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Wireless Power Transfer: A Review of Techniques, Applications, and Challenges

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***Abstract*—Wireless power transfer (WPT) delivers electrical energy from a source to a load without physical connectors. Interest in WPT has grown rapidly because of portable electronics, electric vehicles (EVs), biomedical implants, and Internet-of-Things (IoT) devices. This paper reviews the main WPT approaches: near-field techniques (inductive coupling, magnetic resonance, capacitive coupling) and far-field techniques (microwave and laser transmission). It explains the governing physics, compares efficiency, range, power level, and safety, summarizes standards and applications, and discusses open challenges such as misalignment tolerance, electromagnetic exposure, cost, and dynamic charging.**

***Keywords*—Wireless power transfer, inductive coupling, magnetic resonance, capacitive power transfer, microwave power transmission, EV wireless charging, Qi standard.**

I. INTRODUCTION

A. Background and Motivation

Electrical energy has traditionally been delivered through conductors terminated in plugs, sockets, and connectors. This arrangement is simple and efficient, but it has well-known drawbacks. Connectors wear out with repeated mating cycles, expose bare contacts to moisture and dirt, create sparking hazards in flammable atmospheres, and restrict the mobility of the equipment being powered. Cables also add weight, clutter, and a point of failure in rotating, sliding, or implanted systems.

Wireless power transfer (WPT), also called wireless energy transmission or contactless power transfer, removes the physical link between supply and load. Energy crosses an air gap, or another non-conductive medium, by means of electric, magnetic, electromagnetic, optical, or acoustic fields. WPT must be distinguished from wireless *communication*: in communication the goal is to recover information from a weak signal, whereas in WPT the goal is to deliver the largest possible fraction of the transmitted power to the load. Efficiency, power level, and safety are therefore the central design measures.

Several trends have pushed WPT from a laboratory topic to a commercial one. The number of battery-powered consumer devices has grown enormously, and users expect to charge them without hunting for the right cable. Electric vehicles need convenient, automatable charging, and in the longer term roadway charging that could reduce battery size and cost. Medical implants such as pacemakers, neurostimulators, and cochlear devices benefit from powering that does not require a wire through the skin, which lowers the risk of infection. Industrial automation, automated guided vehicles, and underwater or explosive-atmosphere equipment value sealed, connector-free power. Finally, the spread of low-power IoT sensors makes battery replacement a real maintenance burden, which has motivated radio-frequency energy beaming and harvesting.

Progress in the underlying technology has made these applications practical. High-frequency switching devices, particularly silicon-carbide (SiC) and gallium-nitride (GaN) transistors, allow compact inverters operating from tens of kHz to several MHz. Better magnetic materials, Litz wire, and coil geometries have improved coupling and lowered losses. Advances in compensation networks and closed-loop control have made it possible to regulate power despite changes in distance, alignment, and load.

B. Historical Development

The theoretical foundation of WPT lies in the electromagnetic theory of Maxwell and the experiments of Faraday and Hertz in the nineteenth century. Faraday's law of induction explains how a time-varying magnetic flux in one circuit induces a voltage in another, which is the basis of every inductive link. Hertz demonstrated the generation and

detection of radio waves in 1888, showing that energy could propagate through space.

Nikola Tesla carried out the best-known early experiments on wireless energy transmission, including resonant transformer systems and the Wardenclyffe tower project in the early 1900s. His patents describe the transmission of electrical energy through natural media [1]. Although his large-scale vision was not realized, his work introduced the concept of resonant coupling that is central to modern mid-range WPT.

Far-field WPT developed after the invention of high-power microwave sources in the mid-twentieth century. William C. Brown demonstrated microwave-powered devices in the 1960s, including a small helicopter flown on a beamed microwave power, and later experiments transferred kilowatt-level power over short distances [2]. In 1968, Peter Glaser proposed the satellite solar power station, which would collect sunlight in orbit and beam it to Earth by microwaves [3]. This idea still drives research on large-scale microwave power transmission.

Near-field systems matured in parallel. Contactless inductive power for industrial vehicles and monorail systems appeared in the late twentieth century, with significant work at the University of Auckland on resonant inductive power transfer [4], [5]. A turning point for resonant WPT came in 2007, when a research group at MIT demonstrated the lighting of a 60 W bulb at a distance of about two metres with roughly 40 % efficiency using strongly coupled magnetic resonances [6]. This result renewed interest in mid-range transfer and led to a surge of publications [7]. Around the same time the Wireless Power Consortium developed the Qi standard for charging consumer devices, which was introduced in 2010 and later brought wireless charging into mass-market phones [8].

C. Scope and Contributions

The literature on WPT is large and spread across power electronics, microwave engineering, biomedical engineering, and automotive technology. The aim of this paper is to give a concise but organized review for readers who need a clear picture of the field. Recent surveys have treated individual parts of the field in depth, including EV charging [9], [10], [11], [12], implantable devices [13], [14], [15], [16], foreign-object detection [17], [18], capacitive coupling [19], [20], rectennas [21], and laser transmission [22]; this paper brings these strands together. The main contributions are the following:

- A classification of WPT techniques by physical mechanism and by operating distance relative to wavelength.
- A summary of the coupled-circuit theory, compensation topologies, and efficiency limits that apply to near-field links.
- A description of system architecture, control, and the practical blocks needed to build a working system.
- A review of standards and human-exposure safety rules.
- A comparative analysis of the main techniques and a survey of applications.
- A discussion of open challenges and likely directions for future research.

D. Organization of the Paper

The remainder of the paper is organized as follows. Section II classifies WPT techniques. Section III presents the theoretical foundations. Sections IV and V describe near-field and far-field techniques respectively. Section VI covers system architecture and control, and Section VII covers standards and safety. Section VIII reviews applications, and Section IX gives a comparative analysis. Section X discusses challenges and future directions, and Section XI concludes the paper.

II. CLASSIFICATION OF WPT TECHNIQUES

WPT techniques are commonly classified by the distance over which energy is transferred relative to the wavelength λ of the operating frequency. In the *near field*, at distances much smaller than $\lambda/2\pi$, the electric and magnetic fields are largely decoupled, energy is stored in reactive fields, and power transfer takes place by coupling between the source and receiver structures without radiating power away. In the *far field*, at distances of several wavelengths and beyond, energy propagates as an electromagnetic wave, and the transmitter radiates power that the receiver must capture.

Within these two regions, the techniques can be grouped by the field used. Near-field methods include inductive power transfer, magnetic resonant coupling, and capacitive power transfer. Far-field methods include microwave power transmission and laser power beaming. Ultrasonic power transfer, which uses acoustic waves, is also being studied for implants and underwater systems because sound travels well through tissue and water. Fig. 1 shows the general block structure shared by most near-field systems, and Table I summarizes the classification.

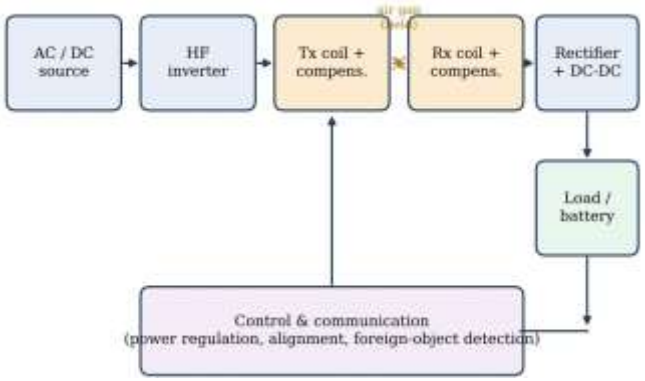


Fig. 1. Block diagram of a typical resonant WPT system, showing the source, high-frequency inverter, compensated coils, rectifier, load, and control loop.

TABLE I
CLASSIFICATION OF WPT TECHNIQUES

Region	Technique	Coupling mechanism
Near field	Inductive (IPT)	Magnetic field between loosely coupled coils
Near field	Magnetic resonance	Magnetic field with tuned resonant coils
Near field	Capacitive (CPT)	Electric field between metal plates
Far field	Microwave (MPT)	Radiated microwaves captured by a rectenna
Far field	Laser	Collimated light captured by photovoltaic cells
Acoustic	Ultrasonic	Pressure waves captured by piezoelectric element

III. THEORETICAL FOUNDATIONS

A. Coupled-Coil Model

The basis of an inductive link is a pair of coils with self-inductances L_1 and L_2 and mutual inductance M. The strength of the magnetic coupling is expressed by the coupling coefficient

$$k = M / \sqrt{(L_1 L_2)} \quad (1)$$

with $0 \le k \le 1$. In a tightly coupled transformer k is close to one, whereas in a WPT link with an air gap k can be as low as 0.05 to 0.3, and falls quickly as distance or misalignment increases. When the receiver coil is connected to a load, it affects the transmitter through a reflected impedance. If the receiver loop has total impedance Z_2, the impedance reflected to the primary is

$$Z_r = \omega^2 M^2 / Z_2 \quad (2)$$

where ω is the angular operating frequency. Equation (2) shows why the transmitter must be designed for a varying load: as the coil moves or the load changes, the reflected impedance changes with it, and so does the current drawn from the inverter.

B. Resonance and Quality Factor

Adding a capacitor C to a coil creates a resonant circuit with natural frequency

$$f_0 = 1 / (2\pi\sqrt{(LC)}) \quad (3)$$

and the quality factor of each coil, which measures how much energy is stored relative to the energy lost per cycle, is

$$Q = \omega L / R \quad (4)$$

where R is the series resistance of the coil. High-Q coils store energy efficiently and respond strongly to the matched resonance of the other coil, which is why resonant systems can transfer power over larger gaps than non-resonant ones. At frequencies of tens to hundreds of kHz, Litz wire reduces skin- and proximity-effect losses and so allows Q values of a few hundred.

C. Compensation Topologies

Capacitors added to the transmitter and receiver coils form the compensation network, which cancels the reactive power of the leakage inductance, raises the power factor seen by the inverter, and shapes the load characteristic. The four basic topologies are series–series (SS), series–parallel (SP), parallel–series (PS), and parallel–parallel (PP), named by how the primary and secondary capacitors are connected. SS compensation is popular because the secondary capacitor is chosen to resonate with the secondary inductance alone, which makes the resonant frequency independent of coupling and load. Its drawback is that the transmitter current can become large when the receiver is absent or very weakly coupled, which calls for protection.

Higher-order networks such as LCL, LCC, and double-sided LCC add inductors in the compensation. They can provide a nearly constant coil current, or constant-voltage or constant-current output independent of load, and greater tolerance to coil variation. These features are valuable in battery charging, where the load changes through the charge cycle, and have made LCC networks common in EV charging research [23]. Magnetic integration of the compensation inductor with the coil has been reported to give about 91 % efficiency with a misalignment tolerance of up to 200 mm [24]. Bifurcation of the operating frequency can occur in strongly coupled systems and must be considered in control design [25].

D. Efficiency Limits

For a two-coil link with a matched load, the maximum achievable efficiency depends only on the figure of merit kZQ_1Q_2, and is given by

$$\eta_{max} = x / (1 + \sqrt{(1 + x)})^2, \quad x = k^2 Q_1 Q_2 \quad (5)$$

Fig. 2 plots this relation. Efficiency rises rapidly as x increases from 1 to about 100, after which the gains become small. The result explains the two main design strategies: raise the coil quality factors, or raise the coupling by bringing the coils closer, enlarging them, or shaping the flux with ferrite. Since k falls roughly with the cube of the distance-to-diameter ratio in simple coil pairs, range extension is hard, and relay resonators and metamaterial slabs have been proposed to extend it [7].

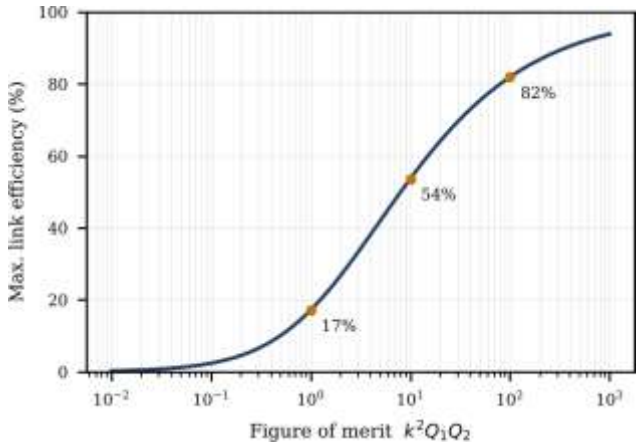


Fig. 2. Maximum link efficiency as a function of the figure of merit kZQ_1Q_2 from (5).

E. Far-Field Power Budget

For far-field systems, the received power follows the Friis transmission equation,

$$P_r = P_t G_t G_r (\lambda / 4\pi R)^2 \quad (6)$$

where P_t is the transmitted power, G_t and G_r are the antenna gains, and R is the distance. The quadratic dependence on $\lambda/4\pi R$ shows that long-range transfer requires high-gain, large-aperture antennas that concentrate the beam on a small receiver. Beam-collection efficiency, defined as the fraction of transmitted power intercepted by the receiving aperture, is therefore a key measure in microwave systems, and it increases with the product of the transmitting and receiving aperture areas divided by $(\lambda R)Z$.

IV. NEAR-FIELD TECHNIQUES

A. Inductive Power Transfer

Inductive power transfer is the most widely deployed WPT method. A transmitter coil driven by an alternating current produces a time-varying magnetic field, and a receiver coil within this field has a voltage induced in it. Operating frequencies are typically from about 20 kHz to a few hundred kHz, chosen to balance switching losses, coil size, and electromagnetic-compatibility limits. IPT works well when the coils are close and aligned, as in phone charging pads, electric toothbrushes, and stationary EV pads, and reaches efficiencies above 90 % in well-designed high-power systems [4].

Coil geometry strongly influences performance. Circular and rectangular spirals are simple and widely used. For vehicles, polarized pads such as double-D and bipolar designs produce a horizontal flux path that improves coupling, increases misalignment tolerance, and reduces the stray field below the vehicle. Ferrite plates behind the windings guide the flux and shield the vehicle underbody, while aluminum shields limit leakage.

B. Magnetic Resonant Coupling

Magnetic resonant coupling extends inductive transfer by tuning both the transmitter and receiver to the same frequency, as in (3). Because both coils have high Q, energy exchange between them is strong even when the coupling is weak, and efficient mid-range transfer becomes possible at distances comparable to or larger than the coil diameter [6]. Four-coil systems, which add a source loop and a load loop to isolate the resonators from source and load resistance, give flexible impedance matching and allow the effective coupling to be adjusted [7].

Resonant systems are sensitive to detuning. Changes in coil inductance caused by nearby metal, or in capacitance caused by temperature, shift the resonant frequency and reduce efficiency. Frequency tracking, switched or tunable capacitor banks, and impedance-matching networks are used to restore tuning. Frequency splitting occurs in the over-coupled region, where two resonant peaks appear instead of one, and designers must operate at a frequency that gives maximum power rather than maximum gain.

C. Capacitive Power Transfer

In capacitive power transfer, energy is transferred through the electric field between pairs of metal plates acting as the coupling capacitors. Because the field is confined between the plates, CPT generates little stray magnetic field, is not affected by nearby metals in the way an inductive link is, and can use thin, light plates, even the existing metal parts of a device. The coupling capacitance is small, typically in the pF range, so operating frequencies must be high, often several hundred kHz to MHz, and resonant inductors are added to compensate for it [26]. Reviews of CPT for EVs describe the coupling-plate structures and compensation networks [19], and a 13.56 MHz experimental system has been reported to transfer 100 W at 87.4 % efficiency over a 30 mm gap [20].

The main challenges of CPT are the high voltages across the plates, which create electric-field exposure and breakdown concerns, and the limited power density for a given plate area. Recent work has demonstrated multi-kilowatt systems for vehicles with plate areas of practical size and efficiencies near those of inductive links, particularly for short air gaps [26].

V. FAR-FIELD TECHNIQUES

A. Microwave Power Transmission

A microwave power transmission (MPT) system consists of a microwave source, a transmitting antenna, a receiving antenna with a rectifier, called a rectenna, and a power-management circuit. The DC input is converted to microwaves by a magnetron, klystron, or solid-state amplifier, radiated as a focused beam, and converted back to DC by Schottky-diode rectifiers at the receiving array [27]. Typical frequencies are 2.45 GHz and 5.8 GHz in the industrial, scientific, and medical (ISM) bands, which offer

reasonable atmospheric transmission and well-developed components.

The rectenna is the key component. Rectenna conversion efficiencies above 80 % have been reported for high input power densities, but they fall at low power levels because the diode threshold becomes significant. The overall end-to-end efficiency, from DC at the transmitter to DC at the receiver, is much lower, since it is the product of the conversion efficiency at the source, beam-collection efficiency, and rectenna efficiency [2], [27]. Phased-array transmitters allow electronic beam steering and retrodirective tracking of the receiver, which is important for moving targets such as drones. Recent reviews of rectenna research cover kHz-, MHz-, and microwave-band designs, including metasurface-assisted and millimetre-wave rectennas [21].

Space-based solar power is the best-known long-term application. A satellite in geostationary orbit would collect sunlight almost continuously and beam it to a ground rectenna several kilometres wide [3]. Smaller-scale demonstrations, including aerial vehicle powering and point-to-point links, show that the technology works, but cost, launch mass, and regulatory questions about large beams remain unresolved.

B. Laser Power Beaming

Laser power beaming converts electricity to a narrow optical beam, which is received by a photovoltaic converter tuned to the laser wavelength. Because optical wavelengths are very short, the beam can be small and well collimated over long distances, and the receiver can be compact and light. This makes the technique attractive for powering drones, remote sensors, and satellites. Disadvantages include limited conversion efficiency at both ends, atmospheric absorption and scattering in fog or rain, the need for a continuous line of sight, and strict eye- and skin-safety rules that require beam interlocks and tracking systems. A review of laser power transmission describes the emitter, the transmission channel, and the photovoltaic receiver as the three main parts of the link, and highlights its small device size, directed beam, and high power density [22].

C. Ultrasonic and Other Methods

Ultrasonic power transfer uses a piezoelectric transmitter to produce acoustic waves and a piezoelectric receiver to convert them back to electricity. Because acoustic wavelengths are short and tissue is a good acoustic conductor, ultrasonic links can power small, deep implants with less exposure to electromagnetic fields. They can also pass energy through metal walls, such as pipes and tanks, where electromagnetic methods are screened out. Power levels remain low, typically from microwatts to a few milliwatts.

VI. SYSTEM ARCHITECTURE AND CONTROL

A practical WPT system, shown in Fig. 1, consists of several functional blocks. On the transmitter side, a grid-connected rectifier with power-factor correction produces a DC bus, and a high-frequency inverter, usually a full or half bridge built from MOSFETs, SiC, or GaN devices, drives the compensated transmitter coil. On the receiver side, the induced AC is rectified and, in battery applications, regulated by a DC–DC converter that sets the charging current or voltage.

Control is needed because the operating point drifts with distance, alignment, temperature, and load. Three control approaches are common. In *primary-side control*, the transmitter estimates receiver conditions from its own measurements and adjusts the inverter frequency, phase, or duty cycle, which keeps the receiver simple. In *secondary-side control*, a DC–DC converter at the receiver regulates the output. In *dual-side control*, a communication link, such as Bluetooth, WLAN, or in-band load modulation as in Qi, lets both sides coordinate to achieve maximum efficiency and to protect the system.

Alignment and detection functions are also part of the architecture. Foreign-object detection identifies metallic objects in the field, which could heat up dangerously, by monitoring changes in power loss or quality factor. Reviews divide the methods into metal-object detection and living-object detection [17], [18]. Living-object protection stops or reduces power when a person or animal enters the active zone. Position-sensing methods, such as low-frequency magnetic beacons, cameras, or coil-voltage comparison, guide the vehicle into the alignment window. Finally, the power electronics must meet electromagnetic-compatibility requirements, which often means filtering and shielding in addition to compliance with exposure limits.

VII. STANDARDS AND SAFETY

A. Standards

Standards are essential to allow devices from different manufacturers to work with common transmitters. For consumer devices, the Wireless Power Consortium maintains the Qi specification, which defines coil placement, operating frequency range (about 100 to 205 kHz for the baseline profile), communication protocol, and foreign-object detection, and has been extended to higher power levels and magnetic-alignment variants [8]. A competing resonant approach was promoted for loosely positioned charging at a frequency near 6.78 MHz.

For electric vehicles, SAE International's J2954 document sets interoperability, performance, and safety requirements for light-duty vehicles, including a nominal operating frequency near 85 kHz and several power classes [28]. International bodies such as the IEC and ISO, and regional organizations, publish related standards for charging systems, electromagnetic compatibility, and functional safety.

B. Human Exposure and Safety

Human exposure to electromagnetic fields is limited by international guidelines. The ICNIRP guidelines specify basic restrictions based on induced electric fields in tissue for low frequencies, and on specific absorption rate and power density for higher frequencies [29], [30]. The IEEE C95 series provides similar limits. Compliance usually requires that field strengths in areas accessible to people remain below reference levels, which are derived from the basic restrictions.

Medical implants add a further constraint, since induced currents may interfere with pacemakers or heat the tissue around the implant. Metallic foreign objects between coils can heat rapidly, so detection or design measures are mandatory. For laser and microwave beams, interlocks, beam shut-off, and exclusion zones are needed. In addition, frequency allocations and out-of-band emissions are regulated by national authorities, which limits the choice of operating frequency, particularly for far-field systems.

VIII. APPLICATIONS

A. Consumer Electronics

Smartphones, earbuds, smartwatches, and toothbrushes are the best-known uses of WPT. Qi chargers typically deliver from about 5 W to 15 W for phones, with higher-power variants for laptops and tablets. The main benefit is convenience and sealed construction, though efficiency is lower than that of a cable, and misalignment causes heating. Charging furniture, car-console pads, and public charging surfaces are expanding the market.

B. Electric Vehicles

Wireless charging offers drivers a hands-free experience, since the vehicle can charge automatically when parked above a pad. Stationary systems commonly provide 3.7 to 22 kW, and heavy-duty pads for buses and trucks reach hundreds of kW. Dynamic charging, in which coils embedded in a roadway charge vehicles in motion, has been demonstrated in pilot projects, for example in the Korean online electric vehicle program, and could reduce battery capacity requirements. High cost, infrastructure complexity, and the need for standard interfaces still limit large-scale adoption [5]. Recent EV-focused reviews examine coil shapes, compensation, safety, and the static, dynamic, and quasi-dynamic charging modes [9], [10], [11], [12].

C. Biomedical Implants

Implants such as pacemakers, neural stimulators, retinal prostheses, and ventricular assist devices need reliable power without percutaneous wires. Inductive links at low MHz frequencies are common for transcutaneous power, while mid-field and ultrasonic links are studied for deeply implanted millimetre-scale devices. Design constraints include small receiver size, limited exposure, tissue heating, and robustness to posture and movement. Surveys of implant powering compare inductive, capacitive, magnetic-resonance, acoustic, and optical methods and treat tissue safety as a main limit [13], [15]. Resonant current-mode designs have been reviewed for battery recharging of implants [14], and metamaterial slabs have been proposed to raise efficiency inside the body [16].

D. Industrial, Robotic, and Underwater Systems

In factories, contactless power supplies rotating tables, robotic joints, and automated guided vehicles, where sliding contacts would wear out and generate dust. In mining, chemical plants, and underwater environments, the absence of exposed connectors removes sparking and corrosion hazards. Underwater inductive chargers are used for autonomous underwater vehicles and subsea sensors.

E. IoT, Aerospace, and Energy Harvesting

Low-power sensors can be fed by beamed RF energy or by harvesting ambient radio signals, which removes batteries from large sensor networks, though the available power is usually in the microwatt range. In aerospace, laser and microwave beaming have been proposed for charging drones in flight, for powering high-altitude platforms, and for space-based solar power systems.

IX. COMPARATIVE ANALYSIS

Table II compares the techniques discussed above. Inductive and resonant links dominate where power levels from watts to tens of kilowatts must be delivered over centimetres to about a metre, and they currently offer the best combination of efficiency, safety, and technological maturity. Capacitive links are a promising alternative for thin or metal-rich environments. Far-field techniques give unique capability at long range but at the cost of lower end-to-end efficiency and stricter safety management. Fig. 3 illustrates the typical combinations of range and power.

TABLE II
COMPARISON OF WPT TECHNIQUES

Technique	Range	Power	Strengths	Limits
Inductive	mm–cm	mW–kW	Mature, efficient	Alignment
Resonant	cm–m	W–kW	Range, tolerance	Detuning
Capacitive	mm	mW–kW	Low EMI, thin	High voltage
Microwave	m–km	W–MW	Long range	Low overall efficiency
Laser	m–km	W–kW	Compact receiver	Line of sight
Ultrasonic	mm–cm	µW–mW	Tissue, metal	Low power

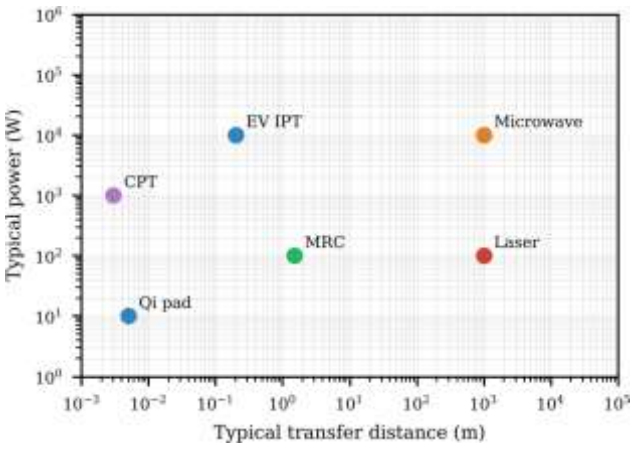


Fig. 3. Indicative range and power regions of common WPT technologies (approximate, for illustration).

X. CHALLENGES AND FUTURE DIRECTIONS

Despite rapid progress, several challenges remain. We summarize the most important ones and the directions being pursued.

- **Misalignment tolerance.** Efficiency drops when coils are displaced or rotated. Polarized pads, multi-coil arrays, and adaptive tuning can widen the usable zone.
- **Efficiency at range.** Coupling falls quickly with distance, so relay resonators, metamaterials, and optimized coil shapes are studied for range extension.
- **Cost, size, and weight.** Ferrite, Litz wire, and power electronics add cost and mass, especially for high-power EV systems. New magnetic materials and integrated coil–electronics designs may help.
- **Standardization and interoperability.** Different vendors and power levels must work with common infrastructure, including dynamic charging, bidirectional power flow, and heavy-duty vehicles.
- **Dynamic charging infrastructure.** Roadway embedding raises problems of cost, durability, grid integration, billing, and maintenance.
- **Wide-bandgap devices and higher frequency.** SiC and GaN devices support MHz-range operation and smaller components, but increase electromagnetic-interference concerns and require careful layout.
- **Safety and public acceptance.** Clear evidence, good shielding, and transparent compliance with exposure limits are required to maintain public confidence.
- **Intelligent control and multi-device charging.** Machine-learning-based tuning, simultaneous charging of several receivers, and integration with smart grids are active research topics.

XI. CONCLUSION

Wireless power transfer has moved from experimental demonstrations to a commercial technology used in billions of consumer devices and an increasing number of vehicles and medical systems. Near-field inductive and resonant systems are the most mature and give high efficiency at short and medium range, while capacitive systems offer a complementary option for particular environments. Far-field microwave, laser, and ultrasonic techniques extend the reach of WPT but face lower efficiency and stricter safety constraints. Efficiency is governed by the coupling and the quality factors of the coils, which defines the main design trade-offs.

Future progress will depend on better coil and compensation design, wide-bandgap power electronics, intelligent control, harmonized standards, and rigorous safety assessment. If these are achieved, WPT could provide a convenient and robust alternative to wired charging across consumer, industrial, medical, and transportation applications.

REFERENCES

[1] N. Tesla, “Apparatus for transmitting electrical energy,” U.S. Patent 1,119,732, Dec. 1, 1914.

[2] W. C. Brown, “The history of power transmission by radio waves,” *IEEE Trans. Microw. Theory Techn.*, vol. 32, no. 9, pp. 1230–1242, Sep. 1984.

[3] P. E. Glaser, “Power from the sun: Its future,” *Science*, vol. 162, no. 3856, pp. 857–861, 1968.

[4] G. A. Covic and J. T. Boys, “Inductive power transfer,” *Proc. IEEE*, vol. 101, no. 6, pp. 1276–1289, Jun. 2013.

[5] G. A. Covic and J. T. Boys, “Modern trends in inductive power transfer for transportation applications,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 1, no. 1, pp. 28–41, Mar. 2013.

[6] A. Kurs *et al.*, “Wireless power transfer via strongly coupled magnetic resonances,” *Science*, vol. 317, no. 5834, pp. 83–86, 2007.

[7] S. Y. R. Hui, W. Zhong, and C. K. Lee, “A critical review of recent progress in mid-range wireless power transfer,” *IEEE Trans. Power Electron.*, vol. 29, no. 9, pp. 4500–4511, Sep. 2014.

[8] Wireless Power Consortium, *Qi Wireless Power Transfer System Specification*.

[9] A. Sagar, A. Kashyap, M. A. Nasab, S. Padmanaban, M. Bertoluzzo, A. Kumar, and F. Blaabjerg, “A comprehensive review of the recent development of wireless power transfer technologies for electric vehicle charging systems,” *IEEE Access*, vol. 11, pp. 83703–83751, 2023, doi: 10.1109/ACCESS.2023.3300475.

[10] B. A. Rayan *et al.*, “Wireless power transfer in electric vehicles: A review on compensation topologies, coil structures, and safety aspects,” *Energies*, vol. 16, no. 7, Art. no. 3084, 2023, doi: 10.3390/en16073084.

[11] Z. Xue, W. Liu, C. Liu, and K. T. Chau, “Critical review of wireless charging technologies for electric vehicles,” *World Electr. Veh. J.*, vol. 16, no. 2, Art. no. 65, 2025.

[12] M. Rabih, M. Takruri, M. Al-Hattab *et al.*, “Wireless charging for electric vehicles: A survey and comprehensive guide,” *World Electr. Veh. J.*, vol. 15, no. 3, Art. no. 118, 2024.

[13] S. R. Khan, S. K. Pavuluri, G. Cummins, and M. P. Y. Desmulliez, “Wireless power transfer techniques for implantable medical devices: A review,” *Sensors*, vol. 20, no. 12, Art. no. 3487, 2020, doi: 10.3390/s20123487.

[14] J.-H. Kim, N. ul Hassan, S.-J. Lee, Y.-W. Jung, and S.-U. Shin, "A resonant current-mode wireless power transfer for implantable medical devices: An overview," *Biomed. Eng. Lett.*, vol. 12, no. 3, pp. 229–238, 2022, doi: 10.1007/s13534-022-00231-1.

[15] A. I. Mahmood, S. K. Gharghan, M. A. Eldosoky, and A. M. Soliman, "Near-field wireless power transfer used in biomedical implants: A comprehensive review," *IET Power Electron.*, 2022.

[16] S. Mahmud, A. Nezaratizadeh, A. B. Satriya, Y.-K. Yoon, J. S. Ho, and A. Khalifa, "Harnessing metamaterials for efficient wireless power transfer for implantable medical devices," *Bioelectron. Med.*, vol. 10, Art. no. 7, 2024, doi: 10.1186/s42234-023-00136-z.

[17] J. Lu, G. Zhu, and C. C. Mi, "Foreign object detection in wireless power transfer systems," *IEEE Trans. Ind. Appl.*, vol. 58, no. 1, pp. 1340–1354, Jan./Feb. 2022, doi: 10.1109/TIA.2021.3057603.

[18] B. Alam *et al.*, "A comprehensive review of foreign object detection methods in wireless power transfer for electric vehicles with conceptual analysis," *IEEE Access*, 2026, doi: 10.1109/ACCESS.2025.3617934.

[19] J. Zhang, S. Yao, L. Pan, Y. Liu, and C. Zhu, "A review of capacitive power transfer technology for electric vehicle applications," *Electronics*, vol. 12, no. 16, Art. no. 3534, 2023, doi: 10.3390/electronics12163534.

[20] H. Mahdi, R. Hattori, B. Hoff, A. Uezu, and K. Akiyoshi, "Design considerations of capacitive power transfer systems," *IEEE Access*, vol. 11, pp. 57806–57818, 2023, doi: 10.1109/ACCESS.2023.3283908.

[21] S. Agarwal, A. Bharadwaj, M. Kumar, A. Iodice, and D. Riccio, "Power without wires: Advancing kHz, MHz and microwave rectennas for wireless power transfer with a focus on India-based R&D," *Sensors*, vol. 26, no. 1, 2026, doi: 10.3390/s26010317.

[22] H. Liu, Y. Zhang, Y. Hu, Z. Tse, and J. Wu, "Laser power transmission and its application in laser-powered electrical motor drive: A review," *Power Electron. Drives*, 2021.

[23] S. Li and C. C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 1, pp. 4–17, Mar. 2015.

[24] P. Zhang, M. Saeedifard, O. C. Onar, Q. Yang, and C. Cai, "A field enhancement integration design featuring misalignment tolerance for wireless EV charging using LCL topology," *IEEE Trans. Power Electron.*, vol. 36, no. 4, pp. 3852–3867, Apr. 2021.

[25] C.-S. Wang, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 148–157, Feb. 2004.

[26] F. Lu, H. Zhang, and C. Mi, "A review on the recent development of capacitive wireless power transfer technology," *Energies*, vol. 10, no. 11, 2017.

[27] N. Shinohara, *Wireless Power Transfer via Radiowaves*. London, U.K.: ISTE/Wiley, 2014.

[28] SAE International, *Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology*, SAE J2954.

[29] ICNIRP, "Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)," *Health Phys.*, vol. 99, no. 6, pp. 818–836, 2010.

[30] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, pp. 483–524, 2020.