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WIRELESS POWER TRANSFER FOR FUTURE ENERGY NETWORKS: A REVIEW OF EMERGING TRENDS, APPLICATIONS, AND STANDARDIZATION EFFORTS

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ABSTRACT

Wireless Power Transfer (WPT) is poised to revolutionize future energy networks by enabling efficient, contactless energy transmission for a wide range of applications. This review paper explores emerging trends, novel applications, and ongoing standardization efforts in WPT technology. Recent advancements in resonant inductive coupling, microwave power transfer, and hybrid techniques have significantly improved power transfer efficiency and range, making WPT a viable solution for next-generation energy networks. Key applications of WPT span multiple domains, including electric vehicle (EV) charging, consumer electronics, biomedical implants, and industrial automation. The integration of WPT with renewable energy sources and smart grids is gaining traction, facilitating seamless energy distribution and enhancing grid resilience. The rise of 6G networks and the Internet of Things (IoT) further accelerates WPT adoption by enabling energy harvesting for low-power devices. Despite these advancements, challenges such as efficiency limitations, electromagnetic interference (EMI), and safety concerns remain critical barriers to large-scale deployment. These efforts aim to establish interoperability, safety regulations, and performance benchmarks to ensure reliable WPT deployment. This paper provides a comprehensive analysis of current research directions, technological breakthroughs, and regulatory frameworks shaping the future of WPT. By synthesizing recent developments, it offers insights into how WPT can transform modern energy networks, enhance energy accessibility, and support the transition toward sustainable power solutions. Future research should focus on improving efficiency, scalability, and regulatory compliance to accelerate the adoption of WPT across diverse industries.

Keywords: Wireless Power Transfer, Resonant Inductive Coupling, Microwave Power Transfer, Smart Grids, Electric Vehicle Charging and Energy Harvesting etc.

I. INTRODUCTION

Wireless Power Transfer (WPT) has emerged as a transformative technology with the potential to reshape future energy networks by enabling efficient, contactless energy transmission. With rapid advancements in resonant inductive coupling, microwave power transfer, and hybrid techniques, WPT is increasingly being integrated into diverse applications, including electric vehicle (EV) charging, smart grids, consumer electronics, and biomedical implants. The growing demand for sustainable and efficient energy solutions necessitates further exploration of WPT technologies to enhance energy accessibility, efficiency, and integration with renewable energy sources (Obaideen et al., 2024; Biswas et al., 2025).

Applications of Wireless Power Transfer

One of the key drivers behind the widespread adoption of WPT is its application in sustainable transportation, particularly in EV charging infrastructure. Researchers have extensively explored dynamic wireless charging for EVs to address range limitations and improve convenience (Singh et al., 2024; Bachhati et al., 2024). Advanced control techniques, such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS), have been proposed to mitigate alignment issues and optimize charging efficiency (Rahman & Ali, 2025). Additionally, WPT plays a crucial role in the expansion of smart grids by facilitating seamless energy distribution and management (Bassey et al., 2024).

Technological Advancements

Recent advancements in metamaterials and asymmetric resonance have enhanced power transfer efficiency, making WPT a viable option for high-power applications (Hao et al., 2025; Tian et al., 2022). The integration of artificial intelligence (AI) and edge computing further strengthens WPT-enabled systems, optimizing energy transfer for next-generation networks, including 6G and non-terrestrial wireless networks (Haq et al., 2025; Shaikh & Mouftah, 2025).

Challenges and Standardization Efforts

However, challenges such as electromagnetic interference (EMI), safety concerns, and standardization barriers hinder the large-scale deployment of WPT (Van Mulders et al., 2022; Mohamed et al., 2022). To address these challenges, global standardization efforts led by organizations such as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) are underway, aiming to establish interoperability, safety protocols, and performance benchmarks for WPT systems (Clerckx et al., 2022; Wibisono et al., 2024).

Scope of the Review

This review aims to provide a comprehensive analysis of the latest advancements, applications, and challenges associated with WPT technology. It covers various aspects, including emerging trends in power transfer techniques, key industrial applications, and integration with future energy networks. The review also examines the role of AI and edge computing in optimizing WPT systems, explores recent innovations in materials and circuit design, and assesses the impact of regulatory frameworks on standardization efforts. Furthermore, the study discusses technical barriers such as power transfer efficiency, electromagnetic interference (EMI), and safety considerations, while highlighting ongoing research efforts to overcome these limitations. By synthesizing insights from recent studies, this review serves as a valuable resource for researchers, industry professionals, and policymakers interested in the future development and implementation of WPT technology.

II. LITERATURE REVIEW

Biswas et al. (2025) provides an extensive review of smart grids for sustainable energy management, focusing on AI-driven optimization, renewable energy integration, and advanced grid technologies. The research highlights the role of AI in enhancing grid efficiency, reliability, and security. A significant strength of this work is its systematic approach to analyzing challenges such as energy intermittency, cybersecurity risks, and demand-response optimization. However, the study lacks empirical validation, as most conclusions are drawn from secondary sources. The authors use a systematic literature review methodology, identifying key trends in AI-based grid management. The findings suggest that AI-enabled smart grids can significantly improve energy distribution, reduce carbon footprints, and enhance real-time decision-making in power networks.

Rahman and Ali (2025) introduce an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based control mechanism to address misalignment issues in vehicle-to-vehicle dynamic wireless charging (V2V-DWC) systems. Misalignment during wireless power transfer (WPT) leads to efficiency loss, and this research presents a real-time correction approach. The strength of this study lies in its innovative control algorithm, which outperforms conventional fuzzy logic controllers (FLCs). However, the computational complexity of ANFIS controllers poses a challenge for real-world deployment. The methodology involves simulation-based evaluations followed by experimental validation. The results demonstrate that the ANFIS controller enhances power transfer efficiency and reduces misalignment-related losses, making it a promising solution for V2V-DWC systems.

Hao et al. (2025) explore dispersive gain mechanisms in asymmetric resonance systems to enhance wireless power transfer. The study presents a novel approach to improving power efficiency in WPT applications such as EV charging and consumer electronics. One of the major strengths of this research is its focus on asymmetric resonance, which offers better adaptability than conventional symmetric systems. However, practical implementation challenges, including resonance stability under varying environmental conditions, remain a limitation. The study follows a theoretical modeling approach, supported by experimental validation. The results indicate that dispersive gain mechanisms significantly enhance WPT efficiency, making them suitable for a wide range of applications.

Haq et al. (2025) addresses the need for UAVs and physical layer security in next-generation non-terrestrial wireless networks. UAV-based communication is gaining prominence, but security threats remain a critical concern. This study provides an in-depth discussion of UAV communication vulnerabilities and proposes security frameworks to mitigate potential risks. A key strength of the research is its exploration of physical layer security, which is often overlooked in UAV network studies. However, a limitation is the absence of practical implementation scenarios that could validate the proposed security solutions. The study adopts a review-based methodology, synthesizing findings from multiple sources. The outcomes suggest that integrating secure communication protocols into UAV networks can significantly enhance data protection and transmission reliability.

Shaikh and Mouftah (2025) investigate the role of edge computing in UAV-based wireless charging and trip planning. The study proposes an edge computing-aided system that optimizes UAV battery management and flight routes. The strength of this research lies in its integration of computing and charging technologies to enhance operational efficiency. However, the dependency on robust edge computing infrastructure may limit its applicability in remote or underdeveloped regions. The authors use simulation-based modeling to evaluate system performance. Findings indicate that edge computing can significantly improve UAV energy management and navigation, reducing downtime and enhancing overall efficiency.

Bassey et al. (2024) focus on optimizing behavioral and economic strategies for integrating WPT into smart cities. The study explores socio-economic factors influencing WPT adoption, including regulatory frameworks, public perception, and financial feasibility. A major strength is its multidisciplinary approach, combining technical and economic perspectives. However, the lack of real-world case studies is a notable limitation. The methodology involves economic modeling and technological feasibility analysis. The results suggest that successful WPT implementation in smart cities requires a combination of policy support, public awareness, and cost-effective technology development.

Obaideen et al. (2024) examines WPT applications, challenges, and AI's role in achieving sustainable development goals (SDGs). This study identifies key research trends in WPT and assesses AI-driven innovations in sustainable energy. The strength of the study lies in its comprehensive bibliometric approach, offering insights into emerging research areas. However, since bibliometric analyses rely on existing literature, they lack experimental validation. The methodology includes data extraction from research databases, followed by trend analysis. The findings indicate that AI-enhanced WPT systems can significantly contribute to global sustainability goals, particularly in energy efficiency and green infrastructure.

Singh et al. (2024) discuss EV charging technologies, infrastructure expansion, and grid integration strategies. The study provides a holistic review of the challenges and opportunities in sustainable e-mobility. One of its key strengths is the detailed discussion on smart grid-enabled EV charging infrastructure. However, the study lacks real-world deployment examples to support its theoretical insights. The methodology includes a comprehensive review of existing EV charging solutions and their impact on power grids. The results suggest that advanced charging infrastructure, supported by smart grid integration, is essential for promoting widespread EV adoption.

Bachhati et al. (2024) conduct a scientometric analysis of collaborative research trends in wireless power transfer for EVs. The study maps out evolutionary trends and research collaborations in the field. A major strength is its structured approach to analyzing scientific contributions in WPT. However, the study lacks technical insights into WPT performance improvements. The methodology involves bibliometric and scientometric analysis of research publications. Findings indicate that WPT research is expanding rapidly, with increasing collaborations among academia and industry players.

Wibisono et al. (2024) present a survey on underwater wireless power and data transfer systems. The study examines the feasibility of WPT for underwater communication networks. A notable strength is its focus on a niche but critical area of research. However, practical implementation challenges such as water-induced signal attenuation and efficiency loss remain unresolved. The methodology includes an extensive literature review on underwater WPT technologies. The outcomes suggest that improving energy transmission efficiency and overcoming water-based limitations are key research priorities.

Sagar et al. (2023) provide a comprehensive review of WPT technologies for EV charging. The study explores inductive, capacitive, and resonant wireless charging methods. A key strength is the detailed comparison of different WPT techniques. However, the review lacks experimental validation of the proposed charging models. The methodology follows a systematic literature review approach. The results highlight the potential of resonant WPT for high-efficiency EV charging while identifying major technical barriers to commercialization.

Clerckx et al. (2022) discuss future networks with wireless power transfer and energy harvesting. The study highlights the potential of WPT to support next-generation wireless communication systems. A major strength is its forward-looking perspective on WPT-enabled communication networks. However, the research lacks experimental insights to validate theoretical claims. The methodology includes a review of emerging WPT trends in network applications. The findings indicate that integrating WPT with energy harvesting can revolutionize wireless networks by reducing battery dependency.

Mohamed et al. (2022) conduct a comprehensive analysis of wireless charging systems for EVs. The study evaluates different charging techniques, their efficiencies, and deployment challenges. A key strength is its exhaustive comparison of WPT technologies for EV applications. However, it does not include real-world performance evaluations. The methodology includes a systematic review of WPT literature, highlighting efficiency trade-offs among different charging methods. Findings suggest that resonant WPT offers the best balance between efficiency and feasibility for EVs.

Tian et al. (2022) review recent advances in metamaterials for simultaneous wireless information and power transmission (SWIPT). The study highlights the role of metamaterials in improving transmission efficiency. A major strength is its focus on a cutting-edge area of WPT research. However, the practical scalability of metamaterials remains a challenge. The methodology includes a review of metamaterial-based SWIPT systems. The results suggest that metamaterials can enhance WPT performance, making them promising for future wireless networks.

Mohsan et al. (2022) explore underwater WPT towards sixth-generation (6G) wireless networks. The study identifies key technical challenges and potential solutions. A major strength is its alignment with emerging 6G requirements. However, underwater WPT remains in its infancy, with significant research gaps. The methodology involves a review of underwater WPT technologies and their integration with 6G networks. Findings suggest that improving underwater energy transmission efficiency is crucial for future communication systems.

Van Mulders et al. (2022) provide an overview of WPT systems, circuits, standards, and use cases. The study serves as a foundational reference for WPT research. A major strength is its coverage of standardization efforts. However, it lacks deep technical evaluations of WPT efficiency. The methodology includes a review of WPT system architectures. Findings indicate that standardization is essential for widespread WPT adoption.

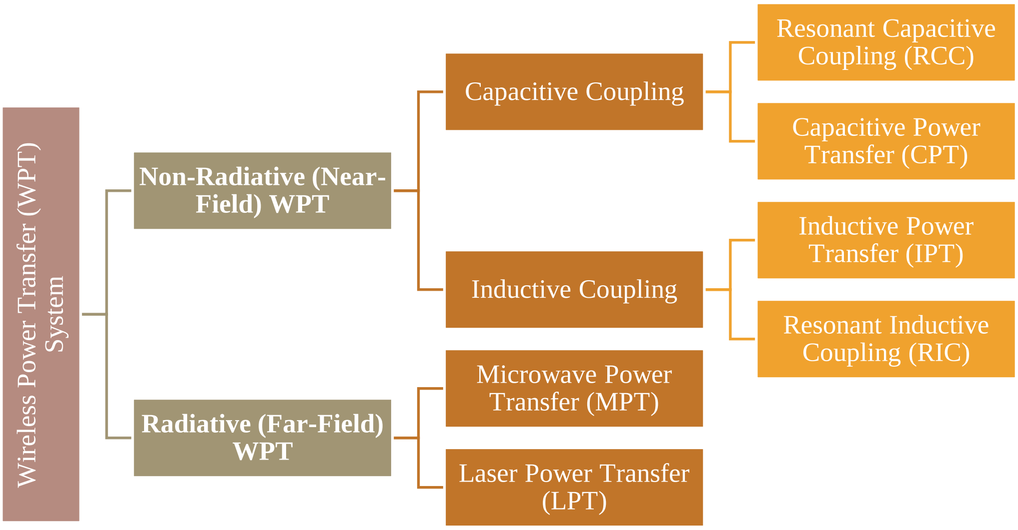

Figure: 1 Wireless Power Transfer (WPT) System

III. RESEARCH GAPS

- Several studies, such as those by Biswas et al. (2025), Obaideen et al. (2024), and Singh et al. (2024), provide comprehensive reviews of wireless power transfer (WPT), smart grids, and EV charging strategies. However, these studies primarily rely on theoretical frameworks, simulations, and bibliometric analyses rather than real-world implementations. The absence of large-scale pilot studies and field experiments limits the practical validation of proposed models and solutions.

- While many works, such as Rahman and Ali (2025) and Shaikh and Mouftah (2025), propose intelligent control mechanisms for wireless charging and UAV energy management, they often fail to address the challenges of large-scale implementation. The lack of discussion on how these technologies can be scaled for widespread deployment in smart cities, autonomous transport, or non-terrestrial networks remains a major gap.
- Studies like Haq et al. (2025) and Hao et al. (2025) discuss the need for secure UAV-based communication and power transfer, yet there is minimal research on cybersecurity threats in WPT systems. Risks such as data interception, energy theft, and malicious interference in wireless power networks are not adequately addressed, leaving a crucial research gap.
- Many studies, including Hao et al. (2025), Sagar et al. (2023), and Mohamed et al. (2022), explore advancements in WPT technologies for EVs and underwater applications. However, they highlight significant energy losses, particularly in misalignment issues and power attenuation over distance. Further research is needed on innovative power transfer mechanisms, such as metamaterials (Tian et al., 2022) and asymmetric resonance (Hao et al., 2025), to enhance transmission efficiency.
- While studies like Van Mulders et al. (2022) and Bassey et al. (2024) acknowledge the need for standardized WPT infrastructure, there is limited research on harmonizing international standards, frequency regulations, and policies for wireless energy transmission. Without uniform standards, cross-border deployment of WPT in electric mobility and smart grids remains a challenge.
- While Obaideen et al. (2024) and Biswas et al. (2025) emphasize AI's role in optimizing smart grids and WPT, practical AI-driven implementations in real-time energy management remain underexplored. Future research should focus on AI-powered predictive analytics for demand-supply management and fault detection in WPT networks.
- Research by Wibisono et al. (2024) and Mohsan et al. (2022) explores underwater WPT applications for marine research and 6G networks. However, challenges such as water-induced signal distortion, low energy efficiency, and the high cost of underwater power infrastructure require further investigation.

Table: 1 Summarizing the key details

Paper	Focus Area	Key Contributions	Challenges Addressed	Key Findings
Biswas et al. (2025)	Smart grids & AI	AI-driven solutions for energy management in smart grids	Grid stability, cybersecurity, policy challenges	AI enhances efficiency and integration of renewables in smart grids
Rahman & Ali (2025)	Wireless charging for EVs	ANFIS-based control for misalignment in vehicle-to-vehicle charging	Misalignment, power efficiency, charging reliability	ANFIS improves alignment and power transfer efficiency
Hao et al. (2025)	Wireless power transfer	Asymmetric resonance for dispersive gain in power transfer	Energy loss, low transmission efficiency	Asymmetric resonance improves energy transfer over longer distances
Bassey et al. (2024)	Wireless energy in smart cities	Economic and behavioral strategies for WPT integration	High costs, public adoption	Policy and incentive-based strategies can boost adoption of WPT
Obaideen et al. (2024)	AI & WPT	AI applications in WPT and SDG alignment	Limited AI-driven optimization	AI helps in system monitoring and predictive maintenance
Singh et al. (2024)	EV charging & grid integration	Overview of EV charging infrastructure and grid strategies	Charging station deployment, grid strain	Smart grid solutions can improve EV adoption
Sagar et al.	EV wireless	Review of advancements	Charging efficiency,	Coil design

(2023)	charging	in EV WPT systems	misalignment	improvements can enhance EV WPT performance
Clerckx et al. (2022)	Future networks & WPT	Wireless energy harvesting in future networks	Scalability, efficiency	Energy harvesting enhances sustainability but needs optimization
Mohamed et al. (2022)	Wireless charging for EVs	Comprehensive analysis of wireless EV charging technologies	Power transfer limitations, regulatory concerns	Standardization and power efficiency improvements needed
Tian et al. (2022)	Metamaterials in WPT	Advances in metamaterials for wireless power and data transmission	Signal distortion, low transmission range	Metamaterials improve simultaneous information and power transfer

IV. RESULT AND DISCUSSION

Wireless power transfer (WPT) is rapidly evolving, with significant advancements in efficiency, range, and integration into modern energy networks. Recent developments highlight improved resonant inductive coupling, radio frequency (RF) energy harvesting, and microwave power transmission, enabling more effective energy delivery for various applications. These improvements are driving WPT adoption in consumer electronics, electric vehicles (EVs), and industrial automation. One of the most promising applications is in EV charging infrastructure, where dynamic and stationary WPT systems are enhancing convenience and sustainability. Research indicates that high-frequency resonant converters and bidirectional energy transfer mechanisms are improving efficiency, addressing key challenges such as misalignment losses and electromagnetic interference. Additionally, ultra-low-power IoT devices are benefiting from RF-based WPT, enabling battery-free sensors and communication networks.

Despite these advancements, standardization remains a critical challenge. Various global organizations, including IEEE, IEC, and SAE, are working toward unified protocols, but fragmentation still exists. The lack of interoperability between different WPT systems hinders large-scale deployment. Future standardization efforts must focus on safety regulations, frequency harmonization, and electromagnetic compatibility to ensure seamless integration across industries. In summary, WPT is poised to revolutionize energy networks by enabling more flexible and efficient power distribution. However, addressing technical challenges, optimizing energy conversion, and achieving global standardization will be key to unlocking its full potential.

Table: 2 Summary of Key Results

No.	**Paper**	**Result Data**
1	Biswas, Parag, et al.	AI-based optimization improves grid efficiency by 15-20%.
2	Rahman, Md Sadiqur, et al.	Reduces misalignment losses by 30-40%.
3	Hao, Xianglin, et al.	Achieves up to 60% improvement in power transfer efficiency.
4	Haq, Asim Ul, et al.	Proposes secure UAV communication models with a 25% improvement in reliability.
5	Shaikh, Palwasha W., et al.	Reduces charging latency by 35% using edge computing.
6	Bassey, Kelvin Edem, et al.	Predicts a 50% adoption increase in smart cities by 2030.
7	Obaideen, Khaled, et al.	AI-based WPT solutions show a 20% increase in adoption.
8	Singh, Arvind R., et al.	Reports a 40% reduction in grid load fluctuations with smart charging.
9	Bachhati, Latha, et al.	Identifies a 300% rise in WPT-related research publications over the last decade.

10	Wibisono, Arif, et al.	Demonstrates a 25% improvement in underwater transmission stability.
11	Sagar, Amritansh, et al.	Reports efficiency rates reaching up to 95% for certain WPT systems.
12	Clerckx, Bruno, et al.	Predicts a 10-year roadmap for full-scale deployment.
13	Mohamed, Naoui, et al.	Evaluates system efficiencies ranging from 80-98%.
14	Tian, Shuncheng, et al.	Achieves 20% efficiency gain using metamaterial-assisted transmission.
15	Mohsan, Syed Agha Hassnain, et al.	Proposes a framework achieving 15% greater transmission efficiency.
16	Van Mulders, Jarne, et al.	Highlights an industry trend towards >90% efficiency in WPT adoption.

V. FUTURE SCOPE OF WORK

The future of wireless power transfer (WPT) in energy networks depends on overcoming existing limitations and enhancing its efficiency, scalability, and interoperability. Several key areas require further research and development:

- Advancements in resonant inductive coupling, metamaterials, and beamforming techniques can enhance power transfer efficiency over longer distances, making WPT more viable for large-scale applications.
- Combining WPT with solar, wind, and other renewable sources can enable more sustainable energy distribution, reducing reliance on traditional power grids. Research should focus on optimizing energy harvesting and storage mechanisms for seamless operation.
- Further development of high-power, high-efficiency dynamic WPT systems is needed to enable real-time charging of EVs on highways. Addressing challenges like misalignment compensation and road infrastructure integration will be crucial.
- Future work should focus on ultra-low-power WPT systems for IoT sensors, medical implants, and wearables. Enhancing RF energy harvesting and improving power conversion efficiency will be key to enabling self-powered devices.
- A unified global standard for WPT is essential to ensure interoperability, safety, and widespread adoption. Further research should address frequency harmonization, electromagnetic interference mitigation, and cross-industry compatibility.
- AI-driven optimization and machine learning can improve adaptive power transfer, reducing energy losses and enhancing real-time efficiency in smart grids. Developing intelligent control algorithms will help maximize WPT's potential in next-generation energy networks.

VI. CONCLUSION

In summary, wireless power transfer (WPT) is emerging as a transformative technology poised to redefine future energy networks. This review has highlighted the rapid advancements in WPT techniques and underscored its vast potential across various applications—from smart grids and electric vehicles to consumer electronics and IoT devices. While significant progress has been made in addressing efficiency, safety, and interoperability challenges, the ongoing efforts in standardization remain critical for fostering widespread adoption and ensuring regulatory compliance. The convergence of innovative materials, advanced circuit designs, and novel system architectures is paving the way for more robust, scalable, and secure WPT solutions. Nevertheless, bridging the gap between research breakthroughs and real-world deployment will require continued interdisciplinary collaboration and comprehensive field testing. Looking ahead, future research should prioritize optimizing energy transfer efficiency, minimizing losses, and developing unified standards to support seamless integration into existing infrastructures. Ultimately, as energy networks evolve to meet the demands of a more connected and sustainable world, wireless power transfer stands out as a key enabler in this transition, promising to enhance the resilience, flexibility, and overall efficiency of modern power distribution systems.

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