Components utilized in the prototype: thorough attention is paid to the criteria used for selecting prototype components. The selection rationale for each component is discussed in detail, with particular emphasis on explaining their individual roles in bolstering the dependability and functionality of the wireless charging system. This methodical and open procedure for component selection exhibits our concern for precision and serves to illuminate the various ways each element works together to contribute to the overall efficiency of the wireless charging system.
b. Controller programming for system control: explaining the code architecture and logic, we are highlighting the pivotal role played by Arduino in allowing uncoordinated control of the entire system. In

doing so, we plumb the very depths of the layers of code structure, dissecting the subtle logic behind every operation. Furthermore, we emphasize the Arduino's position as a focal nexus, central to the coordinating of functionalities of diverse components to pursue a unified and efficient state of wireless charging operation. This in-depth study should offer meaningful insights into how the intricacies of programming converge with the role of the Arduino to bring about a highly advanced and smoothly controlled wireless charging infrastructure.

c. Evaluation of charging efficiency and reliability: a systematic framework has been constructed for charging efficiency evaluation that entails numerous carefully crafted metrics plunging into various quantitative performance measures. Simultaneously, a rigorous protocol set was laid down for reliability testing to judge the strength of the wireless charging system across a variety of conditions. This comprehensive approach guarantees a thorough examination of the system, weighing its viability and unwavering dependability in potential real-world scenarios. Establishing exact metrics and test protocols is aimed not only at adequately measuring charging efficiency with numbers but also at assessing the system's thwarting of and resistance to multiple challenges imposed by multilayered operational conditions.

6. RESULTS AND COMPARATIVE ANALYSIS

The quantitative indicator evaluates charging efficiency, with visual representation on the LCD. The reliability testing weighs in on different conditions. Comparative analysis pits wireless and wired charging alternatives against each other and lays out where gains can be made and realized improvements. Table 1 presents the voltage and efficiency analysis for the wireless energy transfer system, while Table 2 is the comparison of wireless charging versus wired charging.

a. Efficiency metrics and data display: using quantitative metrics like power transfer efficiency and charging time, system evaluation is performed. An LCD that is integrated gives visual feedback in real-time and allows detailed inspection of the general efficiency. Together, quantitative assessment and visual representation give a full and thorough assessment of charging system efficacy.
b. Comprehensive examination of the reliability of the wireless charging system: testing protocols for the wireless charging system cover the areas of stress tests, environmental tests, and real-world simulations to assess reliability from conditions set in divergent situations. Stress tests would have been subjected to performance testing under extreme conditions; environmental tests would assess resilience to climatic factors, in contrast to simulations, which impose operational challenges. These testing assure robustness, adaptivity, and performance on the execution of the system.

Table 1. Voltage and efficiency analysis for a wireless energy transfer system

Parameter	Value
Input (solar panel)	12 V
Voltage to battery	11 V
Transmitter coil voltage	5 V
Receiver coil voltage	3.5 V
Efficiency	70%

Table 2. Comparison of wireless charging vs. wired charging

Aspect	Wireless charging	Wired charging
Charging time	Usually, slower than wired charging.	Faster than wireless charging.
Convenience	It has the advantage of being convenient due to the fact that it does not require cables, especially in cases where devices have no accessible charging ports.	Requires a physical connection, which for some, may be found inconvenient.
Flexibility	Allows charging on the move away from the charging source.	Requires placing the device on a charging pad or connecting it to a cable.
Safety	Usually considered safe with minimal chances of electrocution.	Generally, safe when used correctly but may cause electrical hazards.
Efficiency	The efficiency loss occurs during the WPT.	Potentially more efficient given its direct connection.
Compatibility	Wireless charging may require some sort of device or adapter.	Able to charge most devices with any sort of standard charging port.
Ease of use	Easy to go with wireless; just put and charge.	Easy to go with wired; plug and charge.
Portability	Still more portable, since no cables are involved.	A little less portable because you need the cables.
Overall cost	May be higher, due to the secondary technologies and specialized devices.	May have a comparatively lower price as it involves no secondary technologies or devices.
Energy consumption	Energy consumption may be higher due to inefficiencies during wireless transfer.	Usually, less energy consumption due to direct connection.
Ease of installation	Easy to install since no cable is required.	Charging structure installation is required.

7. CONCLUSION

This research introduces a transformative wireless charging system for EV, leveraging resonant magnetic coupling and Arduino technology to address key challenges in traditional wired charging. With strategic design elements like reconfigurable transformers, high-frequency optimization, and IR sensor-regulated precision, the system minimizes energy loss, enhances operational efficiency, and ensures resilience to environmental factors. Tailored for applications such as shuttle buses and charging stations, it enables reduced charging times, smaller battery sizes, and cost savings, while user-friendly features like LCD displays and automatic controls add to its practicality. This innovation not only simplifies EV charging but also marks a paradigm shift in sustainable transportation, making it more efficient, reliable, and seamlessly integrated into everyday life. As the EV industry advances, this research highlights the potential of technological ingenuity to reshape the future of EV charging.

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No funding was involved in this study.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Rashmi Sharma					✓		✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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