

Cableless Power Transmission System : Problems and Prospects

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Abstract

Cableless power transmission—the transfer of electrical energy through free space rather than a conductor—now spans commodity near-field chargers, standardized electric-vehicle (EV) charging, kilometre-scale microwave and laser beaming, and in-orbit tests of space-based solar power. Existing reviews usually treat one mechanism, quote peak efficiencies without their geometric conditions, and rarely connect performance to exposure regulation or cost. This paper develops a unified framework covering inductive, resonant, capacitive, microwave and laser links. A generalized three-layer system architecture (power, control–communication, safety) is defined. Near-field links are modeled from the Neumann integral to the closed-form bound $\eta_{\max} = F/(1 + \sqrt{(1 + F)^2})$ with $F = k^2 Q_1 Q_2$; far-field links through the Goubau relation $\eta_b = 1 - \exp(-\tau^2)$; optical links through Gaussian-beam propagation with Beer–Lambert extinction; and all mechanisms through a common end-to-end efficiency cascade and a leveled cost of transmission (LCOT). Simulations show that coupling decays approximately as d^{-3} , that 90% coil-to-coil efficiency at $Q = 300$ is limited to gaps of about 22 cm for a 20-cm-radius pad, that a 10-km, 5.8-GHz link needs apertures of about 36 m at each end for 98% beam capture, and that a well-engineered microwave chain delivers about 51% end to end. A 1-MW, 10-km island case study gives an LCOT roughly twice that of a submarine cable, offset by a much shorter repair time. The problems are classified as fundamental, engineering, regulatory and economic, and a staged prospect roadmap is proposed.

Keywords: Capacitive Power Transfer, Coupling Coefficient, Electromagnetic Exposure, Inductive Power Transfer, Laser Power Beaming, Levelized Cost, Microwave Power Transmission, Rectenna, Space-Based Solar Power, Wireless Power Transfer

1. Introduction

Every electrical power system built since the 1880s rests on the assumption that energy travels along a conductor. The conductor is cheap per ampere and its losses are well understood, yet it is also the most permission-intensive and failure-prone element of a supply scheme: an overhead line needs a right of way, a submarine cable needs a seabed route and a repair vessel, and an EV charging cable is the component that wears out, is vandalized or is tripped over. In each case the cost driver is the physical link rather than the energy it carries. Cableless power transmission, used here as a synonym for wireless power transfer (WPT), removes that link. Energy is converted at the source into a field or a beam, crosses air, water, tissue or vacuum, and is reconverted at the load. Tesla's attempt at Wardencliff failed for want of efficient high-frequency sources and of any theory of beam collection [1]. What has changed since about 2005 is the enabling technology: wide-bandgap switches that operate efficiently at hundreds of kilohertz, solid-state microwave amplifiers, litz-wire and ferrite structures with quality factors in the hundreds, digitally steered phased arrays and photovoltaic receivers tuned to monochromatic light [2,3]. The result is a field that is simultaneously mature

and immature. Near-field chargers are commodities and EV wireless charging is standardized [4,5], while in 2025 a laser link delivered more than 800 W over 8.6 km and in 2023 a satellite steered a microwave beam from orbit to a ground receiver [6,7]. A sound engineering assessment must therefore separate the regimes and quantify each, rather than treat “wireless power” as one technology. That separation and quantification are the purpose of this paper.

Recent surveys are rigorous but narrow, each concentrating on one mechanism or one application (Section II and Table I). None provides a single model set, efficiency convention and cost metric that allows a utility or consulting engineer to decide, for a given distance, power and constraint, whether a cableless link is feasible, at what efficiency, at what cost and against which exposure limits. The contributions of this paper are:

- a classification of cableless mechanisms by electromagnetic regime and a generalized three-layer system architecture (power, control–communication, safety) applicable to all of them;
- a consistent mathematical model, from the Neumann integral to the kQ efficiency bound in the near field and from

the Friis and Goubau relations to Gaussian-beam optics in the far field, closed by a common end-to-end efficiency cascade and an LCOT formulation;

- reproducible numerical results for coupling, efficiency, frequency splitting, misalignment, aperture sizing, atmospheric loss and exposure distance;
- a classified problem matrix and standards map, a staged prospect roadmap, and a like-for-like techno-economic case study against a submarine cable.

Section II reviews the state of the art. Section III presents the classification and system architecture, and Section IV the mathematical model. Section V gives the simulation results. Sections VI and VII analyze the problems and the standards framework, Section VIII the prospects and Section IX the case study. Section X discusses limitations and Section XI concludes.

2. State of the Art and Research Gap

2.1. Recent Literature (2021–2026)

Near-field research since 2021 has concentrated on EV applications. Tenllado et al. reviewed simultaneous wireless power and data transfer for EV charging Behnamfar et al.

surveyed power pulsation in dynamic charging Liang et al. analyzed a series-series dynamic system in the frequency domain and reported a power-triangle relation between frequency, phase shift and power and Bouanou et al. reviewed EV wireless charging technologies, challenges and solutions [8–11]. Receiver-side topologies integrated magnetic couplers that suppress power fluctuation in dynamic charging undersea power-and-data links and in-flight drone charging extend the field to new platforms [12–15]. Song et al. surveyed physical concepts such as metamaterials and parity-time symmetry that aim to relax the near-field distance limit and antenna technologies for RF harvesting and WPT were reviewed in [16,17]. Far-field research has been re-energized. Rodenbeck et al. set out the principles of microwave and millimeter-wave power beaming, proposed a benchmarking method and reviewed spectrum and safety regulation a follow-up demonstration delivered 1.6 kW at 1046 m from a 5.4-m X-band transmitter with 73% RF-to-DC conversion [3,18]. Signal-processing aspects of far-field WPT for networks were reviewed in and laser power transmission in [19,20]. Table I positions the present work against these recent reviews.

Ref.	Year	Primary scope	NF	FF	Reg.	Econ.
[16]	2021	Novel physical concepts for WPT	●	—	—	—
[3]	2021	Microwave/mmWave power beaming	—	●	●	—
[19]	2021	Far-field WPT for networks	—	●	—	—
[18]	2022	Terrestrial km-range beaming	—	●	●	—
[8]	2024	Power + data for EV charging	●	—	—	—
[9]	2024	Pulsation in dynamic EV WPT	●	—	—	—
[15]	2024	In-flight drone charging	●	—	—	—
[11]	2025	EV wireless charging review	●	—	—	—
This work	2026	Unified NF–FF model, problems, prospects	●	●	●	●

● primary focus; ● discussed; — not a stated focus, judged from each work's title and abstract. NF/FF: near/far field; Reg.: exposure and spectrum regulation; Econ.: techno-economics.

Table 1: Positioning of this Work Against Recent Reviews

2.2. Milestone Demonstrations

Table II lists the demonstrations that bound present performance. Two points follow. The near-field entries have converged: 85–95% at gaps of 10–25 cm is routine and standardized [21,22]. The far-field entries are records rather

than operating points, and their efficiencies usually refer to a single conversion stage; comparing them with end-to-end near-field figures is the most common error in the popular literature.

Year	Programme / organization	Mechanism	Power	Distance	Reported efficiency
1975	JPL Goldstone [1]	Microwave, 2.45 GHz	≈ 30 kW	1.54 km	> 80% (RF–DC stage)
2007	MIT [23]	Magnetic resonance, 9.9 MHz	60 W	2 m	≈ 40%
2009–13	KAIST OLEV [24]	Dynamic IPT, 20 kHz	100-kW class	≈ 20 cm	70–85% (by generation)
2021	NRL, Blossom Point [18]	Microwave, X band	1.6 kW	1046 m	73% (RF–DC)
2023	Caltech SSPD-1 / MAPLE [7], [25]	Microwave, LEO → ground	Detectable	≈ 550 km	Proof of beam steering
2025	DARPA POWER / PRAD [6]	Laser	> 800 W, 30 s	8.6 km	≈ 20% (receiver)
2024–26	Xidian “Sun Chasing” [26]	Microwave	up to 1.18 kW; 143 W to UAV	> 100 m; 30 m moving	≈ 87% beam capture

Table 2: Milestone Demonstrations in Cableless Power Transmission

2.3. Research Gap

Three gaps follow from Tables I and II. First, there is no common efficiency convention: near-field results are quoted coil-to-coil or DC-to-DC, far-field results per stage. Second, the technical literature is weakly coupled to exposure and

spectrum regulation, which in practice fix the minimum aperture and the exclusion zone [27,28]. Third, leveled-cost analysis is almost absent, although the conductor being replaced is 97–99% efficient and is displaced only because of its capital cost. Sections IV–H, VI–C and IX address these

gaps in turn.

3. Classification and System Architecture

3.1. Near-Field/Far-Field Boundary

The physically meaningful classification is by electromagnetic regime (Fig. 1). Within about $\lambda/2\pi$ of the source the field is reactive: energy is exchanged by coupling, decays rapidly

with distance, and is scarcely radiated. Beyond the Rayleigh distance $2D_a^2/\lambda$, where D_a is the aperture dimension, energy propagates as a wave that can be directed. The two regimes fail in opposite ways: a near-field link is efficient but short, a far-field link has no intrinsic range limit but pays for range in aperture area and is bounded by beam collection and exposure limits. Table III compares the mechanisms.

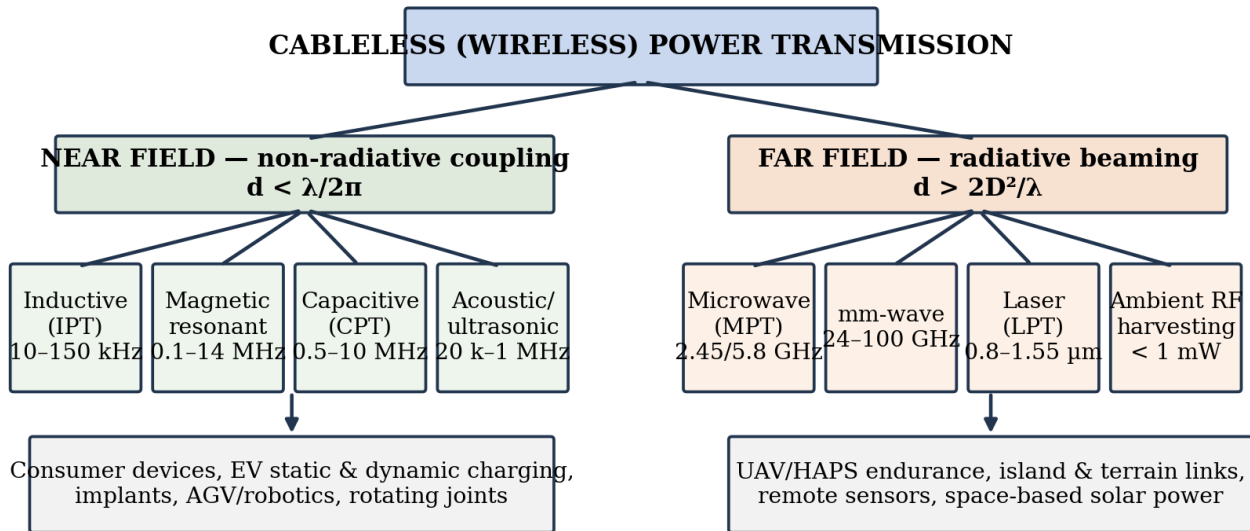


Figure 1: Taxonomy of Cable Less Power Transmission by Electromagnetic Regime, with Characteristic Operating Frequencies and Principal Application Domains

Attribute	Inductive (IPT)	Resonant (MRC)	Capacitive (CPT)	Microwave (MPT)	Laser (LPT)
Typical frequency	10–150 kHz	0.1–14 MHz	0.5–10 MHz	2.45 / 5.8 / 24 GHz	0.8–1.55 μm
Practical range	≤ 1 coil diameter	≤ 2 coil diameters	$\leq$ a few cm	m to 10^4 km	m to 10^3 km
Power level	1 W – 300 kW	1 W – 10 kW	1 W – 10 kW	1 W – GW (projected)	1 W – 10 kW
End-to-end efficiency	85–95%	50–90%	70–90%	10–55%	5–25%
Dominant loss	Coil ESR, core loss	Coil ESR, detuning	Dielectric loss	DC–RF and RF–DC	Laser wall-plug, PV
Safety concern	B-field, FOD heating	B-field	E-field	RF exposure, interference	Ocular and skin hazard
Maturity (TRL)	9	8	6	4–5	5

Table 3: Comparison of Cableless Power Transmission Technologies

3.2. Generalized System Architecture

Fig. 2 defines a three-layer architecture that applies to every mechanism. The power path comprises the source, a front-end converter (active rectifier with power-factor correction and a DC link), a high-frequency power stage (inverter, solid-state power amplifier or laser driver), the transmitting element, the medium, the receiving element, output conditioning and the load. Its efficiency is the product of the stage efficiencies, formalized in (29). The control-communication layer closes the loop between a primary controller, which sets frequency, phase, power and beam

direction, and a secondary controller, which reports state of charge, load demand and alignment. In near-field systems the link is typically Bluetooth Low Energy or Wi-Fi; in far-field systems a retro-directive pilot beacon both carries the request and steers the beam. The safety layer—foreign- and living-object detection, field monitoring, a pilot-loss interlock that stops the beam within milliseconds, thermal and insulation supervision, and authenticated commands—acts on both controllers. The safety layer has no counterpart in a cabled system and is a permanent cost of going cableless.

$$\text{POWER PATH: } \eta_{\text{sys}} = \eta_{\text{conv}} \eta_{\text{osc}} \eta_{\text{link}} \eta_{\text{rec}} \eta_{\text{cond}}$$

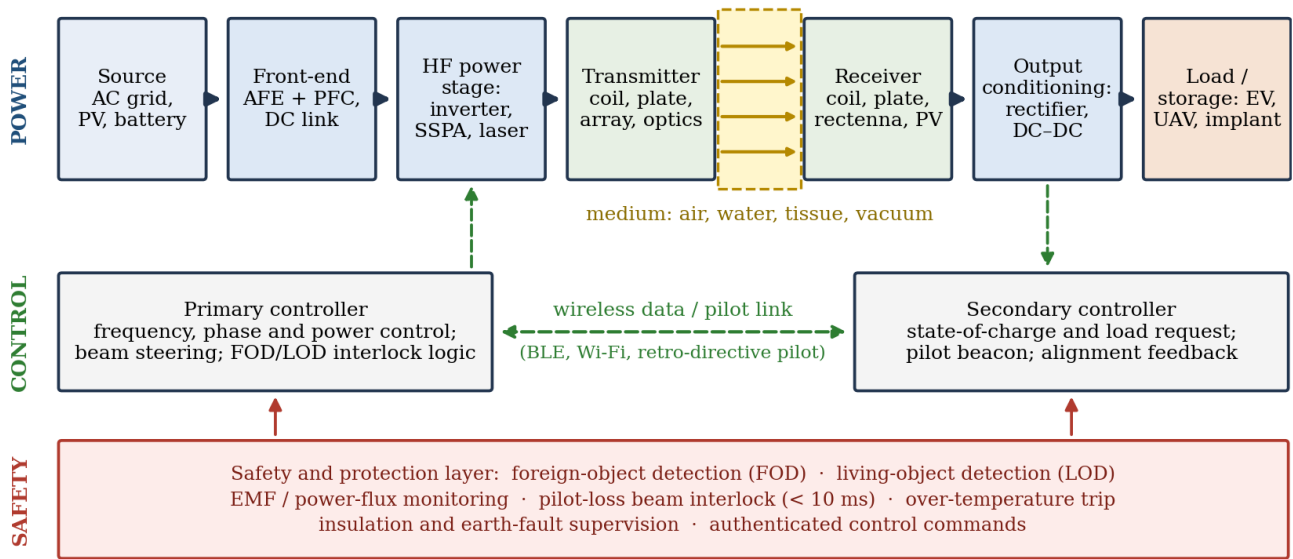


Figure 2: Generalized Three-Layer Architecture of a Cableless Power Transmission System: Power Path (Top), Control-Communication Layer (Middle) and Safety and Protection Layer (Bottom)

3.3. Near-Field Architecture and Compensation

Fig. 3 shows the series-series (SS) compensated equivalent circuit of an inductive link. The compensating capacitors C1 and C2 cancel the large leakage reactance of the loosely coupled transformer; without them the inverter volt-ampere rating would be many times the transferred power [21].

Table IV compares the common topologies [29]. SS is the most widely used for vehicle charging because its resonant frequency is independent of coupling and load; the double-sided LCC network decouples resonance from coupling entirely and gives a constant-current output, and is preferred for high-power and dynamic charging [30].

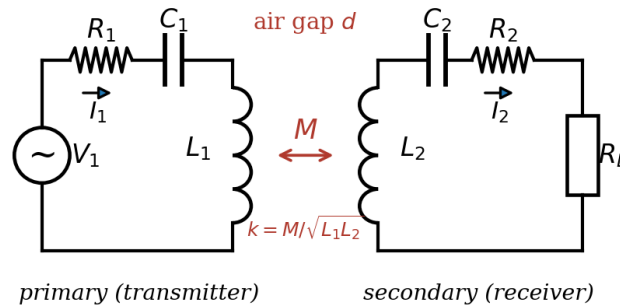


Figure 3: Series-Series Compensated Equivalent Circuit of a Two-Coil Inductive Link; R1 and R2 are the Coil Equivalent Series Resistances and RL the Equivalent Load

Topology	f_0 vs. k	f_0 vs. load	Output	Typical use
SS	Independent	Independent	CV	EV static charging
SP	Dependent	Independent	CV	Low-power devices
PS	Dependent	Dependent	CC	Current-fed industrial
PP	Dependent	Dependent	CC	Legacy industrial
LCC-S	Independent	Independent	CV	Medium-power charging
LCC-LCC	Independent	Independent	CC	High-power, dynamic

CV: constant voltage; CC: constant current.

Table 4: Comparison of Resonant Compensation Topologies

3.4. Far-Field Architecture

A far-field link (Fig. 4) comprises a DC-to-RF or DC-to-optical converter, a transmitting aperture with beam forming and pointing control, the propagation path, a receiving aperture

and a rectenna or photovoltaic converter. The transmitting aperture is not merely a component but a capital asset whose area is fixed by the link budget (Section IV-F). A retro-directive pilot loop is always required, both to maintain

pointing and to provide the fail-safe interlock, and the receiving site must be fenced so that the flux density at the boundary meets the public exposure limit.

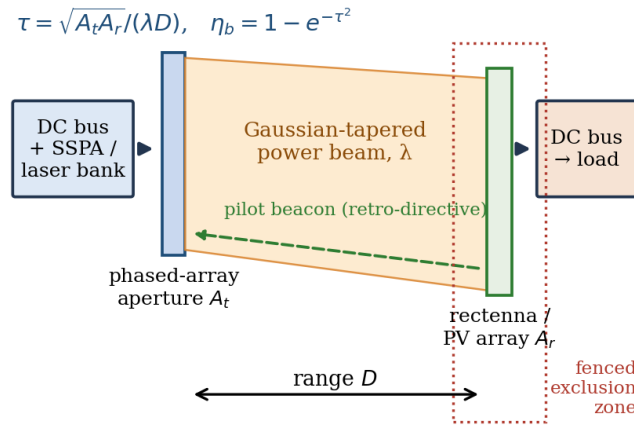


Figure 4: Far-Field (Microwave or Laser) Link Architecture with Retro-Directive Pilot Beacon, Receiving Array and Fenced Exclusion Zone; τ is the Goubau Aperture Parameter

4. Mathematical Model

4.1. Mutual Inductance and Coupling Coefficient

Near-field magnetic transfer is governed by the mutual inductance between the transmitting and receiving circuits, given by the Neumann integral [31].

$$M = (\mu_0/4\pi) \oint \oint (dl_1 \cdot dl_2) / |r_{12}| \quad (1)$$

and normalized by the coupling coefficient

$$k = M / \sqrt{(L_1 L_2)}, \quad 0 \leq k \leq 1. \quad (2)$$

For coaxial circular loops of radii r_1, r_2 at axial separation d , Maxwell's closed form is

$$M = \mu_0 \sqrt{(r_1 r_2)} [(2/\kappa - \kappa)K(\kappa) - (2/\kappa)E(\kappa)] \quad (3)$$

$$\kappa^2 = 4r_1 r_2 / [(r_1 + r_2)^2 + d^2] \quad (4)$$

where K and E are complete elliptic integrals of the first and second kind. For large d compared with the radii, (3) reduces to

$$M \approx \mu_0 \pi r_1^2 r_2^2 / [2(r_1^2 + d^2)^{3/2}] \Rightarrow k \propto d^{-3} \quad (5)$$

which is the governing scaling law of near-field transfer. The self-inductance of a single-turn loop of wire radius a is

$$L = \mu_0 r [\ln(8r/a) - 2]. \quad (6)$$

Because k is a geometric ratio, it is independent of the number of turns for windings of fixed shape; turns affect L and Q but not k . This separates the coupling and loss analyses.

4.2. Two-Port Model and Efficiency Bound

For the SS circuit of Fig. 3, Kirchhoff's voltage law gives

$$V_1 = Z_1 I_1 + j\omega M I_2, \quad 0 = j\omega M I_1 + Z_2 I_2 \quad (7)$$

$$Z_1 = R_1 + jX_1, \quad Z_2 = R_2 + R_L + jX_2 \quad (8)$$

with $X_i = \omega L_i - 1/(\omega C_i)$. The secondary appears at the primary as the reflected impedance

$$Z_{ref} = \omega^2 M^2 / Z_2. \quad (9)$$

At $\omega_0 = 1/\sqrt{(L_1 C_1)} = 1/\sqrt{(L_2 C_2)}$ both reactances vanish and the coil-to-coil efficiency is

$$\eta = \omega^2 M^2 R_L / [R_1(R_2 + R_L)^2 + \omega^2 M^2 (R_2 + R_L)]. \quad (10)$$

Setting $\partial\eta/\partial R_L = 0$ gives the optimum load and, on substitution, the efficiency bound [32,33].

$$R_{L,opt} = R_2 \sqrt{(1 + k^2 Q_1 Q_2)} \quad (11)$$

$$\eta_{max} = k^2 Q_1 Q_2 / [1 + \sqrt{(1 + k^2 Q_1 Q_2)}]^2 \quad (12)$$

$$Q_i = \omega L_i / R_i, \quad kQ = k \sqrt{(Q_1 Q_2)}. \quad (13)$$

Equation (12) shows that geometry, material and frequency enter only through the figure of merit kQ . For large kQ , $\eta_{max} \approx 1 - 2/(kQ)$: the shortfall from unity is about twice the reciprocal of the figure of merit. Since k falls as d^{-3} and Q cannot practically exceed the low hundreds, the achievable gap is physically bounded.

4.3. Frequency Splitting

For identical resonators the poles of (7) lie at

$$\omega_{\pm} = \omega_0 / \sqrt{(1 \pm k)} \quad (14)$$

and bifurcation appears above the critical coupling

$$k_c \approx 1/\sqrt{(Q_1 Q_2)} \Leftrightarrow kQ > 1. \quad (15)$$

Above k_c the delivered power at ω_0 becomes a local minimum. A fixed-frequency system must therefore stay at or below critical coupling over its whole gap and alignment range, or use frequency tracking, impedance tuning or a coupling-independent topology.

4.4. Lateral Misalignment

For equal loops in parallel planes separated by d with axes offset by Δ , (1) becomes

$$M(\Delta) = (\mu_0 r^2 / 4\pi) \iint \cos(\varphi_1 - \varphi_2) / \rho \, d\varphi_1 d\varphi_2 \quad (16)$$

$$\rho^2 = (r \cos \varphi_1 - \Delta - r \cos \varphi_2)^2 + r^2 (\sin \varphi_1 - \sin \varphi_2)^2 + d^2 \quad (17)$$

with both angles integrated over $[0, 2\pi]$. The integral has no elementary closed form and is evaluated numerically in Section V-D.

4.5. Capacitive Power Transfer

A capacitive link transfers energy by displacement current between electrode pairs. For plate area A , separation d and relative permittivity ϵ_r , and electrode voltages V_1, V_2 with phase difference δ [34].

$$C_M = \epsilon_0 \epsilon_r A / d \quad (18)$$

$$P = \omega C_M V_1 V_2 \sin \delta. \quad (19)$$

Because C_M is of the order of picofarads for practical plates, (19) requires megahertz operation and high electrode voltages, which produce strong electric fields that are harder to shield than magnetic fields. Capacitive transfer therefore suits millimetre gaps in rotating machines, robotic joints and board-level links rather than gaps of more than a few centimetres.

4.6. Far-Field Microwave Transfer

Beyond the Rayleigh distance

$$d_F = 2D_a^2 / \lambda \quad (20)$$

the Friis equation and the aperture gain apply:

$$P_r = P_t G_t G_r (\lambda / 4\pi D)^2 \quad (21)$$

$$G = 4\pi A \eta_{ap} / \lambda^2. \quad (22)$$

Equation (21) assumes the receiver intercepts a small fraction of the beam and is therefore misleading for power links. The correct aperture-to-aperture relation for optimally tapered illumination is due to Goubau [35,36]:

$$\tau = \sqrt{(A_r A_t) / (\lambda D)} \quad (23)$$

$$\eta_b = 1 - \exp(-\tau^2). \quad (24)$$

Equation (24) is the governing economic relation of beamed power: at fixed efficiency, doubling the range requires doubling the aperture area at each end or halving the wavelength. The rectenna converts the captured power to DC with an efficiency that depends strongly on incident flux density, so the illumination taper must be traded against average conversion efficiency. For a Gaussian beam of waist w at the receiving plane,

$$S(\rho) = S_0 \exp(-2\rho^2/w^2), \quad S_0 = 2P_t \eta_b / (\pi w^2) \quad (25)$$

and (25) evaluated at the site boundary and in the sidelobes is what must meet the exposure limits of Section VI-C.

4.7. Optical (Laser) Transfer

The far-field divergence half-angle of a beam of waist w_0 and quality factor M^2 is

$$\theta = M^2 \lambda / (\pi w_0) \quad (26)$$

so (23) is satisfied with apertures of centimetres rather than tens of metres, which is the decisive advantage of optical transfer [20]. The penalty is atmospheric extinction, described by the Beer–Lambert law, and the overall optical efficiency:

$$P_r = P_t \exp(-\alpha L), \quad \alpha = \alpha_{abs} + \alpha_{sca} \quad (27)$$

$$\eta_{opt} = \eta_{las} \cdot \exp(-\alpha L) \cdot \eta_{coll} \cdot \eta_{pv}. \quad (28)$$

With diode-laser wall-plug efficiencies of 0.3–0.5 and receiver conversion of about 0.2 in the 2025 field record the product rarely exceeds 0.25 in practice [6].

4.8. End-to-End Efficiency and Cost

To compare all mechanisms on one basis, the end-to-end efficiency along the power path of Fig. 2 is defined as

$$\eta_{sys} = \eta_{conv} \eta_{osc} \eta_{link} \eta_{rec} \eta_{cond} \quad (29)$$

where η_{link} includes coupling or beam collection and propagation. For delivered power P_d and capacity factor CF, the annual delivered energy, the levelized cost of transmission and the capital recovery factor are

$$E_d = 8760 \cdot P_d \cdot CF \quad (30)$$

$$LCOT = (CAPEX \cdot CRF + OPEX + c_e E_{loss}) / E_d \quad (31)$$

$$CRF = i(1 + i)^n / [(1 + i)^n - 1] \quad (32)$$

where c_e is the value of lost energy, $E_{loss} = E_d(1/\eta_{sys} - 1)$, i the discount rate and n the economic life. For a three-phase line of resistance R per phase the conventional benchmark loss is

$$P_{loss} = P^2 R / (V^2 \cos^2 \varphi). \quad (33)$$

Equating the LCOT of a cable (c) and a cableless link (w) delivering the same service gives the break-even condition

$$\Delta CAPEX \cdot CRF + \Delta OPEX > c_e \Delta E_{loss} \quad (34)$$

with $\Delta CAPEX = CAPEX_c - CAPEX_w$, $\Delta OPEX = OPEX_c - OPEX_w$ and $\Delta E_{loss} = E_{loss,w} - E_{loss,c}$. A cableless link wins not when it becomes efficient, but when the conductor route becomes expensive enough to pay for the extra loss.

5. Simulation Results

5.1. Setup

The models were implemented in Python using SciPy elliptic integrals for (3) and a 500×500 -point quadrature for (16); refining the grid to 1200×1200 changed the result by less than 0.1%. Table V lists the near-field reference case, which approximates a light-duty vehicle pad. Efficiencies in Sections V-B to V-D are coil-to-coil at the optimum load (11) and exclude converter losses; the full chain is treated in Section V-F.

Parameter	Value	Basis
Coil radius r	0.20 m	Light-duty EV pad
Wire radius a (equiv.)	1.0 mm	Litz bundle
L , single turn	1.35 μ H	From (6)
Frequency f_0	85 kHz	SAE J2954 band [5]
$Q_1 = Q_2$	100–800	Litz + ferrite
Gap d	0.05–0.80 m	Ground clearance
Offset Δ	0–0.40 m	Parking tolerance
Load R_L	$R_{L,opt}$, (11)	Maximum efficiency

Table 5: Near-Field Reference Case

5.2. Coupling Versus Gap

Fig. 5 shows k from (3) and (6) for three radii. On the logarithmic axis the d^{-3} asymptote of (5) is visible. The practical inductive band, $k = 0.1$ – 0.35 , is reached only for gaps below about three quarters of the coil radius; the curve

shifts in direct proportion to the radius, which is why the only reliable way to widen the gap is a larger pad; and at a gap of two radii k is of order 0.01, beyond any realistic kQ requirement.

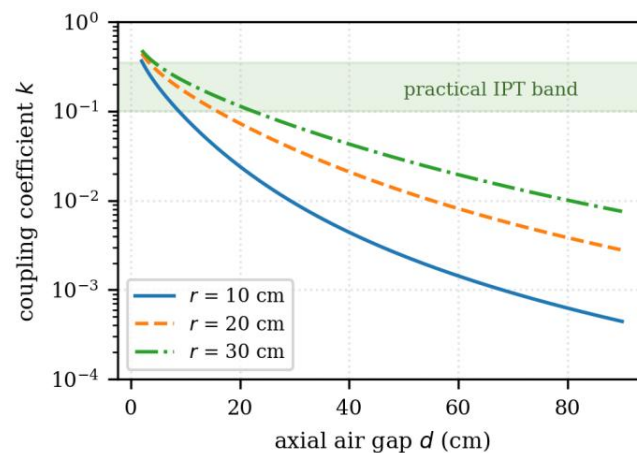


Figure 5: Coupling Coefficient of Coaxial Circular Coils Versus Axial Gap for Three Coil Radii, From (3) and (6). Shaded: Practical Inductive Power Transfer Band

5.3. Efficiency Bound and Gap

Fig. 6 plots (12). The curve is universal for two-element links: $kQ = 1$ caps efficiency at 17.2%, $kQ = 10$ at 81.9% and $kQ = 100$ at 98.0%. Combining Figs. 5 and 6 yields Fig. 7 and Table VI for the reference pad. The 85% grid-to-vehicle target of

SAE J2954 implies roughly 90% coil-to-coil once converter losses are included; at $Q = 300$ this is met up to a gap of about 22 cm and at $Q = 800$ up to about 30 cm, consistent with the ground-clearance classes of the standard.

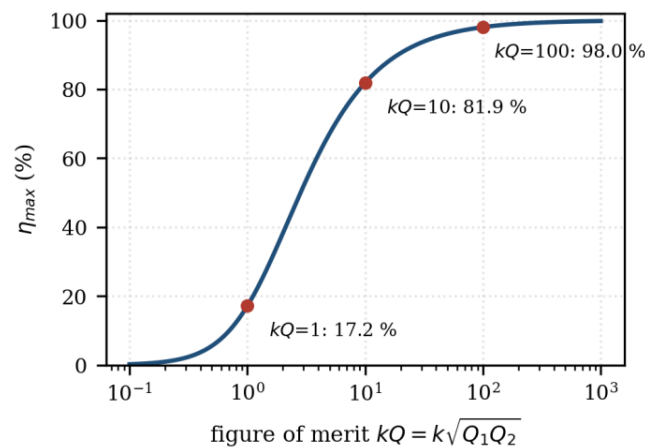


Figure 6: Maximum Coil-to-Coil Efficiency Versus The Figure of Merit kQ , from (12)

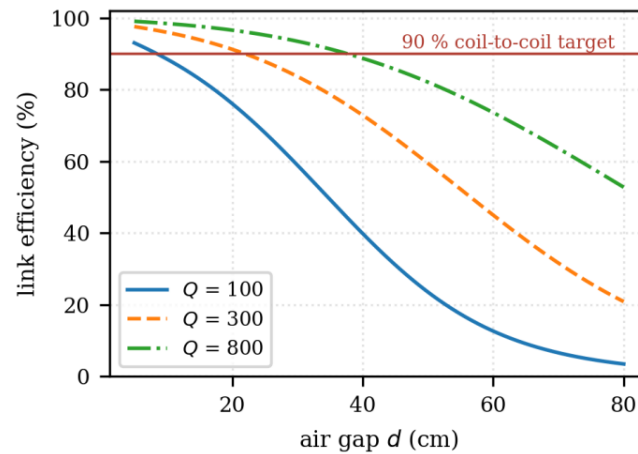


Figure 7: Coil-to-Coil Efficiency Versus Gap for a 20-cm-Radius Pair at Optimum Load, for Three Quality Factors

d (cm)	M (μH)	k	kQ	$\eta_{\max}$ (%)
5	0.378	0.279	83.8	97.6
10	0.223	0.165	49.4	96.0
15	0.145	0.107	32.1	94.0
20	0.099	0.073	21.9	91.3
25	0.070	0.052	15.5	87.9
30	0.051	0.037	11.2	83.7
40	0.028	0.021	6.30	72.9
50	0.017	0.013	3.80	59.5

M is for single-turn loops; k and $\eta_{\max}$ are independent of turn count.

Table 6: Near-Field Performance Versus Gap (R = 0.20 M, Q = 300)

Doubling the gap from 15 to 30 cm divides M by 2.8 and lowers the bound from 94.0% to 83.7%; at 50 cm it falls below 60%, where primary-coil heating, not energy cost, becomes the binding constraint.

5.4. Frequency Splitting and Misalignment

Fig. 8 shows normalized delivered power versus frequency

at Q = 20, for which (15) gives $k_c = 0.05$. The over-coupled case ($k = 0.15$) peaks at 79.3 and 92.2 kHz as predicted by (14), with a dip at the nominal 85 kHz. A fixed-frequency controller would therefore deliver less power at close range than at medium range, a counter-intuitive behavior that is a frequent cause of misdiagnosed faults.

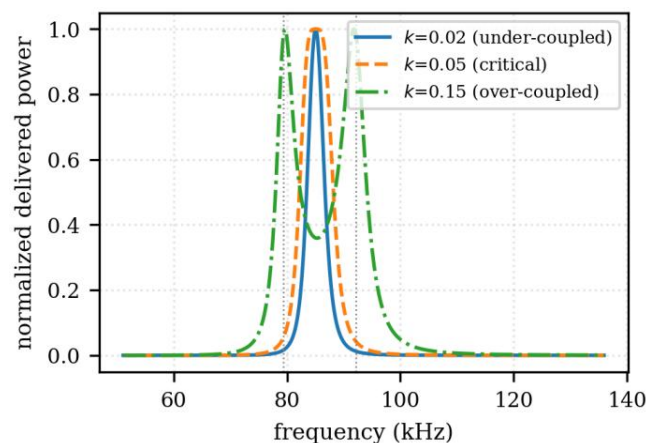


Figure 8: Frequency Splitting of an SS Link at Q = 20 for Under-, Critically and Over-Coupled Conditions; Dotted Lines Mark $\omega_{\pm}$ from (14) for $k = 0.15$

Fig. 9 evaluates (16)–(17) for the reference pad at a 15-cm gap ($k = 0.107$ aligned). Coupling decays smoothly: it retains 89% of its aligned value at the ± 7.5 -cm tolerance of unaided parking and 50% at $\Delta \approx 0.95r$, and crosses zero at $\Delta \approx 1.9r$ (37.5 cm), beyond which it reverses sign. With Q = 300, efficiency stays at or above 90% up to $\Delta \approx 0.83r$

(16.5 cm) and falls to 64% at $1.5r$. For circular pads at this gap-to-radius ratio the tolerance is therefore wider than often assumed, but the collapse toward the null is abrupt; double-D and bipolar pads are used to widen the tolerance further and to lower leakage fields [11,21].

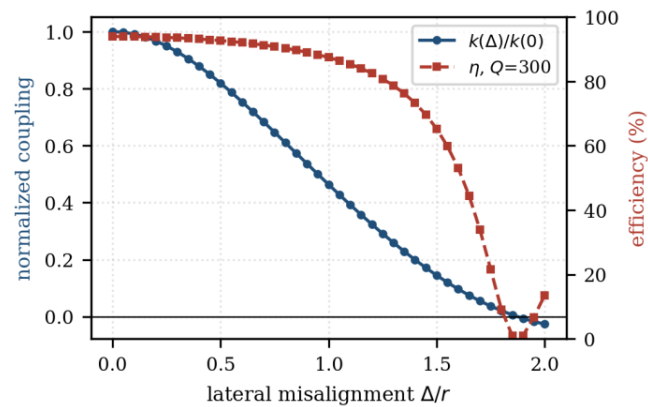


Figure 9: Normalized Coupling and Efficiency Versus Lateral Misalignment for a 20-cm-Radius Pair at a 15-cm Gap, From (16)–(17)

5.5. Far-Field Aperture and Propagation

Fig. 10 plots (24). Collection reaches 63% at $\tau = 1$ and 98% at $\tau = 2$, with negligible gain beyond 2.5. Since aperture area scales as τ^2 , going from $\tau = 1$ to 2 costs four times the area

for 35 percentage points of efficiency—the central capital decision in beamed-power design. Table VII evaluates the equal-aperture requirement at $\tau = 2$.

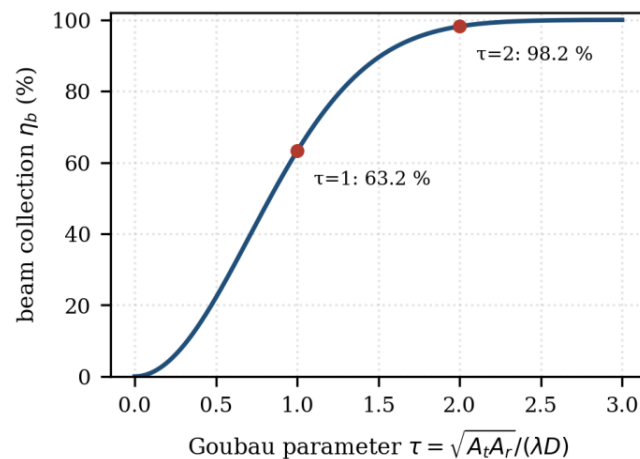


Figure 10: Beam Collection Efficiency Versus the Goubau Parameter τ , from (24)

Link	f (GHz)	D	Area each end	Diameter
Industrial	24	1 km	25 m ²	5.6 m
Terrestrial	2.45	10 km	2449 m ²	55.8 m
Terrestrial	5.8	10 km	1034 m ²	36.3 m
Island	5.8	100 km	1.03×10 ⁴ m ²	115 m
SBSP (GEO)	5.8	36 000 km	3.72×10 ⁶ m ²	2.18 km

Table 7: Aperture Requirement for 98% Collection ($T = 2$)

The 2.2-km aperture needed from geostationary orbit is why space-based solar power has not been built; current concepts accept η_b well below 0.98 and rectenna sites 5–10 km across to relax the space segment. Fig. 11 shows why the frequency cannot simply be raised: clear-air attenuation is

about 0.01 dB/km at 2.45 and 5.8 GHz, rises through the 22-GHz water-vapor line and reaches about 15 dB/km at the 60-GHz oxygen resonance [37]. Windows near 35 and 94 GHz suit short, dense links, but rain fade there reduces availability and thus the capacity factor in (30).

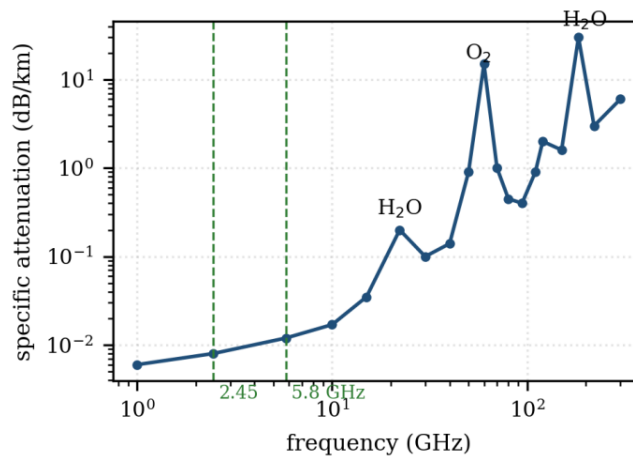


Figure 11: Indicative Clear-Air Specific Attenuation at Sea Level Versus Frequency, After ITU-R P.676, with the 2.45- and 5.8-GHz ISM Bands Marked

5.6. End-to-End Efficiency Cascade

Fig. 12 applies (29) to a 5.8-GHz link designed for $\tau = 2$, with a GaN solid-state amplifier at 72% DC-to-RF, 90% net beam capture (98% from (24) less taper, pointing and propagation losses), an 82% rectenna and 96% output conditioning.

The result is 51.0%, against 97–99% for a conductor over the same distance. By (34) this is not decisive in itself, but it establishes beamed power as an option for where a conductor cannot reasonably go, not as a substitute for bulk transmission.

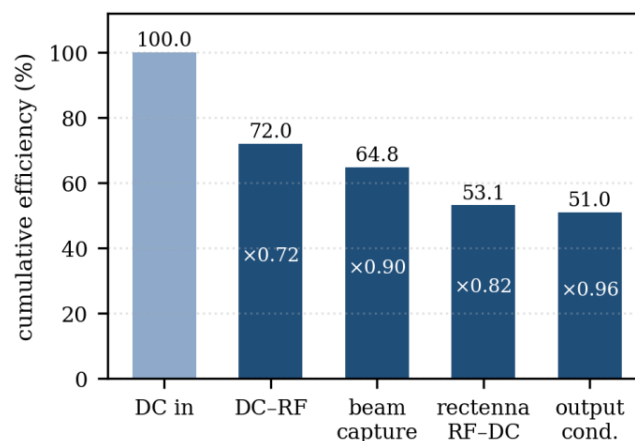


Figure 12: Cumulative end-to-end Efficiency of a 5.8-GHz Microwave Power Link; White Labels Give Each Stage Efficiency

6. Problems and Technical Barriers

The obstacles are classified here as fundamental (set by the physics of Section IV and not removable by technology), engineering, regulatory and economic (contingent on components, rules and markets).

6.1. Fundamental Limits

• **Distance-Efficiency Scaling:** The d^{-3} decay of (5) and the aperture law (24) together leave a range gap between about 1 m and 1 km in which neither regime is attractive: too far for coupling, too short to justify large apertures. Most proposals that fail technical review occupy this gap.

• **Aperture-Wavelength Trade:** The aperture product is fixed by (23). A smaller aperture requires a shorter wavelength, which imports atmospheric loss (Fig. 11), tighter pointing and higher component cost; no configuration

escapes this trade.

• **Frequency Splitting:** The bifurcation of (14)–(15) prevents fixed-frequency operation across a wide coupling range without tracking, tuning or a coupling-independent topology [10].

6.2. Engineering Limits

• **Power Conversion:** Every cableless link adds at least two conversion stages. At 85 kHz, SiC inverters reach 97–98%, but switching loss grows with frequency, so megahertz resonant and capacitive links need zero-voltage-switching class-E or class- Φ stages that are sensitive to load variation.

• **Magnetics and Thermal Management:** Ferrite loss rises steeply with flux density and temperature, creating positive thermal feedback. Removing a few hundred watts from a pad buried in a road surface is a harder thermal problem than

it appears, and power pulsation in dynamic charging adds cyclic stress [9], [13].

- **Foreign- and Living-Object Detection:** Metal debris in a high-power field can exceed several hundred degrees Celsius within seconds, and animals may enter the field region. Detection must be fast, reliable and immune to false triggering by the vehicle structure; no cabled system bears this cost.

- **Pointing and Interlock:** A beam must be steered to a small fraction of its beamwidth and stopped within milliseconds on pilot loss or obstruction. The retro-directive pilot is elegant but becomes a single point of failure and an attack surface.

- **Weather and Dust:** Optical links are interrupted by fog,

cloud and dust. In Gulf climates airborne dust and high humidity are both significant, so a laser link must carry a large margin or accept lower availability; microwave links at the ISM bands are essentially weather-independent.

6.3. Exposure and Interference

Human exposure is often the constraint that fixes the physical layout. Table VIII lists the relevant ICNIRP and IEEE C95.1 level [27,28,38]. For an 85-kHz link the binding quantity is magnetic flux density (27 μT public), which near a 50-kW pad requires shielding or active cancellation; above 2 GHz it is power flux density, 10 W/m² for the public and 50 W/m² occupationally.

Quantity	Band	Public	Occupational
B (rms)	3 kHz–10 MHz	27 μT	100 μT
E (rms)	3 kHz–10 MHz	83 V/m	170 V/m
S	2–300 GHz	10 W/m ²	50 W/m ²
Whole-body SAR	100 kHz–6 GHz	0.08 W/kg	0.4 W/kg
Local SAR (head/trunk)	100 kHz–6 GHz	2 W/kg	10 W/kg
Laser, 1.55 μm	Optical	Class 1 AEL	Controlled area

Sources: ICNIRP 2010 (B, E), ICNIRP 2020 (S, SAR), IEC 60825-1 (laser).

Table 8: Exposure Reference Levels Relevant to Cableless Power

The specific absorption rate is $\text{SAR} = \sigma |E|^2 / \rho_m$, with σ and ρ_m the tissue conductivity and density. To size the exclusion zone of a microwave transmitter, a fraction ε of the transmitted power is assumed to escape the main beam (spill-over, sidelobes, scattering) and spread over a hemisphere:

$$S_{\text{stray}}(r) = \varepsilon P_t / (2\pi r^2) \quad (35)$$

$$r_{\text{ex}} = \sqrt{[\varepsilon P_t / (2\pi S_{\text{lim}})]}. \quad (36)$$

With a pessimistic $\varepsilon = 10\%$ and $S_{\text{lim}} = 10 \text{ W/m}^2$, (36) gives $r_{\text{ex}} \approx 12.6 \text{ m}$ for 100 kW and 40 m for 1 MW (Fig. 13). The main beam, far above the public level at its centre, must be wholly inside the fenced receiving site.

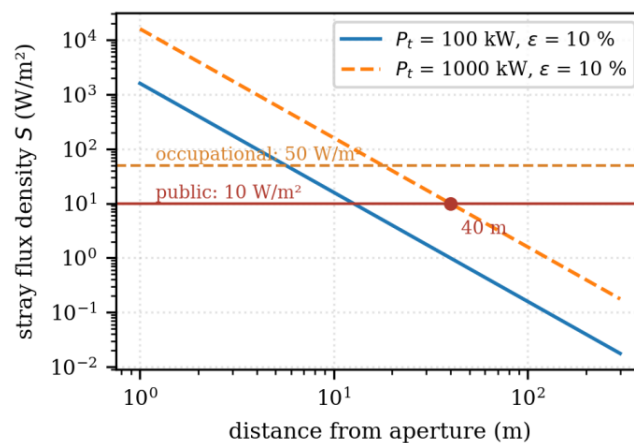


Figure 13: Stray Flux Density Versus Distance for 100-kW and 1-MW Transmitters with a 10% stray Fraction, From (35), Against ICNIRP 2020 Reference Levels

Electromagnetic compatibility is a separate constraint. Inverter harmonics must satisfy CISPR 11 and a beam of hundreds of kilowatts in the 5.8-GHz ISM band is an extreme interferer for every other user of that band [39].

6.4. Regulatory Limits

The ITU Radio Regulations allocate spectrum to services defined by information transfer; WPT in the ISM bands operates on a non-protected, non-interference basis [40].

That is acceptable for a phone charger but not for an asset carrying firm capacity, and until a primary allocation exists no utility-scale beamed link can obtain the operating certainty that project finance requires.

6.5. Economic Limits

Cableless transmission substitutes capital in converters, apertures and land for capital in conductors and rights of way, while multiplying energy loss by a factor of 2 to 50.

Fig. 14 places indicative bulk-scale LCOT values on one axis: overhead lines cost a few US dollars per megawatt-hour, submarine HVDC tens, and beamed links roughly one

to two orders of magnitude more. The case is unfavorable for bulk transfer and favorable only where the conductor is impossible, prohibited or disproportionately expensive.

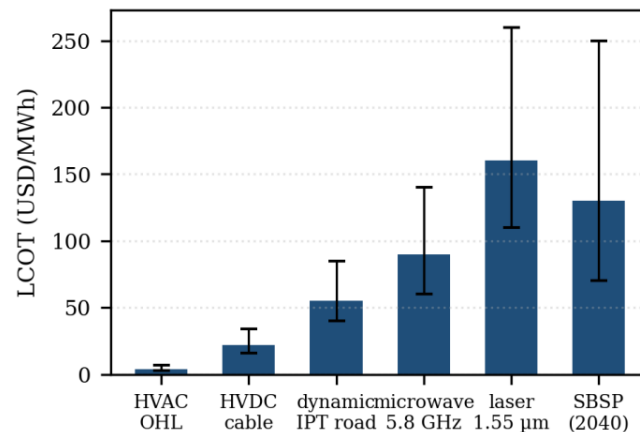


Figure 14: Indicative Levelized Cost of Transmission for Bulk-Scale (≥ 100 MW, 100-km class) Links, with Ranges. Order-of-Magnitude Values for Comparison Only

6.6. Summary

Table IX consolidates the analysis into a problem–cause–impact–mitigation matrix that can serve as a design-review checklist.

Problem	Underlying cause	Impact	Mitigation	Class
Efficiency collapse with gap	$k \propto d^{-3}$, (5)	Range limited to ≈ 1 coil diameter	Larger pads, higher Q, relay resonators	Fundamental
Large apertures	Goubau relation (24)	Capital dominates far-field schemes	Shorter λ , accept lower η_b , tapered illumination	Fundamental
Frequency splitting	Over-coupling, $kQ > 1$	Power dip at nominal f_0	Frequency tracking, LCC–LCC, bounded k range	Fundamental
Misalignment null	Flux cancellation, (16)	Collapse beyond $\approx 1.5r$	DD/bipolar pads, alignment guidance	Engineering
Switching loss	Hard switching at high f	Lower η , thermal stress	SiC/GaN, ZVS, soft switching	Engineering
Core and winding heating	Ferrite loss vs. temperature	Derating, ageing	Litz wire, thermal design, cooling	Engineering
Foreign-object heating	Eddy currents in debris	Fire and burn hazard	FOD sensing, power interlock	Engineering
Living-object intrusion	Unguarded field region	Exposure non-compliance	LOD radar/capacitive sensing	Engineering
Pointing and beam loss	Steering error	Loss, stray illumination	Retro-directive array, pilot interlock	Engineering
Weather interruption	Scattering, (27)	Optical availability loss	Microwave fallback, margin, diversity	Engineering
Exposure compliance	ICNIRP / IEEE C95.1	Exclusion zones, shielding cost	Shielding, cancellation coils, siting, (36)	Regulatory
Spectrum interference	No primary allocation	Operating uncertainty	ITU-R allocation, filtering	Regulatory
Fragmented standards	Divergent national practice	No interoperability or finance	IEC/SAE/IEEE harmonization	Institutional
High levelized cost	Capital plus loss	Uncompetitive for bulk power	Target conductor-impossible niches	Economic
Land take	Aperture area	Siting and consent risk	Co-use (agriculture, parking), offshore sites	Economic
Cyber-physical security	Control and pilot links	Spoofing, loss of link	Authenticated pilot, fail-safe shutdown	Institutional

Table 9: Problem–Cause–Impact–Mitigation Matrix

7. Standards and Regulatory Framework

Because exposure limits fix field strength and hence geometry, compliance is a design input rather than a verification step. Table X lists the principal instruments. The near field is comprehensively standardized, including, since

2024, a publicly available specification for dynamic charging the far field has no product standard, only the exposure guidelines and radio regulations written for other purposes [41]. A technology without a product standard cannot readily be certified, insured or financed.

Instrument	Scope
IEC 61980-1:2020 [4]	EV WPT systems, general requirements
IEC PAS 61980-5:2024 [41]	Dynamic (in-motion) EV WPT, interoperability and safety
SAE J2954 [5]	Light-duty EV wireless charging, 85-kHz band, alignment
IEC 63028:2017 [42]	Resonant WPT (AirFuel), 6.78 MHz
ICNIRP 2010, 2020 [27], [38]	EMF exposure, 1 Hz–300 GHz
IEEE Std C95.1-2019 [28]	RF exposure safety levels, 0 Hz–300 GHz
CISPR 11 [39]	ISM equipment emission limits
ITU-R SM.2392 [40]	WPT via RF beam: applications, spectrum
IEC 60825-1:2014 [43]	Laser product safety classes

Table 10: Principal Standards and Regulatory Instruments

For projects in the United Arab Emirates, spectrum and equipment type approval fall under the Telecommunications and Digital Government Regulatory Authority, and the electrical installation under the relevant emirate authority. With no local WPT-specific standard, the practical route is to design near-field vehicle systems to IEC 61980 and SAE J2954 and to demonstrate ICNIRP compliance by measurement.

8. Prospects

Fig. 15 maps the principal applications onto the technology readiness scale as of 2026, and Table XI arranges them by planning horizon.

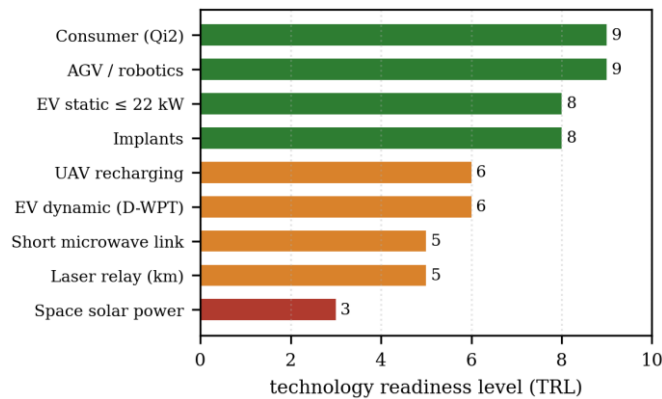


Figure 15: Technology Readiness of Cableless Power Applications as Assessed in 2026

8.1. Short Term (0–5 Years)

Near-field transfer below 100 kW is commercially settled in consumer devices, automated guided vehicles, implants and static EV charging. Growth will come from standard convergence, integration of inverter and coil, extension of power classes to buses and trucks, and pairing wireless charging with vehicle-to-grid operation, where removing the plug removes the last friction from demand response. Sealed inductive couplers in hazardous areas eliminate a connector and thus an ignition source.

8.2. Medium Term (5–15 Years)

Dynamic in-road charging is the most consequential medium-term prospect because it permits smaller vehicle batteries; its obstacles are civil and institutional (installation cost, segment control, cost allocation and energy settlement) rather than electrical [9,41]. Beamed recharging of drones

and remote sensors has become tractable at hundreds of watts over kilometres [6,15,26]. Short fixed microwave links across water, ravines or contaminated ground become defensible wherever the route cost satisfies (34) [18].

8.3. Long Term (15–30 Years)

Space-based solar power offers firm, low-carbon supply with a capacity factor above 0.9, but Table VII shows kilometre-scale apertures and the mass to orbit is thousands of tonnes per gigawatt. The variable that has changed is launch cost. Beam steering from orbit has been demonstrated [7,25]. The European Space Agency has studied the concept under SOLARIS and Japanese and Chinese programmes have announced orbital power-beaming tests for the second half of this decade [26,44,45]. The physics is settled and the demonstration path credible; the economics remain unproven [3,46].

Horizon	Application	Enabling development required	Confidence
0–5 years	Consumer and medical devices; AGV and robotics; static EV charging ≤ 22 kW	Cost reduction, standard convergence, inverter–coil integration	High (commercial)
0–5 years	Hazardous-area and sealed-enclosure couplers	IECEX/ATEX certification route	High
5–15 years	Heavy-vehicle and bus static charging, 50–500 kW	Thermal design, pad standardization, grid connection	Medium–high
5–15 years	Dynamic in-road charging corridors	Civil-cost reduction, segmented primary control, energy settlement	Medium
5–15 years	UAV and sensor-node beamed recharging	Compact efficient receivers, interlock certification	Medium
5–15 years	Short fixed microwave links (1–20 km)	Spectrum allocation, exclusion-zone siting	Medium–low
15–30 years	Space-based solar power	Launch cost $< \text{US}\$200/\text{kg}$, in-orbit assembly, km-scale apertures	Low, non-speculative

Table 11: Prospect Roadmap by Planning Horizon

8.4. Regional Relevance

In the Gulf region high irradiance and available land make terrestrial photovoltaics cheap, weakening the case for space solar power. Conversely, heat and dust degrade plug-and-socket connectors, port and industrial automation is expanding, and autonomous and electric fleets are growing in Abu Dhabi and Dubai, which favors static and later dynamic wireless charging. Offshore installations are a further niche, where sealed couplers remove connectors from hazardous areas and short inter-platform microwave links may undercut subsea cable.

9. Techno-Economic Case Study

Consider firm supply of 1 MW at the load of an island facility 10 km offshore, by a 33-kV submarine cable or by a 5.8-GHz microwave link designed for $\tau = 2$. Both options deliver the same service, $E_d = 7446$ MWh/yr at $\text{CF} = 0.85$ from (30); the microwave transmitter must therefore be rated at $1/0.510 \approx 1.96$ MW. With $i = 8\%$ and $n = 25$ years, (32) gives $\text{CRF} = 0.0937$; $c_e = \text{US}\$60/\text{MWh}$; OPEX is taken as 1.5% (cable) and 3% (microwave) of CAPEX per year. Table XII evaluates (31).

Item	Submarine cable	Microwave link
η_{sys}	97.5%	51.0% (Fig. 12)
Source rating	1.03 MW	1.96 MW
Delivered energy E_d	7446 MWh/yr	7446 MWh/yr
Energy loss E_{loss}	191 MWh/yr	7151 MWh/yr
CAPEX (indicative)	US\$12–25 M	US\$18–40 M
CAPEX·CRF	US\$1.12–2.34 M/yr	US\$1.69–3.75 M/yr
OPEX	US\$0.18–0.38 M/yr	US\$0.54–1.20 M/yr
Cost of losses	US\$0.01 M/yr	US\$0.43 M/yr
LCOT	US\$177–366/MWh	US\$357–722/MWh
Lead time	18–36 months	12–18 months
Repair after failure	Weeks to months	Days
Principal risk	Anchor/trawl damage	Spectrum consent, exclusion zone

Table 12: Case Study: 1 MW Delivered Over 10 KM

The cable wins on LCOT by a factor of about two. The gap is shared among the three terms of (31): relative to the cable, the microwave link adds US\$0.6–1.4 M/yr of annualized capital, US\$0.4–0.8 M/yr of O&M and US\$0.42 M/yr of losses, the last reflecting about 37 times the energy loss. The per-megawatt-hour values are an order of magnitude above those of Fig. 14 because fixed costs are spread over only 7446 MWh/yr; the ratio between the options, not the absolute level, is the transferable result. The microwave link offers repair in days rather than months and avoids seabed consenting, so it becomes preferable where the route is obstructed or unavailable, where a long cable outage is unacceptable, or where the supply is temporary—exactly the structure predicted by (34).

10. Discussion and Limitations

Three findings deserve emphasis. First, the near-field design problem reduces to one number: (12) lets a designer judge feasibility from geometry and materials before any detailed design, and explains why published efficiencies vary so widely—they are measured at different kQ. Second, far-field

transfer is an aperture-purchasing decision rather than an efficiency-engineering problem; conversion efficiencies have been adequate since the 1970s while the willingness to build apertures of the size in Table VII has not [1]. Third, the binding system constraint is often regulatory: exposure limits applied through (25) and (36) fix a minimum receiving area and exclusion zone independent of rectenna quality. The limitations of this study are stated plainly. The results are simulation-based and have not been validated by experiment in this work; they are, however, consistent with the standardized ground-clearance classes and with the published demonstrations of Table II. The near-field model is lumped and uses filamentary single-turn loops, so ferrite, shielding and multi-turn proximity effects—which alter misalignment behavior in real pads—are not captured; full-wave simulation is needed for a specific design. The far-field model is scalar and assumes ideal Gaussian taper. The stray fraction $\epsilon = 10\%$ is deliberately pessimistic. Cost figures are order-of-magnitude values from public programme data, not tender estimates, and the LCOT metric does not value the shorter repair time identified in Section IX. The models

should be read as a screening tool that bounds the answer before resources are committed.

11. Conclusion

A unified framework for cableless power transmission has been presented, comprising a regime-based classification, a three-layer system architecture, a consistent mathematical model with a common efficiency cascade and LCOT metric, numerical results, a classified problem matrix, a standard map and a staged roadmap. Near-field efficiency is bounded by kQ through (12), and because $k \propto d^{-3}$, high efficiency is confined to gaps of about one coil diameter. Far-field efficiency is bounded by the Goubau relation (24), which fixes the aperture that must be bought for a given range and wavelength. End-to-end efficiency is 85–95% in the near field and about 50% at best in the microwave far field, against 97–99% for a conductor. Cableless transmission will therefore not displace the conductor for bulk power, but it is the established solution where a conductor cannot be used, and increasingly the preferred one where the cost of the route, rather than the energy, dominates. Designers are recommended to screen near-field concepts with the kQ bound before choosing a topology; to use coupling-independent compensation where gap or alignment varies widely; to derive exclusion zones and minimum receiving areas from exposure limits at the outset; to evaluate beamed-power proposals on aperture area and LCOT rather than efficiency; and to support a primary ITU-R allocation for beamed power, which no technical advance can substitute for. Future work will replace the filamentary coupling model with full-wave simulation of DD and quadrature pads, model the transient of a vehicle crossing segmented in-road primaries, study dust-loaded optical availability for Gulf sites, and add the option value of repair time to the economic model.

Data Availability

The Python scripts that generate all numerical results and figures are available from the author on reasonable request.

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