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Solar-Driven Wireless Charging: Innovations in Electric Vehicle Energy Systems

Ali Nofal Abd Ali al-Musawi[1], Divya Shree V [2], Ashish Nema[3], D Little Femilinjana[4], Ankita Joshi[5] and R. Vimala Devi[6]

[1]*Department of Dentistry, Al-Zahrawi University College, Karbala, Iraq.*
[2]*Assistant professor, School of Business & Management, Bangalore, India.*
[3]*Department of Electronics & Communication Engineering, IES College Of Technology, IES University, Bhopal, Madhya Pradesh 462044 India.*
[4]*Assistant Professor, Department of S&H, Prince Shri Venkateshwara Padmavathy Engineering College, Chennai – 127, India.*
[5]*Department of Management ,Uttaranchal Institute of Management, Uttaranchal University, Dehradun-248007, India.*
[6]*Assistant Professor, Department of BCA, K. S. Rangasamy College of Arts and Science (Autonomous), Tiruchengode. Mail Id: vimalrmail@gmail.com*.

Abstract. Electric vehicles (EVs) are gaining traction globally due to their energy efficiency and eco-friendliness compared to traditional internal combustion engine vehicles. However, the limited availability of charging infrastructure impedes their widespread adoption. As EV usage grows, public spaces are installing EV charging stations, but charging via fossil fuel-powered grids harms the environment. Utilizing solar power through photovoltaic (PV) panels offers a sustainable solution. This review examines recent developments in solar PV-EV charging systems worldwide, covering EV charging behaviour, station operations, and user geography. The proposed analytical methods are efficient and beneficial for researchers and students in the field. The article also explores innovations in wireless power transfer (WPT) systems for charging EV batteries using solar panels. Various solar-powered EV charging station types and WPT components, such as compensators and coil structures, are analysed. Additionally, the integration of artificial intelligence (AI) within WPT systems is discussed, emphasizing its role in enhancing efficiency. This review consolidates the evolving landscape of solar-driven wireless charging systems, advancing our understanding of sustainable transportation.

[1]Corresponding Authour :*allawinawfal@gmail.com*

[2]*divyashree.v@christuniversity.in*
[3]research@iesbpl.ac.in
[4]*d.littlefemilinjana_maths@psvpec.in*

[5]*Ankitajoshi2010@yahoo.com*

1 Introduction

Air pollution, specifically the presence of harmful particulate matter (PM), poses a significant challenge for the global transportation sector. This issue is of paramount concern due to its adverse effects on public health and the environment. Despite ongoing efforts to reduce emissions, air pollution remains a pressing problem. In 2012, it led to a staggering number of premature deaths worldwide, with a majority occurring in developing countries. Presently, millions of lives, including those of children, are at risk each year. Additionally, outdoor air pollution has been linked to a significant proportion of premature births worldwide, with some countries, such as China, reporting a substantial number of premature deaths.

The gravity of the air pollution crisis underscores the urgency for innovative solutions. This review article seeks to contribute to the ongoing discourse on air pollution mitigation and sustainable transportation. It aims to comprehensively explore various facets and methodologies related to solar-driven wireless charging within the context of electric vehicle (EV) systems. The paper covers critical areas such as charging standards, solar charging techniques and modes, economic considerations, challenges, and sustainability factors. It also delves into control and safety techniques within the realm of photovoltaic charging systems (PVCS) and elaborates on the functioning of commercialized business models in this context. Furthermore, the paper offers a detailed assessment of the feasibility of diverse proposed solar PV charging technologies.

In response to the pressing need for sustainable energy solutions, this review article navigates through the intricate landscape of solar-powered wireless charging. It aims to provide a comprehensive roadmap for harnessing the potential of renewable energy sources, mitigating air pollution, and fostering a greener, more sustainable future.

2 Review and discussion

In a study by Khan et al. (2018), a comprehensive analysis was conducted on solar-powered electric vehicle charging systems [1]. The study delved into the increasing popularity of electric vehicles (EVs) and the challenges associated with their charging infrastructure. The research emphasized the potential of solar photovoltaic (PV) panels in providing a sustainable solution for EV charging. The study also highlighted the environmental challenges posed by traditional transportation methods and the potential benefits of transitioning to EVs powered by renewable energy sources.

Table 1. Comparative Analysis of Solar Charging Technologies [3-8]

Solar Charging Technologies	Key Findings	Challenges	Advantages
Standalone-Backup Power PVCS	Standalone power system forming a microgrid to feed EVs during the daytime without battery bank.	Intermittency in solar radiation.	Can be installed anywhere.
Solar Powered EV Charging System	Integration of Photovoltaic (PV) solar power, electric	Constraints on largescale	Reduction in EV charging load penetration

		vehicles (EVs), and battery energy storage into a gridbased charging station.	production and installation of PV modules.	on the grid.
Solar Powered DC Fast Charging System		A bidirectional DCDC EV charger is positioned between the highvoltage DC bus of a PV system and the EV battery.	Fast changes in PV power output.	EVs have inbuilt direct DC fast charging port.
Solar Rooftop or Ground Mounted System	On-grid Solar EV Charging System	Solar PV panels installed on a roof of a building supplying the individual load as well as connected to utility grid power.	Cannot operate without grid reference voltage and frequency.	Increased load demand is fulfilled by the grid.
	Off-grid Solar EV Charging System	Standalone power system which can fully charge at home or supply the residential load through EV battery.	Intermittency in solar radiation.	Can be installed anywhere.
	Hybrid Solar EV Charging System	System connected to grid along with a battery backup. Hybridization means charging the EVs from more than one source working in conjunction with one another.	Need for multiple energy sources.	Can work during the day and also during night hours.
Vehicle-Integrated PV (ViPV) System		EV (or HEV) car’s body is embedded with solar photovoltaic material. Solar cells might be embedded into the chassis part exposed to sunlight.	The amount of electrical energy required in vehicles is increasing.	The vehicle itself resembles a small solar power plant. Hybrid vehicles converted into more environmentally friendly.

In tying up the findings of the study to our review article, it's evident that the integration of solar PV systems with EV charging infrastructure offers a promising solution to the challenges faced by the transportation sector. Not only does this approach promote environmental sustainability, but it also addresses the energy demands of a growing EV market. As we progress towards a greener future, the insights from Khan et al.'s study provide valuable guidance for policymakers, researchers, and industry stakeholders. The potential of solar energy, combined with the benefits of EVs, presents a compelling case for a sustainable transportation ecosystem.

Another study by Kashani et al. (2022) delves into the realm of wireless charging stations for electric vehicles (EVs) powered by solar energy [2][13]. This investigation explores various aspects of this technology, encompassing solar power generation systems, different types of photovoltaic systems, DC-DC converters, maximum power point tracking (MPPT) methods, energy storage options, and the distinctions between static and dynamic wireless

EV charging systems. Additionally, it delves into the models of EV connection to the grid and various modes of wireless power transmission, discussing critical factors influencing their efficiency and safety.The study by Kashani et al. (2022) yielded several noteworthy findings:

Table 2. Key technologies in Kashani et al's study [9-12]

Technology	Details	Key Findings	Comparative Analysis	Safety Considerations
Solar Power Generation Systems	Photovoltaic Systems	- Grid-connected and off-grid systems serve distinct purposes. - Off-grid systems are vital in remote locations.	- Grid-connected offers easy integration. - Off-grid provides autonomy.	- Weather-resistant materials are important. - Off-grid systems require reliable storage.
	DC-DC Converters	- Converters are essential for voltage adjustments. - Include reducers and boosters.	- Reducers decrease voltage; boosters increase it. - Efficient converters maximize power output.	- Heat dissipation is crucial for longevity. - Robust components enhance reliability.
	Maximum Power Point Tracking (MPPT)	- MPPT algorithms ensure peak efficiency of solar cells. - Perturbation and observation and fuzzy logic are common methods.	- Perturbation and observation react to voltage changes. - Fuzzy logic adapts to varying conditions.	- MPPT algorithms must respond quickly to changing conditions. - Calibration and testing are critical.
	Energy Storage	- Lithium-ion batteries and supercapacitors are favored for EVs. - Storage compensates for low solar output.	- Lithium-ion batteries offer high energy density. - Supercapacitors provide rapid charging.	- Battery management systems monitor health. - Supercapacitors require voltage balancing.
Wireless EV Charging Systems	Static Charging Systems	- Fixed charging pads offer convenience. - Cost-effective for homes and commercial areas.	- Static systems are well-suited for overnight charging. - Ideal for residential and public use.	- Safety protocols protect users and vehicles. - Durability for high usage is essential.
	Dynamic Charging Systems	- Charging while in motion addresses EV range limitations. - Alignment and efficiency are key challenges.	- Dynamic systems enable continuous charging. - Alignment technology is crucial for efficiency.	- Dynamic systems require advanced safety measures. - Real-time alignment adjustments needed.
EV	Grid-to-Vehicle	- Balances load during	- G2V allows	- Smart grids ensure

Connection to Grid Models	(G2V)	EV charging. - Supports grid stability.	controlled power flow from grid to EVs. - Grid stability is enhanced with smart G2V systems.	safe and efficient G2V operations. - G2V standards promote interoperability.
	Vehicle-to-Grid (V2G)	- Utilizes EVs to feed energy back to the grid during peak demand. - Requires bidirectional charging standards.	- V2G minimizes peak demand on the grid. - Standards enable V2G compatibility.	- Cybersecurity measures protect against unauthorized access. - Regulatory compliance is critical.
Wireless Power Transmission (WPT)	Resonance Induction	- Efficient short-distance power transfer. - Coupling coefficient and quality factor impact efficiency.	- Resonance induction simplifies WPT design. - High coupling coefficient maximizes power transfer.	- EMI shielding safeguards against interference. - Alignment is critical for efficient coupling.
	Compensators	- Address coil leakage and impedance issues. - Various configurations available (SS, SP, PS, PP).	- Compensators enhance coupling efficiency. - Configurations cater to different WPT needs.	- Compensators reduce heat generated by coils. - Proper tuning is essential for optimal performance.
	Coil Structures	- Different coil structures improve efficiency and safety in WPT. - DDQ structure shows promise.	- DDQ structure minimizes alignment sensitivity. - Safety improves with shielded coil designs.	- Shielding minimizes magnetic field exposure. - Coil materials affect efficiency and cost.
Key Parameters	Coupling Coefficient (k)	- Higher k values improve power transfer efficiency. - Impacts alignment and efficiency.	- High k values are ideal for efficient WPT. - Alignments must be precise for high k systems.	- Alignment technology ensures high k values. - Calibration maintains efficiency.
	Quality Factor (Q)	- Q affects efficiency and power transfer capabilities. - Must be balanced with coupling coefficient.	- High Q values enhance power transfer. - Balance with k ensures optimal efficiency.	- Proper tuning maximizes Q and overall efficiency. - Q impacts resonant frequency.
	Alignment and Distance	- Precise alignment is crucial for efficient WPT. - Distance impacts power transfer efficiency.	- Advanced alignment technology improves efficiency. - Distance must be considered for WPT range.	- Real-time alignment adjustments enhance user experience. - Longer distances may require more

				power.
	Safety and Shielding	- Safety measures are essential to prevent hazards. - Shielding minimizes electromagnetic interference.	- Safety protocols ensure user protection. - Shielding maintains electromagnetic compatibility.	- Safety testing and certifications validate system reliability. - EMI shielding prevents interference

This table provides an overview of the main findings and aspects covered in Kashani et al.'s study, offering insights into the diverse components of solar-driven wireless EV charging systems.These findings collectively provide insights into the multifaceted domain of solar-driven wireless EV charging systems, offering valuable information for the development and optimization of this sustainable technology.

The application of Artificial Intelligence (AI) in Wireless Power Transmission (WPT) is a pivotal aspect explored in the author's study. WPT has undergone notable advancements, particularly in improving long-distance power transmission. Traditionally, designing WPT systems involved time-consuming trial-and-error processes. However, AI, particularly Artificial Neural Networks (ANNs), offers a more efficient approach. ANNs can swiftly optimize various factors in WPT design, such as coil configuration and inverters, enhancing transmission efficiency. These networks, which simulate human neural processes, excel in handling complex problems and have broad applications in various fields. In WPT, they help improve power transfer efficiency and reduce the design process's resource-intensive nature[14-15]. The integration of AI techniques holds substantial promise for advancing WPT systems, offering quicker and more reliable design solutions.

3 Future Scope of Research

The realm of sustainable energy and emerging technologies is ever-evolving, and there exist exciting avenues for future research and development. In this section, we shall delve into the potential directions that researchers and innovators can explore to further advance our understanding and harness the full potential of Solar Power Generation Systems, Wireless EV Charging Systems, EV Connection to Grid Models, and Wireless Power Transmission (WPT). These future prospects aim to contribute significantly to the ongoing transition towards cleaner and more efficient energy solutions.

- **Advanced Materials and Efficiency Enhancement:** Investigating novel materials for solar cells and energy storage solutions holds immense promise. Research into materials with higher efficiency and durability can propel the solar power generation field forward. Additionally, exploring ways to enhance the efficiency of energy storage systems, such as next-gen batteries and supercapacitors, remains a critical research avenue.
- **Smart Grid Integration:** As our energy infrastructure becomes more interconnected, the development of intelligent and adaptive grid systems is crucial. Future research can focus on creating advanced algorithms and control systems for better grid-to-vehicle (G2V) and vehicle-to-grid (V2G) integration, enhancing energy management, and optimizing power flow.

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- **Wireless Power Transmission Innovations:** The field of Wireless Power Transmission (WPT) continues to hold untapped potential. Future studies can explore advanced resonance induction techniques, compact coil structures, and highly efficient compensator configurations to further improve the efficiency and range of WPT systems. Moreover, exploring WPT applications in emerging fields like electric aviation and autonomous vehicles is a promising area.

4 Knowledge Gaps

While our review has provided a comprehensive overview of these technologies, it is important to acknowledge the existing knowledge gaps that require further investigation. Identifying these gaps is crucial for directing future research efforts effectively. In this section, we shall highlight key areas where our understanding remains incomplete or where more data and analysis are needed to drive innovation and inform policy decisions.

- **Safety Standards and Certification:** One prominent knowledge gap relates to the development of universally accepted safety standards and certification processes. While we have touched upon the importance of safety, comprehensive guidelines and international standards specific to wireless EV charging and WPT need to be established to ensure user and environmental safety.
- **Environmental Impact Assessment:** Although we've discussed the environmental benefits of these technologies, a deeper analysis of their long-term environmental impact, including life cycle assessments and ecological footprints, is essential. Understanding the full sustainability implications will help shape future strategies and mitigate unintended consequences.
- **Interoperability and Regulatory Frameworks:** The interoperability of EV charging systems and grid connection models across different regions and manufacturers remains an intricate issue. Research into standardized protocols, seamless cross-border integration, and international regulatory frameworks will be vital for the global adoption of these technologies.

By addressing these knowledge gaps and exploring the future scope of research, we can contribute to the ongoing transition towards a more sustainable and technologically advanced energy landscape. Researchers and stakeholders in these fields will find valuable insights in these areas as they continue to push the boundaries of innovation.

5 Conclusion

In conclusion, our exploration of the three seminal studies on solar-driven wireless charging within the framework of electric vehicle (EV) systems has illuminated crucial insights and raised vital questions in the pursuit of sustainable and efficient energy solutions. Drawing from these articles and extending our analysis, we have distilled key findings that underscore the evolving landscape of solar-driven wireless charging and its integration with EV systems:

- **Diverse Solar Power Configurations:** Our review has highlighted the versatility of solar power generation systems, which can be integrated into both grid-connected and off-grid EV charging setups. This diversity caters to a range of applications, from urban charging stations to remote, off-grid locations.
- **Optimizing Photovoltaic Efficiency:** Research in solar power generation continually strives to enhance photovoltaic efficiency. With a focus on advanced

materials and efficient DC-DC converters, these innovations promise higher energy yields from solar panels, a vital step towards self-sustaining EV systems.

- **Adaptive Maximum Power Point Tracking:** The development of intelligent Maximum Power Point Tracking (MPPT) algorithms, including conventional methods and emerging technologies like fuzzy logic, is paving the way for precise control of solar cells. These advancements maximize energy capture, even in variable environmental conditions.
- **Diverse Wireless Charging Systems:** We have seen that wireless EV charging systems come in static and dynamic configurations. The dynamic wireless charging model, often referred to as an "electric road," holds great promise for increasing EV range and reducing costs, addressing critical challenges faced by battery electric vehicles.
- **Grid Integration and Vehicle-to-Grid (V2G):** The transition to electric mobility requires a thoughtful approach to grid integration. Vehicle-to-grid (V2G) models empower EVs not only to draw energy from the grid but also to feed excess energy back, offering grid support during peak demand and showcasing the potential of two-way power exchange.
- **Enhancing Wireless Power Transmission:** The evolution of wireless power transmission (WPT) technologies remains a frontier of innovation. Advances in coil structures, compensation networks, and resonant induction techniques are steadily improving the efficiency and safety of WPT systems, making them more practical for various applications.

These findings collectively underscore the burgeoning potential of solar-driven wireless charging within EV systems, heralding an era of cleaner and more sustainable transportation. As we reflect on these insights, our abstract's vision of "revolutionizing the way we power electric vehicles" comes into sharper focus. The integration of solar energy, advanced charging technologies, and grid intelligence stands poised to transform the future of electric mobility, promising reduced environmental impact and greater energy resilience. In the pursuit of these objectives, our review has contributed to a deeper understanding of the challenges and opportunities that lie ahead, guiding researchers, policymakers, and industry stakeholders towards the sustainable and electrified future envisioned in our abstract.

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