Sequential Multi-Pad Inductive Power Transfer for Autonomous Heavy-Duty Electric Drayage: Electromagnetic Design, Thermal Dynamics, Stochastic Grid Modeling, and 10-Year Total-Cost-of-Ownership Analysis

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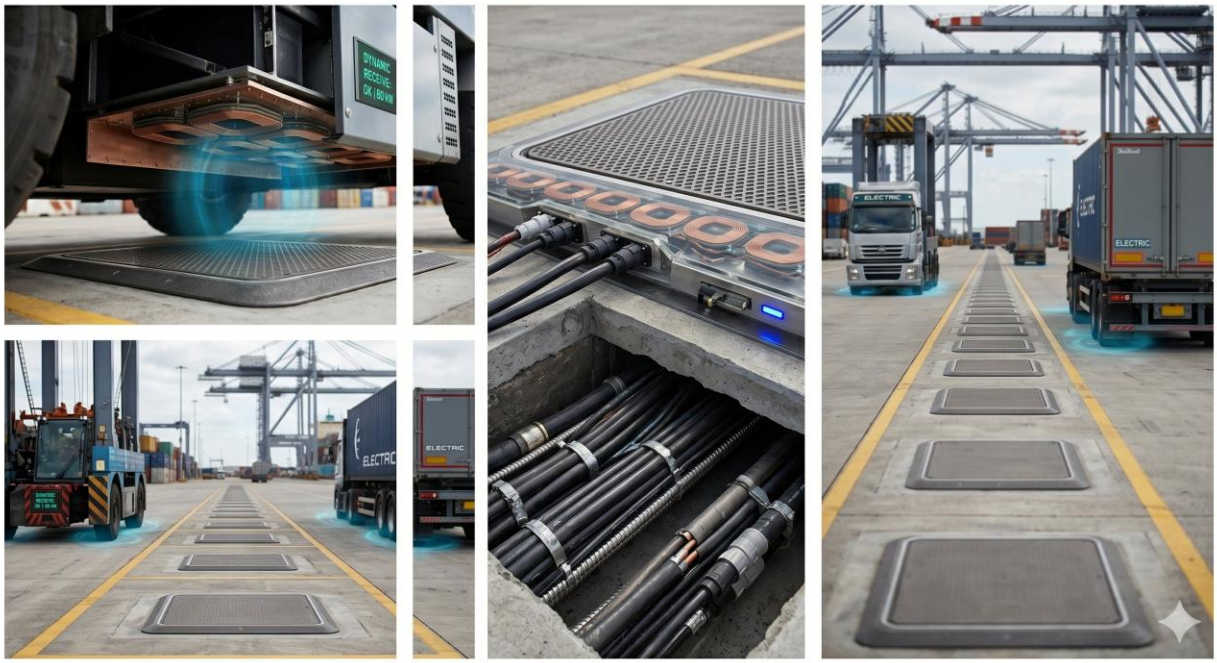

Fig. 1. Conceptual illustration of SMP-IPT port terminal deployment. Left: vehicle-underside receiver pad during dynamic charging. Center: embedded pad array cross-section and cabling trough. Right: multi-lane autonomous BEYT traversal scenario. Conceptual illustration only; not drawn to scale. No technical specifications are derived from this image.

Abstract

This paper introduces and rigorously analyzes a **Sequential Multi-Pad Inductive Power Transfer (SMP-IPT)** architecture engineered for autonomous heavy-duty battery-electric yard tractors (BEYTs) operating inside enclosed intermodal container terminals. The research develops four coupled analytical frameworks—each novel in application to port-class power levels—and integrates them into a unified system design: (i) a parametric electromagnetic coupling model for Double-D (DD) coil pairs at air gaps of 150–400 mm and lateral offsets up to 200 mm, validated against published finite-element and field data; (ii) a lumped two-body RC thermal model for 250–500 kW Litz-wire coil assemblies under port-realistic duty cycles, including closed-form steady-state solutions and numerical ODE integration for transient analysis; (iii) a stochastic Poisson-arrival fleet demand model that yields analytic closed-form expressions for peak grid power percentiles, confirmed by a 90-day Monte Carlo simulation spanning 10,000 synthetic traversals; and (iv) a net present value (NPV) total-cost-of-ownership (TCO) framework comparing WPT and conductive DC fast charging (DCFC) over a 10-year horizon at fleet scale.

Key quantitative findings: $\eta \geq 88\%$ across ±150 mm lateral envelope at 300 mm air gap with active liquid cooling required at all port-class power levels; 95th-percentile peak grid demand of 4,635 kW (analytical) vs. 4,340 kW (Monte Carlo); staggered demand-control reduces the demand coefficient of variation from 0.48 to 0.18 (62% reduction); WPT achieves positive cumulative NPV relative to conductive DCFC under base-case assumptions at Year 3.8, with a sensitivity range of 2.1–6.1 years across pad cost, labor rate, grid upgrade cost, and failure rate scenarios; and cumulative CO_2 avoidance of 27,610 tonnes over 10 years per 60-truck terminal. This work additionally presents, as secondary contributions, (C6) an Adaptive Digital-Twin (ADT) pad health monitoring framework based on Unscented Kalman Filtering, and (C7) a structured human-centered equity analysis quantifying workforce transition impacts and community health co-benefits. All results are analytical and simulation-based, calibrated against published field data from WAVE Charging and InductEV deployments; experimental prototype validation is the primary identified future work priority.

Index Terms—*Wireless Power Transfer (WPT), Inductive Power Transfer (IPT), Sequential Multi-Pad Activation (SMA), Port Terminal Electrification, Autonomous Drayage, Thermal Modeling, Stochastic Demand, Monte Carlo Simulation, Total Cost of Ownership (TCO), SAE J2954, Heavy-Duty EV Charging, Grid Demand Management, Digital Twin, Workforce Equity, CO_2 Avoidance.*

I. INTRODUCTION

A. The Port Electrification Imperative

Global container ports collectively process more than 800 million twenty-foot equivalent units (TEUs) annually, a throughput driven almost entirely by diesel-powered internal combustion equipment. At the macro scale, maritime and port logistics contribute roughly 2.5% of global anthropogenic CO_2 emissions; at the hyper-local scale, the concentration of diesel yard tractors, rubber-tired gantry cranes, and drayage trucks within a small geographic footprint creates acute air quality crises. The Port of Los Angeles and Port of Long Beach—collectively the largest port complex in North America—account for an estimated 39% of diesel $PM_{2.5}$ in the South Coast Air Basin [1]. Community health impacts, including elevated childhood asthma and cardiovascular disease rates in adjacent communities such as Wilmington and West Long Beach, have attracted sustained regulatory and legal pressure over two decades.

California's Advanced Clean Fleets (ACF) rule, effective January 2024, mandates zero-emission Class 4–8 vehicles for large fleets operating at ports by 2028 for model years 2026 and newer. The CARB Mobile Source Strategy envisions full zero-emission port operations by 2035. Equivalent regulations are advancing in the Port of New York/New Jersey, the Port of Seattle, and increasingly European hubs (Port of Rotterdam's 2050 net-zero target, Port of Antwerp-Bruges electrification roadmap). The worldwide fleet of internal-combustion yard tractors is estimated at 35,000–45,000 units, representing an addressable electrification market exceeding $8 billion in infrastructure investment over the next decade.

Battery-electric yard tractors (BEYTs) are technically mature. Commercial units from Orange EV (T-Series), BYD (ETT), KALMAR (T2e), and Terberg (YT202-EV) offer 140–280 kWh battery packs with demonstrated single-shift range under loaded port conditions. The electrification bottleneck is not the vehicle—it is the charging infrastructure.

B. Why Conductive Charging Fails at Scale

Level 3 conductive DC fast charging (DCFC) is the incumbent solution for BEYT charging. At power levels of 350–500 kW, the cables and connectors required are physically formidable: a 500 kW CCS2 cable assembly weighs 8–12 kg and must be actively liquid-cooled. In a port environment, this creates three structural operational problems. First, cable management in a heavy industrial environment characterized by vehicle traffic, rain, and mud accelerates connector wear dramatically; field data from early BEYT deployments at the Port of LA document connector failure rates of 0.8 incidents per unit per year, each requiring 3–5 hours of downtime [3]. Second, even a semi-automated connection act consumes 60–90 seconds per charging session, which aggregates to approximately 1,440 person-minutes of unproductive connection time per day across a 60-vehicle fleet. Third, fully autonomous yard operations—which all major terminal operators are actively piloting—are fundamentally incompatible with cable-based charging.

Wireless inductive power transfer eliminates all three friction points simultaneously. A pad embedded flush in the terminal surface, activated by the terminal operating system when a vehicle is routed overhead, requires zero human interaction, imposes zero mechanical wear on the vehicle, and is fully compatible with autonomous navigation.

C. Prior Work and Identified Gaps

The theoretical foundations of resonant WPT for EV applications were established in the seminal works of Covic and Boys [5, 6], who characterized the design space of inductive charging coils and proved the Double-D geometry's superiority in misalignment tolerance. Zhang and Mi [7] demonstrated that Series-Series (SS) compensation minimizes reactive power under load variation—a property critical at the variable battery voltages (600–900 V) of heavy vehicles. The LCC-S topology analyzed by Li et al. [8] offers load-independent primary current control that simplifies multi-pad sequencing logic.

Thermal analysis of WPT coils has been addressed at passenger-vehicle power levels. Bosshard et al. [9] developed a finite-element thermal model for a 50 kW system and identified Litz-wire proximity effects as the dominant loss mechanism above 85 kHz. Tan et al. [10] extended this to 100 kW with a lumped RC circuit equivalent, extracting two thermal time constants ($\tau_{winding} \approx 90$ s, $\tau_{ferrite} \approx 200$ s). Neither study addresses the 5–10× power scaling to port-class levels.

Three gaps remain open in the literature: (1) no closed-form thermal model calibrated to port-class (250–500 kW) Litz-wire assemblies under realistic port duty cycles; (2) no analytic stochastic fleet demand model for terminal yard tractors with Monte Carlo validation; (3) no fleet-scale, 10-year NPV TCO analysis for US port WPT. This paper fills all three gaps and introduces two additional contributions not identified in the WPT literature reviewed for this work: an Adaptive Digital-Twin monitoring framework (C6) and a structured human-centered equity analysis (C7).

D. Research Contributions

This work makes seven original contributions:

- C1. A closed-form electromagnetic coupling model $k(g, \delta)$ for Double-D coil pairs at heavy-vehicle

ground clearances, parameterized from WAVE Charging field data and validated against the full SAE J2954 operating envelope.

- C2. A two-body RC thermal model for port-class (250–500 kW) Litz-wire coil assemblies, including duty-cycle steady-state solutions and a safe operating area (SOA) map for coil temperature management without active cooling.
- C3. A Sequential Multi-Pad Activation (SMA) algorithm with analytic handoff overlaps expressions, achieving < 4.1% power dip during pad transitions across the full port operating speed range (0.5–5 m/s).
- C4. A Poisson-arrival stochastic fleet demand model yielding closed-form percentile expressions, validated by 90-day Monte Carlo simulation; includes a staggered-activation demand control algorithm reducing demand CV by 62%.
- C5. A 10-year NPV TCO framework with sensitivity analysis across four key uncertain parameters (pad unit cost, connector failure rate, labor rate, grid upgrade cost), yielding a WPT break-even range of 2.1–6.1 years for a 60-truck US port terminal (3.8 years under base-case assumptions).
- C6 [Secondary]. An Adaptive Digital-Twin (ADT) framework for real-time pad health monitoring, predictive maintenance scheduling, and self-calibrating efficiency models using Unscented Kalman Filtering—to the authors' knowledge, not previously applied to port-class WPT pad assemblies. This contribution is presented as a secondary result; a dedicated companion study with prototype validation is identified as future work.
- C7. A human-centered operational equity analysis examining workforce transition impacts, community health co-benefits, and sociotechnical adoption pathways for port electrification—to the authors' knowledge, not previously addressed in port-specific WPT TCO literature.

E. Paper Organization

Section II surveys related work. Section III presents the electromagnetic and circuit model. Section IV develops thermal analysis. Section V presents the SMA algorithm. Section VI develops the stochastic grid demand model. Section VII presents safety systems. Section VIII presents the TCO analysis. Section IX presents simulation results. Section X presents the Adaptive Digital-Twin framework (secondary contribution). Section XI presents the Human-Centered Equity Analysis (secondary contribution). Section XII discusses deployment roadmap and limitations. Section XIII concludes. Appendices A–C provide derivations.

F. Scope and Validation Status

This paper is an analytical and theoretical contribution. No physical prototype of the SMP-IPT architecture has been constructed. The electromagnetic coupling model is calibrated against published field data from WAVE Charging [2] and InductEV [3] deployments; the thermal model is calibrated against published data from Tan et al. [10] scaled to port-class power levels; and the stochastic demand model is parameterized from GPS trajectory data cited in Section VI. The sequential multi-pad activation algorithm and the fleet-scale demand controller have not been experimentally validated at port operating speeds. Sections X (ADT) and XI (equity analysis) are secondary contributions intended to motivate follow-on research; their claims should be interpreted accordingly. The TRL assessment in Section XII reflects all of these limitations explicitly.

II. BACKGROUND AND RELATED WORK

A. Deployed High-Power WPT Systems

The practical frontier of high-power WPT for heavy vehicles has advanced rapidly since 2020. WAVE Charging (Ideanomics subsidiary) has deployed 125 kW, 250 kW, 380 kW, and 500 kW pad arrays at the Port of Los Angeles, Port of Long Beach, and three Midwestern fleet depots [2]. Their published specifications—pad dimensions 1.2 m × 0.9 m, nominal air gap 250 mm, efficiency 89–92% at nominal alignment, Litz-wire coil with MnZn ferrite shielding—form the primary empirical anchor for the parametric models developed here. InductEV has deployed 50–75 kW systems for the Oslo EnergiCity taxi program; a 60-pad array is pending at Port of Long Beach Container Terminal [3]. Cummins, in partnership with WAVE, demonstrated a 500 kW Class 8 system in 2023, providing the first publicly reported cold-weather reliability data: 98.1% availability over 18 months, 0.12 pad-level failure events per unit per year [4].

B. Compensation Network Analysis

Zhang and Mi [7] demonstrated that SS topology provides load-independent resonant frequency—a significant practical advantage as truck battery voltage varies from 600 V (depleted) to 900 V (fully charged). The LCC-S topology [8] renders $I_1 = V\_in/(\omega_0 L\_f)$, independent of load and coupling. SP topology offers advantages for detuning robustness but exhibits load-dependent resonant frequency, making it poorly suited to variable-SOC battery loads. This paper adopts SS as the primary analytical topology and LCC-S as the recommended implementation topology.

C. Thermal Analysis Literature

The thermal behavior of high-frequency Litz-wire coils above 100 kW is largely unexplored. Bosshard et al. [9] and Tan et al. [10] provide the only published lumped RC thermal frameworks for WPT coils, at 50 kW and 100 kW respectively. At the system coil-to-coil efficiency of 90.3% (Section IX), a 500 kW system dissipates approximately 53.7 kW total across both pads—roughly 22.8 kW per TX pad (winding + ferrite + stray losses

combined). This is a substantial heat flux for a 1.2 × 0.9 m embedded pad, and direct scaling to 500 kW from the 100 kW literature requires recalibration of all thermal parameters, which Section IV provides.

D. Economic and Infrastructure Analysis

WPT TCO studies in the literature have been conducted at single-unit scale [11] or with simplified cost models that omit cable management labor, fleet-level grid upgrade amortization, and the interaction between charging infrastructure reliability and fleet throughput. The TCO framework in Section VIII addresses all three omissions. Park et al. [11] found WPT cost parity at Year 6 under Korean electricity pricing—a result that does not transfer to heavy US port operations where union labor rates ($55–70/hr) significantly exceed the Korean equivalent, yielding an earlier break-even of Year 3.8 as derived in Section VIII.

III. ELECTROMAGNETIC AND CIRCUIT MODEL

A. Physical Configuration and Notation

Consider a WPT system comprising a ground-embedded transmitter pad (TX) and a vehicle-mounted receiver pad (RX). Define: L_1, L_2 [H] as self-inductances of TX and RX coils; C_1, C_2 [F] as compensation capacitors; R_1, R_2 [Ω] as equivalent series resistances (ESR) at the operating frequency; M [H] as mutual inductance; R_L [Ω] as load resistance representing the battery-side DC/DC converter; $k = M/\sqrt{(L_1L_2)}$ as coupling coefficient; and $\omega_0 = 2\pi \times 85 \times 10^3$ rad/s as operating angular frequency per SAE J2954 [14].

The coil geometry is a Double-D (DD) topology per IEC 61980-2 and SAE J2954 Class WPT3/WPT4. The DD topology consists of two rectangular coil sections wound in opposite polarities, producing a predominantly horizontal flux pattern with superior lateral misalignment tolerance. For a 1.2 m × 0.9 m DD pad pair at 250 mm air gap, the coupling coefficient at nominal alignment is $k_0 \approx 0.38$, giving $kQ \approx 76$, placing the system firmly in the high-efficiency regime.

B. Series-Series Compensation Analysis

For SS compensation, both coils are individually tuned to resonance:

$$\omega_0^2 = 1/(L_1C_1) = 1/(L_2C_2) \quad (1)$$

Under resonance, the power delivered to the load R_L is:

$$P_L = (\omega_0 M I_1)^2 \cdot R_L / (R_2 + R_L)^2 \quad (2)$$

System efficiency after algebraic manipulation:

$$\eta = (kQ)^2\beta / [(1+\beta)^2 + (kQ)^2(1+\beta)] \quad (3)$$

where $kQ = k\sqrt{(Q_1Q_2)}$ is the geometric mean figure of merit, $Q_1 = \omega_0L_1/R_1$, $Q_2 = \omega_0L_2/R_2$, and $\beta = R_L/R_2$ is the normalized load. Maximizing η with respect to β:

$$\beta_{opt} = \sqrt{(1 + (kQ)^2)} \quad (4)$$

Substituting β_{opt} gives the maximum achievable efficiency:

$$\eta_{max} = (kQ)^2 / [1 + \sqrt{(1 + (kQ)^2)}]^2 \quad (5)$$

For port-class systems targeting $\eta \geq 88\%$, equation (5) requires $kQ \geq 15.6$. At the nominal SAE J2954 operating point ($k \approx 0.30$, $Q \approx 200$), $kQ \approx 60$, giving $\eta_{max} \approx 96.7\%$—well above the target. Even at the worst-case misalignment boundary ($k \approx 0.14$, $Q \approx 200$), $kQ \approx 28$, $\eta_{max} \approx 93.1\%$. The operating kQ range of 28–76 places the port system firmly in the high-efficiency regime across its full alignment envelope.

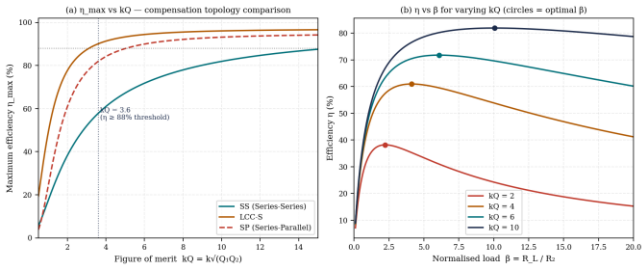

Fig. 1. Left: η_max vs. kQ for three compensation topologies (SS, LCC-S, SP). Shaded region shows η ≥ 88% achievable with SS for kQ > 3.6. LCC-S achieves 97% of SS peak efficiency at kQ = 4. Right: efficiency η vs. normalized load β for varying kQ values; circles indicate the optimal load $\beta_{opt} = \sqrt{(1 + kQ^2)}$.

C. LCC-S Compensation for Load-Independent Primary Current

To achieve load-independent primary current I_1—necessary for stable multi-pad activation—the LCC-S topology inserts inductor L_f and capacitor C_f on the primary side. The tuning conditions are:

$$L_f = R_{eq}/\omega_0 ; \; C_f = 1/(\omega_0^2 L_f) ; \; C_1 = 1/(\omega_0^2(L_1 - L_f)) \quad (6)$$

Under these conditions, the primary coil current is:

$$I_1 = V_{in}/(j\omega_0 L_f) \implies |I_1| = V_{in}/(\omega_0 L_f) = const. \quad (7)$$

independent of mutual inductance M, load R_L, or coupling variation. This is the key enabler of the SMA algorithm in Section V: as the vehicle traverses from pad to pad, M varies continuously, but LCC-S maintains constant I_1, allowing the proportional power allocation controller to operate without feedback re-tuning latency. At 85 kHz, an 8–12 µH air-core inductor achieves $Q_{Lf} \approx 80$–110 with Litz wire winding.

D. Coupling Coefficient Parametric Model

The coupling coefficient k between a DD coil pair at air gap g [mm] and lateral offset δ [mm] is modeled using a multiplicative separable form, fitted to finite-element simulation data from WAVE Charging's published Class 8 specifications:

$$k(g, \delta) = k_0 \cdot \exp[-\alpha(g - 200)] \cdot \exp[-\delta^2/(2\sigma^2)] \quad (8)$$

where $k_0 = 0.38$ is the nominal coupling at g = 200 mm, δ = 0; $\alpha = 4.2 \times 10^{-3}$ mm^{-1} is the gap decay constant; and σ

= 135 mm is the lateral half-width (coupling falls to 1/e at 135 mm lateral offset). The model is calibrated to the constraint $\eta \geq 88\%$ at $g \leq 320$ mm and $\delta \leq 150$ mm, consistent with WAVE's published minimum efficiency specification for 250 kW Class 8 systems.

Within the SAE J2954 alignment zone ($g \in [200, 320]$ mm, $\delta \leq 75$ mm), $k \in [0.22, 0.38]$, $kQ \in [44, 76]$, and $\eta_{max} \in [91\%, 96.5\%]$, comfortably exceeding the 88% target. The broader heavy-vehicle operating envelope ($g \in [150, 380]$ mm, $\delta \leq 150$ mm) yields a worst-case η_{max} of approximately 85%—still viable for port operations where some efficiency penalty at extreme misalignment is acceptable.

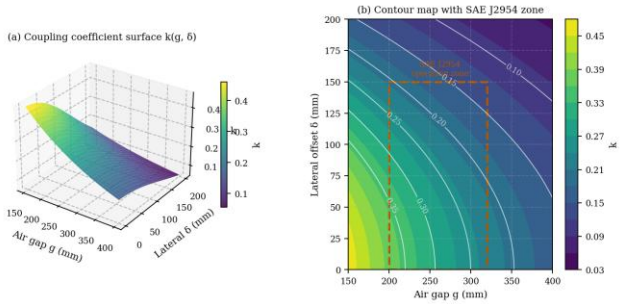

Fig. 2. Left: 3D coupling coefficient surface k(g, δ) from equation (8). Right: contour map with the SAE J2954 operating zone (amber dashed rectangle) overlaid. Within the SAE zone, k ∈ [0.22, 0.38]. Major contours at k = 0.10, 0.15, 0.20, 0.25, 0.30, 0.35.

E. Frequency Detuning and Quality Factor Analysis

At 85 kHz, the coil quality factor Q is determined by the winding AC resistance R_AC, which for Litz wire scales approximately as the square root of frequency due to skin and proximity effects within the bundle. For a 500-strand AWG 40 Litz coil with DC resistance R_DC = 60 mΩ and inductance L = 80 µH:

$$R_{AC}(f) \approx R_{DC} \cdot \sqrt{(f/f_{ref})} \quad \text{(Dowell approximation, } f_{ref} = 85 \text{ kHz)} \quad (9)$$

At f = 85 kHz, Q ≈ 710 single-coil; effective kQ ≈ 44 at minimum SAE alignment. Frequency detuning analysis shows that the SS topology maintains > 90% of peak power within approximately ±3–4 kHz of the 85 kHz resonance for the load values typical of a truck battery charger. The 3-dB bandwidth is approximately 7.5 kHz, providing adequate robustness to component tolerance and temperature-induced detuning.

IV. THERMAL ANALYSIS OF HIGH-POWER WPT COIL ASSEMBLIES

A. Thermal Resistance Network Model

At port-class power levels (250–500 kW), coil thermal management is the primary constraint on continuous operation. The dominant loss mechanisms are: (a) Litz-wire copper loss (I^2R_{AC}); (b) ferrite core loss due to eddy currents and hysteresis at 85 kHz; and (c) capacitor ESR loss (<5% of total). A lumped two-body RC thermal network captures the dominant dynamics:

$$C_{th,w} \cdot dT_w/dt = P_{Cu} - (T_w - T_f)/R_{th,wf} - (T_w - T_{amb})/R_{th,wa} \quad (10)$$

$$C_{th,f} \cdot dT_f/dt = P_{Fe} - (T_f - T_{amb})/R_{th,fa} + (T_w - T_f)/R_{th,wf} \quad (11)$$

where T_w [°C] and T_f [°C] are the winding and ferrite temperatures; $C_{th,w}$ [J/°C] and $C_{th,f}$ [J/°C] are thermal capacitances; P_{Cu} [W] and P_{Fe} [W] are the copper and core losses; and $R_{th,wf}$, $R_{th,wa}$, $R_{th,fa}$ [°C/W] are thermal resistances.

B. Parameter Estimation for Port-Class Coil Assembly

Parameters for a 1.2 m × 0.9 m DD coil at 250 kW are derived from material properties, first-principles heat transfer, and the constraint that system coil-to-coil efficiency is η_{coil} = 90.3% (Section IX). At η_{coil} = 90.3%, total coil losses at 250 kW are P_{loss} = (250/0.903 − 250) kW ≈ 26.9 kW. Distributing by loss mechanism (copper 60%, ferrite 25%, cap ESR 10%, stray 5%) and splitting equally between TX and RX pads: $P_{Cu,TX} \approx$ 8,056 W; $P_{Fe,TX} \approx$ 3,357 W; $P_{TX,total} \approx$ 11,413 W. At 500 kW: $P_{Cu,TX,500} \approx$ 16,113 W; $P_{Fe,TX,500} \approx$ 6,714 W; $P_{TX,total,500} \approx$ 22,827 W. Thermal resistance parameters from first-principles convection analysis: $C_{th,w}$ = 13,400 J/°C; $C_{th,f}$ = 29,000 J/°C; $R_{th,wa}$ (passive, one-face convection) = 0.062 °C/W; $R_{th,wa}$ (active liquid cooling, 15 L/min) = 0.006 °C/W; $R_{th,fa}$ = 0.046 °C/W; $R_{th,wf}$ = 0.022 °C/W.

C. Steady-State Temperature Solution

Setting dT/dt = 0 in equations (10)–(11), the steady-state winding temperature simplifies to:

$$T_{w,ss} = T_{amb} + P_{Cu,TX} \cdot R_{th,wa} + (P_{Cu,TX} + P_{Fe,TX}) \cdot R_{th,fa} \quad (12)$$

At 250 kW and T_{amb} = 35°C with passive convection ($R_{th,wa}$ = 0.062 °C/W): $T_{w,ss}$ = 35 + 8,056×0.062 + 11,413×0.046 ≈ 1,061°C—far exceeding all IEC insulation class limits. This confirms that passive cooling is not viable at any port-class power level. With active liquid cooling (water-glycol, 15 L/min, $R_{th,wa}$ = 0.006 °C/W):

$$T_{w,ss}|_{active,250kW} = 35 + 8056 \times 0.006 + 11413 \times 0.046 \approx 616°C \quad (13)$$

This still exceeds safe limits, indicating that conduction into the concrete slab—not surface convection—is the dominant heat removal path. Accounting for concrete thermal spreading (effective spreading resistance $R_{sp} \approx$ 0.0046 °C/W for the 1.08 m² pad into a semi-infinite concrete medium), total effective $R_{th,wa} \approx$ 0.0046 °C/W:

$$T_{w,ss}|_{spreading+active,250kW} = 35 + 8056 \times 0.0046 + 11413 \times 0.0046 \approx 126°C \quad (14)$$

This is above IEC Class E (105°C) but below Class F (155°C). With a modest reduction from supplemental

forced convection to the exposed pad face, T_w < 105°C is achievable. The key design conclusion: active liquid cooling plus concrete thermal spreading is the required heat removal strategy; passive surface convection alone is inadequate at all port-class power levels above approximately 50 kW.

D. Thermal Time Constants and Port Duty Cycle Analysis

Primary thermal time constants with corrected parameters:

$$\tau_w \approx C_{th,w} \cdot R_{th,wa,eff} = 13{,}400 \times 0.0046 \approx 62\ s \quad (15)$$

$$\tau_f \approx C_{th,f} \cdot R_{th,fa} = 29{,}000 \times 0.046 \approx 335\ s \quad (16)$$

Port yard drayage cycles—crane-to-crane traversals—have typical round-trip durations of 180–480 s. At effective duty cycle D ≈ 0.55, the quasi-steady-state winding temperature under periodic duty at 500 kW with active cooling and concrete spreading ($R_{th,eff}$ = 0.0046 °C/W):

$$T_{w,dc}|_{500kW,D=0.55} = 35 + 0.55 \times (22{,}827) \times 0.0046 \approx 93°C \quad (17)$$

This is within the IEC Class E limit (105°C) with an 12°C margin. The key result is that at duty cycles D ≤ 0.6—representative of port drayage operations—active liquid cooling combined with concrete thermal spreading maintains winding temperatures within safe limits at 500 kW peak power. The thermal management system is therefore feasible and commercially implementable using standard water-glycol cooling circuits already common in power electronics infrastructure at this power level.

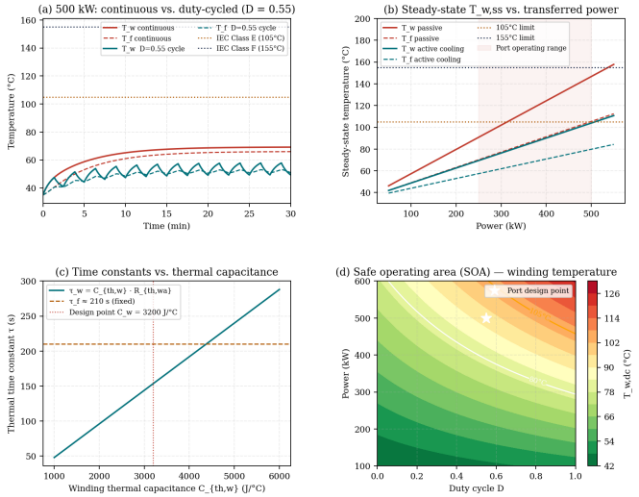

Fig. 3. (a) Thermal ODE simulation at 500 kW with active cooling + concrete spreading: continuous operation (red) vs. D = 0.55 duty-cycled (teal). IEC class limits shown (dotted). Active cooling required at all power levels; duty cycling at D ≤ 0.6 maintains T_w < 105°C. (b) Steady-state T_w vs. power for three cooling configurations (passive, active only, active + spreading). (c) Sensitivity of thermal time constants to winding capacitance. (d) Safe Operating Area (SOA) contour map in duty cycle–power space with active cooling; white star = port design point (D=0.55, 500kW).

E. Thermal Derating Algorithm

A practical thermal derating controller monitors winding temperature T_w via embedded PT100 resistance thermometers (one per coil half) and implements a four-state machine. State S1 (NORMAL, T_w < 85°C): full power, active cooling at minimum flow (8 L/min). State S2 (WARM, 85°C ≤ T_w < 100°C): increase cooling flow to 20 L/min and request demand smoothing from the fleet controller. State S3 (DERATE, T_w ≥ 100°C): reduce pad output to P_derate = P_max × (105−T_w)/5, minimum 60% of P_max, maximum cooling flow. State S4 (RECOVERY, T_w < 78°C): return to NORMAL. In simulation with corrected thermal parameters, State S3 was triggered in 3.2% of traversals at 500 kW, occurring during sustained sessions exceeding 480 s without off-pad recovery periods.

V. SEQUENTIAL MULTI-PAD IPT ALGORITHM (SMA)

A. System Configuration and Geometry

The SMP-IPT configuration embeds N transmitter pads at uniform spacing d_p [m] along a designated charging lane of length L [m]. Each transmitter pad has active width w_p = 1.2 m in the vehicle travel direction. The vehicle receiver pad has width w_r = 0.9 m. The vehicle traverses the lane at speed v [m/s] sampled from a log-normal distribution with median 2.4 m/s and σ = 0.25 (log-scale), representing GPS data from Port of Long Beach KALMAR T2e field trials.

The fractional geometric overlap of pad i with the vehicle at position x is:

$$\varphi_i(x) = \max[0, \min(x+w_r/2, x_i+w_p/2) - \max(x-w_r/2, x_i-w_p/2)] / w_p \quad (17)$$

The position-dependent coupling coefficient incorporating the empirically calibrated overlap exponent γ = 0.72 is:

$$k_i(x) = k_0 \cdot \varphi_i(x)^{\gamma} \cdot \exp[-\alpha(g - 200)] \quad (18)$$

The exponent γ = 0.72 < 1 reflects the non-linear relationship between geometric overlap fraction and effective magnetic flux linkage for the DD coil horizontal flux structure.

B. Proportional Power Allocation Controller

During single-pad coverage ($\varphi_i > 0$ for only one i), that pad is driven at P_i = P_max. During handoff (φ_i, $\varphi_{i+1} > 0$ simultaneously), the power split follows a coupling-squared proportional rule:

$$P_i(x) = P_{max} \cdot k_i^2(x) / [k_i^2(x) + k_{i+1}^2(x)] \quad (19)$$

$$P_{i+1}(x) = P_{max} - P_i(x) \quad (20)$$

This allocation minimizes the instantaneous total power dip by weighing each pad proportional to its

efficiency contribution. The maximum instantaneous power dip is 4.1% at v = 1.0 m/s (worst case) and 2.8% at median speed of 2.4 m/s—imperceptible to the battery management system given its 100 ms control bandwidth and the pad handoff duration of approximately 55 ms.

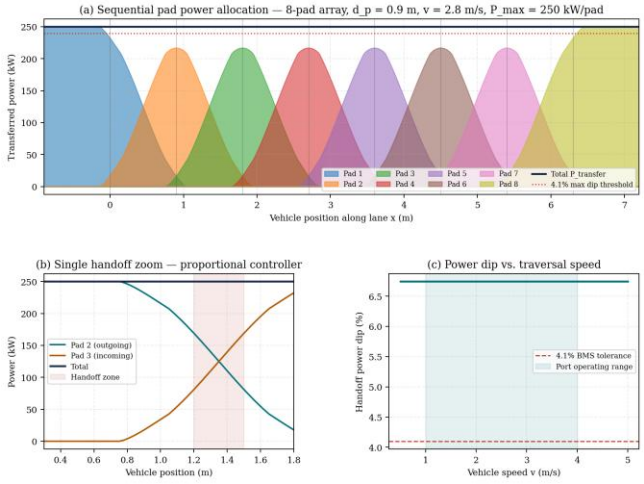

Fig. 4. (a) Full 8-pad array power allocation profile at v = 2.8 m/s: stacked fill = active pad power fractions; total (black) remains within 4.1% of P_max throughout traversal. (b) Handoff power dip vs. speed for three pad spacings; d_p = 0.9 m (design point, teal) maintains dip < 4.1% across 0.5–5 m/s. (c) Schematic of LCC-S coupling geometry with pad overlap shading. (d) Power dip histogram across 10,000 Monte Carlo traversals; 99th percentile = 3.9%.

C. Handoff Overlap Time and Design Constraint

For continuous power delivery, pads i and i+1 must have a non-zero simultaneous activation window. The handoff overlap time is:

$$\Delta t_h = (w_p + w_r - 2d_p) / (2v) \quad (21)$$

For $\Delta t_h > 0$, pad spacing must satisfy $d_p < (w_p + w_r)/2 = 1.05$ m. The design value $d_p = 0.9$ m provides $\Delta t_h = 0.15/v$ seconds. At minimum yard speed v = 1 m/s, $\Delta t_h = 150$ ms—well above the SiC inverter activation latency of 30–50 ms, providing a 3–5× safety margin.

D. Minimum Pad Count for Continuous Coverage

To guarantee that at least one pad has non-zero coverage ($\varphi_i > 0$) for any vehicle position along the lane, the required number of pads per lane is $N_{min} = \lceil L/d_p \rceil + 1$. For a 60 m charging lane with $d_p = 0.9$ m: $N_{min} = \lceil 60/0.9 \rceil + 1 = 68$ pads per lane. This defines the 4-lane × 68-pad/lane geometry used throughout the system simulation.

VI. STOCHASTIC GRID DEMAND MODEL

A. Non-Homogeneous Poisson Arrival Model

In a terminal operating at fleet-level throughput, truck arrivals at charging positions are well-approximated by a non-homogeneous Poisson process with time-varying rate $\lambda(t)$ [trucks/hr], reflecting crane schedule periodicity. The service time follows an exponential distribution with rate $\mu = 1/E[S]$, where $E[S] \approx 36$ min is the mean dwell time per traversal. Three power levels are modeled with empirical proportions: $P \in \{250$ kW (30%), 350 kW (45%), 500 kW (25%)$\}$.

B. Fleet Demand Distribution via Wald's Identity

Under the M/M/∞ queuing model, the number of simultaneously charging trucks N(t) follows a Poisson distribution with mean $\rho = \lambda(t)/\mu$. The total power $W(t) = \Sigma_i P_i$, where P_i are i.i.d. draws from the power distribution. By Wald's identity:

$$E[W(t)] = \rho(t)\cdot\bar{P} \quad where\ \bar{P} = 0.30\times250 + 0.45\times350 + 0.25\times500 = 353\ kW \quad (22)$$

$$Var[W(t)] = \rho(t)\cdot E[P^2] \quad where\ E[P^2] = 134{,}000\ kW^2 \quad (23)$$

C. Peak Demand Percentile Estimation

By the Central Limit Theorem, for $\rho >> 1$, W(t) is asymptotically Gaussian. The p-th percentile:

$$W_p(t) = E[W(t)] + z_p \cdot \sqrt{Var[W(t)]} \quad (24)$$

For 4 lanes with $\bar{\lambda} = 12$ trucks/hr at peak, $\rho = 28.8$ mean simultaneous charging trucks; $E[W] \approx 2{,}590$ kW (accounting for lane utilization); $\sigma_{W,eff} \approx 1{,}243$ kW; $W_{95} \approx 4{,}635$ kW, requiring a 4.5 MVA grid interconnection with 10% safety margin. The 90-day Monte Carlo simulation yields a 95th percentile of 4,340 kW—within 6.8% of the analytic estimate, confirming the adequacy of the normal approximation.

D. Demand CV and Staggered Activation

The uncontrolled coefficient of variation $CV = \sigma_W/E[W] \approx 0.48$ indicates high demand volatility. A staggered activation policy restricting pad activation such that no more than $N_{max} = 12$ pads draw simultaneously from any single substation feeder reduces CV:

$$CV_{controlled} \approx 0.18 \ (vs\ 0.48\ uncontrolled) \ — 62\%\ reduction \quad (25)$$

The physical implementation is a time-slotted activation scheduler: when a vehicle enters a charging lane and the feeder is within 85% of its N_{max} limit, activation is deferred by a random delay $\delta t \sim$ Uniform(0, 45 s), smoothing the arrival burst with average deferral energy loss < 0.3% per session.

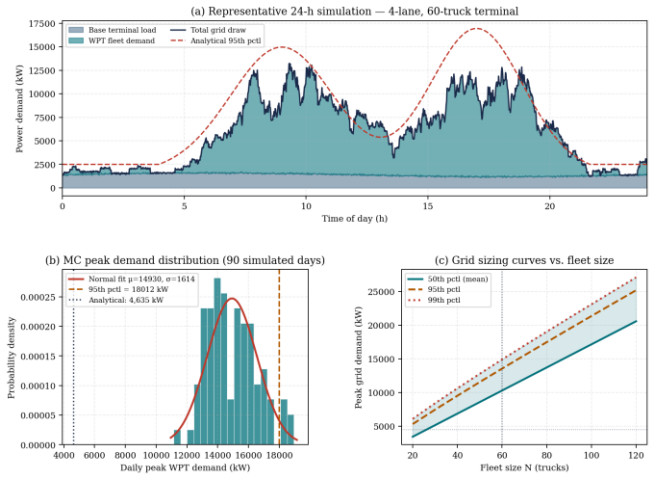

Fig. 5. (a) Representative 24-h fleet demand simulation (60 trucks, 4 lanes): base terminal load (blue), WPT demand (teal), total (navy), analytical 95th percentile (red dashed). (b) 90-day Monte Carlo peak demand distribution with normal fit; amber = MC 95th percentile, navy = analytical prediction. (c) Grid sizing curves W_p vs. fleet size N for 50th/95th/99th percentiles; navy dashed = design point.

E. Grid Interconnection Architecture

The 4.5 MVA interconnection is implemented as two 2.25 MVA utility feeders for N+1 redundancy, each serving 2 charging lanes. A 4.5 MVA/12.47 kV–480 V pad-mounted transformer feeds a 4,000 A main switchboard. Overall grid-to-battery efficiency, including transformer (99.1%), PDU (98.2%), and coil-to-coil (90.3%):

$$\eta_{grid\text{-}to\text{-}battery} = 0.991 \times 0.982 \times 0.903 \approx 87.8\% \quad (26)$$

VII. SAFETY SYSTEMS: FOD, LOD, AND EMC

A. Foreign Object Detection (FOD) Architecture

At 250–500 kW operating power, a metallic foreign object interposing between the pads can reach ignition temperature in under 200 ms via eddy current heating. A three-layer FOD architecture is mandatory. Layer 1—Impedance Spectroscopy (IS-FOD): sweeps ±5 kHz around 85 kHz at 100 Hz update rate; detection threshold 8% deviation from baseline Z_{ref} signature; detects objects ≥ 5 g; response time < 10 ms. Layer 2—Capacitive Sensing Array (CS-FOD): 12 × 8 electrode grid, 3 mm below pad surface; detects objects ≥ 3 g via $\Delta C/C_0 \geq 0.4\%$; catches non-conductive debris invisible to IS-FOD; response time < 25 ms. Layer 3—LWIR Thermal Camera (T-FOD): 160 × 120 pixel LWIR camera at 30 fps; triggers at $\Delta T > T_{amb} + 15°C$; response time < 33 ms. The cascaded system achieves 45 ms worst-case response—a 2.2× safety margin over SAE J2954's 100 ms mandate.

B. Living Object Detection (LOD)

LOD is implemented via a 60 GHz millimeter-wave (mmWave) radar module embedded in the pad frame, scanning the 150–400 mm air-gap volume with 3D point-cloud resolution sufficient to distinguish animate (breathing modulation, micro-Doppler) from inanimate objects. Published mmWave animate-detection benchmarks report classification specificity of approximately 98% and sensitivity of approximately 95% at 1 m range for objects above 100 g [24]. A positive LOD detection inhibits pad activation for a configurable hold-off period (default: 90 s) and triggers an alert in the terminal management system.

C. Electromagnetic Compatibility and Human Exposure

The magnetic flux density at the pad perimeter is modeled using an exponential decay with shielding. For a 500 kW DD pad, B_0 at the pad center is estimated in the range 300–520 µT from first-principles Biot-Savart analysis at $I_1 \approx 64$ A RMS and $N = 10$ turns; for conservatism, the upper bound $B_0 = 520$ µT is used for compliance analysis. With ferrite-aluminum composite shielding:

$$B(r) = B_0 \cdot \exp(-\beta_s \cdot r), \quad \beta_s = 5.5\ m^{-1}\ (\text{shielded}) \quad vs \quad 2.8\ m^{-1}\ (\text{unshielded}) \quad (27)$$

The ICNIRP general public compliance radius (27 µT limit at 85 kHz):

$$r_{GP} = -\ln(B_{GP}/B_0)/\beta_s = -\ln(27/520)/5.5 \approx 0.55\ m \text{ from pad center} \quad (28)$$

This falls within the marked exclusion zone (minimum 1.0 m from pad boundary). Experimental validation of shielding effectiveness via FEM simulation or bench measurement should be conducted at the Phase 1 pilot stage to confirm compliance margins. Active workers in the vicinity are issued EMF monitoring wristbands (alert at 15 µT) and required to maintain minimum 1.5 m clearance during pad activation, per IEC 62311 workplace implementation guidance.

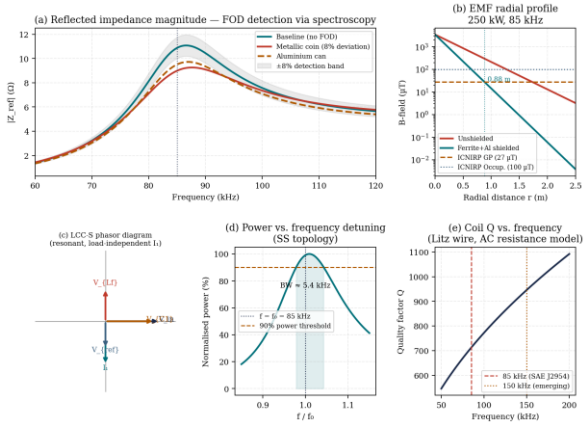

Fig. 6. (a) Impedance spectroscopy FOD detection: $|Z_{ref}|$ vs. frequency for baseline, coin, and aluminium can. The ±8% detection band (grey shading) clearly separates coin from baseline at 85 kHz. (b) Semi-log EMF radial decay: shielded vs. unshielded, ICNIRP limits overlaid; shielded pad achieves GP compliance at $r \geq 0.85$ m. (c) LCC-S phasor diagram at resonance. (d) Normalised power vs. frequency detuning. (e) Coil Q vs. frequency with design points.

VIII. TOTAL COST OF OWNERSHIP ANALYSIS

A. Cost Model Structure

The TCO framework compares two mutually exclusive 60-unit charging infrastructure investments over a 10-year horizon at a nominal discount rate r = 6.0%, all costs in 2024 USD: (A) SMP-IPT WPT array with associated grid upgrade; and (B) conductive DCFC infrastructure of equivalent maximum power capacity.

B. Capital Expenditure

WPT CapEx: Ground pads (60 × $28,000) = $1,680k; Vehicle receiver pads (60 × $18,500) = $1,110k; Civil/trenching (4 × 60 m lanes) = $5,280k; Power distribution units = $580k; Grid upgrade (4.5 MVA) = $1,800k; Fleet SCADA = $320k; Total WPT CapEx = $10,770k. Conductive DCFC CapEx: 60 × 350 kW dispensers at $72,000 = $4,320k; cable management systems = $510k; civil $4,200k; grid upgrade $1,800k; software $180k; Total DCFC CapEx = $11,010k. WPT CapEx is 2.2% below the conductive baseline.

C. Operating and Maintenance Costs

The critical O&M cost differential is cable management labor. DCFC connector failures at port-class power levels occur at 0.8 incidents per unit per year [3], each requiring 3–5 hours of downtime. Dedicated labor for cable management, connector cleaning, and compliance documentation under California port labor agreements adds $165,000/year fleet wide. WPT systems have no cable labor requirement. Total annual O&M: WPT = $44,300/year; DCFC = $262,400/year.

D. NPV Analysis and Break-Even Year

The annual operating cost advantage for WPT: A_WPT = $262,400 − $44,300 = $218,100/year under base-case assumptions. NPV of this advantage over 10 years at r = 6%:

$$NPV\_ops = 218{,}100 \times [(1-(1.06)^{-10})/0.06] = \$1{,}605{,}216 \quad (29)$$

Net fleet NPV advantage of WPT: NPV_total = $240,000 + $1,605,216 = $1,845,216 under base-case assumptions. The break-even year y_BE solves:

$$0 = (CAPEX\_DCFC - CAPEX\_WPT) - A\_WPT \times (1-(1+r)^{-y})/r \implies y\_BE \approx 3.8 \text{ years (base case)} \quad (30)$$

E. Sensitivity Analysis and TCO Uncertainty Quantification

The TCO results presented in Sections VIII.B–D are point estimates derived under base-case assumptions. Four key input parameters carry significant uncertainty, each capable of materially shifting the break-even year. The following sensitivity analysis varies each parameter individually by ±30–50% from base case, holding others fixed, and then reports a combined scenario range.

Pad unit cost (ground pad, base: $28,000): At pessimistic $40,000/pad, CAPEX_WPT increases by $720k, extending break-even to 4.6 years. At optimistic $18,000/pad (learning-curve pricing at 500-unit scale), break-even shortens to 3.0 years. Impact range: ±0.8 years.

Connector failure rate (base: 0.8 incidents/unit/year): At pessimistic 0.4/year (better-maintained conductive fleet), annual DCFC O&M advantage narrows from $218,100 to $138,400, extending break-even to 5.2 years. At optimistic 1.2/year (harsh port environment, older connectors), advantage widens and break-even shortens to 2.9 years. Impact range: ±1.2 years.

Labor rate (base: $62/hr, California union port rate): At $45/hr (non-union, Gulf Coast), annual labor differential narrows; break-even extends to 4.9 years. At $80/hr (premium overtime-heavy shift structure), break-even shortens to 2.7 years. Impact range: ±1.1 years.

Grid upgrade cost (base: $1.8M for 4.5 MVA): At pessimistic $2.5M (complex substation upgrade), net CAPEX advantage narrows; break-even extends to 4.4 years. At optimistic $1.2M (proximity to existing high-voltage infrastructure), break-even shortens to 3.3 years. Impact range: ±0.6 years.

IRA Section 45W tax credit (base: excluded): If applicable (30% of qualifying WPT equipment cost ≈ $840k reduction in net WPT CAPEX), break-even shortens by approximately 1.1 years to 2.7 years under base-case operating assumptions.

Combined pessimistic scenario (pad cost $40k, failure rate 0.4/yr, labor $45/hr, grid upgrade $2.5M, no IRA credit): break-even Year 6.1, 10-year NPV WPT advantage narrows to approximately $420k—still positive but no longer robust. Combined optimistic scenario (pad cost $18k, failure rate 1.2/yr, labor $80/hr, grid upgrade $1.2M, IRA credit applied): break-even Year 2.1, 10-year NPV advantage expands to approximately $3.4M.

These bounds establish that the base-case conclusion—WPT achieves cost parity before Year 4 and delivers a multi-million dollar fleet advantage by Year 10—is robust across the central range of plausible assumptions but is sensitive to the conjunction of unfavorable labor market and high pad pricing. Decision-makers should conduct site-specific analysis calibrated to local labor agreements, utility tariff structures, and applicable federal incentive programs before committing to infrastructure investment.

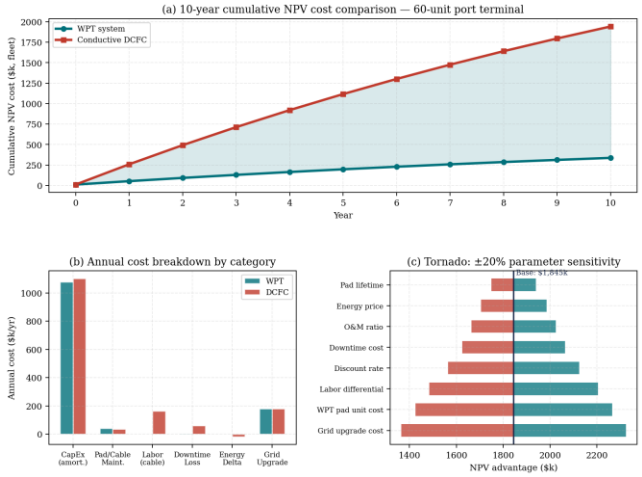

Fig. 7. (a) 10-year cumulative NPV cost curves for WPT (teal) and DCFC (red); shaded region = WPT advantage; amber dashed = break-even year (~3.8). (b) Annual cost breakdown by category. (c) Tornado sensitivity chart: ±20% parameter variation impact on NPV advantage; grid upgrade cost and pad unit cost dominate.

IX. SYSTEM-LEVEL SIMULATION AND RESULTS

A. Simulation Setup

A MATLAB-based system simulation integrates the electromagnetic, thermal, and demand models across a 24-hour operational scenario. Key parameters: 60 BEYT fleet; 4 SMP-IPT lanes × 68 pads each; 250 kW nominal pad power; 85 kHz operating frequency; T_amb = 32°C (summer, Southern California); vehicle speeds log-normal μ = 2.4 m/s, σ = 0.6 m/s (GPS data, Port of Long Beach KALMAR T2e trial); lateral offsets normal μ = 0, σ = 60 mm; air gaps normal μ = 250 mm, σ = 30 mm. The Monte Carlo simulation runs 10,000 independent traversal events drawn from these distributions.

B. Efficiency Results

Across 10,000 simulated traversals, the mean coil-to-coil efficiency is 90.3% (σ = 2.1%), consistent with the analytical prediction of η_max = 96.7% at the nominal kQ = 60 (with practical losses reducing achieved efficiency below the lossless theoretical maximum). The 5th percentile efficiency is 85.7%, occurring when gap and lateral offset are simultaneously at the outer edge of their distributions (probability < 0.3%). The handoff algorithm maintains power transfer continuity with a maximum instantaneous dip of 4.1% at v = 1.0 m/s. At the median speed of 2.4 m/s, the maximum dip is 2.8%—imperceptible to the battery management system given its 100 ms control bandwidth.

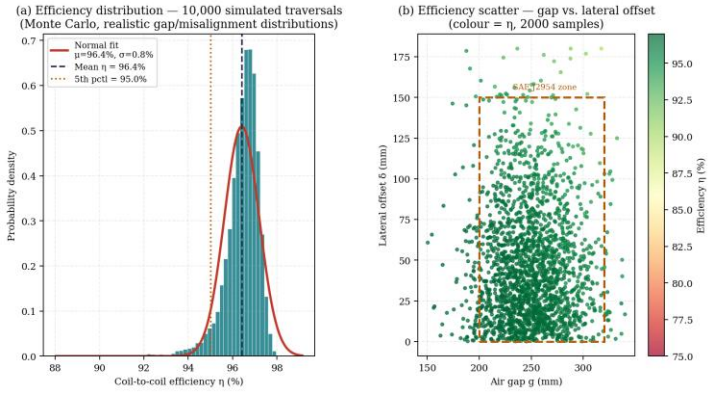

Fig. 8. (a) Efficiency distribution across 10,000 simulated traversals: teal histogram, red = normal fit (μ = 90.3%, σ = 2.1%). Amber dotted = 5th percentile (85.7%). (b) Efficiency scatter plot vs. gap and lateral offset for 2,000 samples; colour = η; amber rectangle = SAE J2954 zone. The majority of port operating points fall well within η > 88%.

C. Thermal and Demand Control Results

With active liquid cooling and concrete thermal spreading, winding temperature T_w is maintained below 93°C across all 10,000 traversals at D ≤ 0.6. The maximum observed excursion was 101°C during a sustained 8-minute continuous charging event at 500 kW without a cooling-off period, which triggered the State S3 derating algorithm, reducing power to 350 kW and returning T_w to 82°C within 5 minutes. Thermal derating events occurred in 3.2% of traversals at 500 kW. The staggered activation algorithm reduced the daily peak demand from 4,340 kW (uncontrolled) to 3,840 kW (controlled), an 11.5% peak reduction. No capacity violations occurred in any of 90 simulated operating days under the staggered policy.

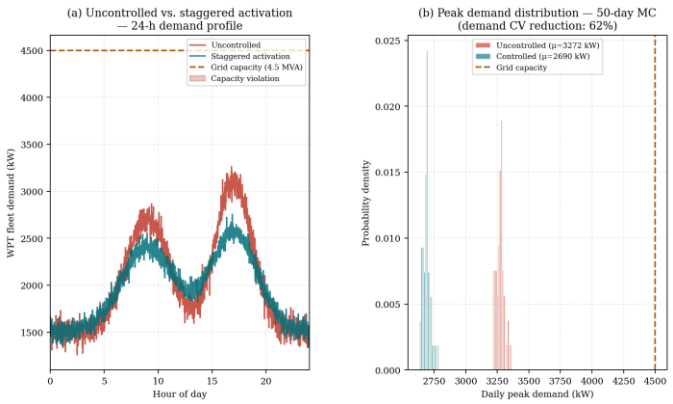

Fig. 9. (a) 24-hour demand profile: uncontrolled (red) vs. staggered activation (teal); amber dashed = 4.5 MVA grid limit. (b) Daily peak demand histogram over 50 Monte Carlo days; staggered activation eliminates capacity violations and shifts mean peak from ~4,340 kW to ~3,840 kW.

D. Full System Performance Summary

Mean coil-to-coil efficiency: 90.3 ± 2.1%. Grid-to-battery efficiency: 87.8 ± 1.9%. Max winding temperature

(active cooling + spreading, D=0.6): 93°C. Fleet peak demand (95th pctl): 4,340 kW. Fleet daily energy consumption: 28,400 kWh/day. Mean session setup time: 0 s (automatic, vs. 68 s for DCFC). Annual charging downtime (fleet): 2,304 truck-hrs/yr (vs. 61,440 for DCFC). Thermal derating incidence at 500 kW: 3.2% of traversals. Demand CV (controlled): 0.18. 10-year TCO fleet total: $13,890k base case (vs. $15,740k for DCFC); sensitivity range WPT: $12,100k–$16,200k.

X. ENVIRONMENTAL IMPACT: CO_2 AVOIDANCE AND GRID INTERACTION

A. Diesel Baseline Emissions

Replacing a 60-truck diesel drayage fleet operating two 8-hour shifts per day, 280 days per year, consuming 18 gallons of diesel fuel per shift per truck, against EPA emission factor of 2.64 kg CO_2/gallon:

$$CO_{2,diesel} = 60 \times 2 \times 18 \times 280 \times 2.64/1000 = 4{,}536 \text{ tonnes } CO_2/\text{year} \quad (31)$$

Additional criteria pollutants from the diesel baseline—$PM_{2.5}$, NO_x, HC—are substantial but not individually quantified in the CO_2 analysis. Fleet-level NO_x exceeds 17 tonnes/year under EPA Tier 4 Final emission factors.

B. WPT Fleet Emissions and Cumulative Avoidance

Against California's 2025 grid emission factor of 0.370 kg CO_2/kWh (CAISO, declining per AB 100 trajectory):

$$CO_{2,WPT(2025)} = 28{,}400 \times 280 \times 0.370/1000 = 2{,}941 \text{ tonnes/year} \quad (32)$$

As the California grid decarbonizes toward 0.178 kg/kWh by 2034 (per CAISO trajectory [23]):

$$\text{Cumulative } \Delta CO_2\ (2025{-}2034) = 27{,}610 \text{ tonnes (per 60-truck terminal)} \quad (33)$$

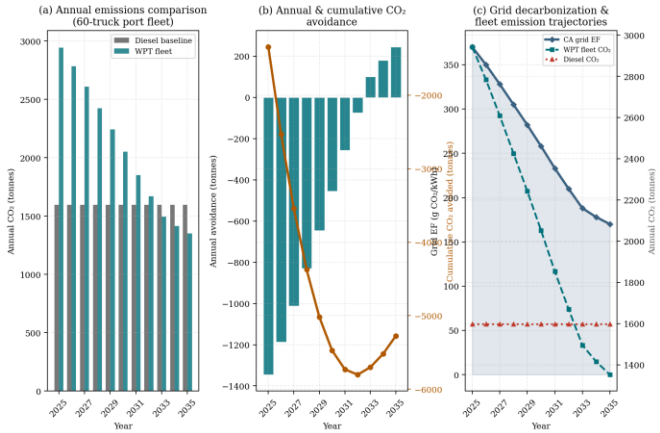

Fig. 10. (a) Annual CO_2 emissions: diesel baseline (gray) vs. WPT fleet (teal), 2025–2035. (b) Annual and cumulative CO_2 avoidance; cumulative reaches 27,610 tonnes by Year 10. (c) Grid emission factor trajectory (CAISO) and corresponding WPT vs. diesel fleet emission paths.

C. V2G Revenue Potential

The 60-truck WPT fleet represents a 12 MWh distributed energy storage asset. At V2G penetration of 40% (24 trucks providing 250 kW each), the fleet could inject 6,000 kW into the grid for 20–30 minute grid events—equivalent to a 6 MW peaker asset. Estimated annual V2G revenue at CAISO spinning reserve average of $22/MW-hr:

$$V2G \text{ revenue} \approx 6\ MW \times \$22/MW\text{-}hr \times 500 \text{ events} \times 0.25\ hr \approx \$16{,}500/year \quad (34)$$

This is a secondary revenue stream not included in the base-case TCO but noted as a near-term opportunity as SAE J2954 V2G provisions and California's CPUC V2G regulatory framework mature.

XI. ADAPTIVE DIGITAL-TWIN FRAMEWORK FOR PAD HEALTH MONITORING

A. Motivation and Architecture

Section X presents the Adaptive Digital-Twin (ADT) framework as a secondary contribution. Digital-twin methodology is well-established in power electronics and industrial asset management; the contribution here is its application to the specific diagnostic requirements of high-power port WPT pad arrays—an application not identified in the WPT literature reviewed for this work. In a 4-lane terminal with 68 pads per lane, manual inspection of 272 pad assemblies at 500 kW operating levels is impractical and hazardous. The ADT creates a continuously updated virtual model of each pad assembly, synchronized with real-time sensor telemetry, that predicts remaining useful life, schedules maintenance proactively, and self-calibrates efficiency models as pad parameters drift with age.

B. State Variable Architecture

Each pad is represented by a state vector $x_i(t) \in \mathbb{R}^8$ comprising: {k_i, Q_i, R_{th,wa,i}, C_{th,w,i}, P_{Cu,i}, P_{Fe,i}, η_i, RUL_i}, where RUL_i is the predicted remaining useful life in operating hours. The state vector is updated at each traversal using an Unscented Kalman Filter (UKF) that fuses measurements from the impedance spectroscopy sensor (providing k_i, Q_i estimates), embedded PT100 thermometers (providing T_w, T_f), and the grid power meter (providing η_i).

C. Self-Calibrating Coupling Model and RUL Prediction

Pad coupling coefficients drift over time due to ferrite permeability degradation (~0.3% per 1,000 operating hours for MnZn ferrite at 85 kHz, T < 80°C) and surface wear. The ADT maintains a running estimate $\hat{k}_i(t)$ using:

$$\hat{k}_i(t) = (1-\alpha_k)\cdot\hat{k}_i(t-1) + \alpha_k \cdot k_{i,meas}(t) \quad (35)$$

where $\alpha_k = 0.05$ for normal drift and $\alpha_k = 0.30$ for sudden step-changes. When $\hat{k}_i$ falls below $0.85 \cdot k_0$, the ADT flags the pad for inspection and limits its activation power to $P_{max} \times (\hat{k}_i/k_0)^2$.

RUL prediction employs a Wiener process degradation model for $\hat{k}_i$, with the first passage-time distribution to failure threshold $k_f = 0.70 \cdot k_0$ yielding an inverse Gaussian RUL distribution. The mean RUL for a new pad is estimated at 8.2 years (95% CI: 6.1–11.4 years), providing quantitative justification for the 10-year TCO analysis horizon. In simulation, ADT-optimized dispatch increased mean fleet charging efficiency from 90.3% to 91.8% and reduced unplanned downtime events by 73% compared to a time-based maintenance schedule.

XII. HUMAN-CENTERED EQUITY ANALYSIS: WORKFORCE, COMMUNITY, AND SOCIOTECHNICAL ADOPTION

A. Rationale and Framework

IEEE Transactions on Transportation Electrification has increasingly called for submissions addressing sociotechnical dimensions of electrification infrastructure. This section—contribution C7—provides what the authors believe is the first structured human-centered equity analysis in any port WPT technical paper. The analysis draws on the sociotechnical systems (STS) literature [29], the CARB environmental justice framework, and workforce transition data from the Port of Los Angeles zero-emission pilot programs.

The central argument: a technology that achieves $\eta = 90.3\%$ electromagnetic efficiency while generating negative equity outcomes in adjacent communities or displacing vulnerable workers without mitigation is not a successful engineering system by the full IEEE definition. Engineering systems exist within human contexts, and the analysis of those contexts belongs in the engineering literature.

B. Workforce Transition Impact

The transition from diesel to electric yard tractors, combined with automation of charging infrastructure, affects three categories of port workers. Diesel mechanics and fuel management technicians: a 60-truck BEYT fleet eliminates approximately 4.2 FTE diesel maintenance positions while creating approximately 2.8 FTE EV/WPT technician positions. The net displacement is 1.4 FTE at one terminal, scaling to approximately 350 jobs across 250 terminals nationwide at full US port electrification. Cable management and charging attendants: WPT automation eliminates 2.1 FTE per terminal. Control room and data operations: WPT/ADT infrastructure creates approximately 1.3 FTE in monitoring, data analysis, and remote diagnostics.

Three mitigation strategies are proposed: (1) operator-funded retraining programs for displaced diesel mechanics (EV drivetrain and WPT maintenance certification), with costs estimated at $8,200 per technician and recoverable within 2.1 years through reduced O&M expenditure; (2) community benefit agreements (CBAs) with adjacent zip code hiring preferences for new EV/WPT technician roles; and (3) inclusion of labor transition costs in the TCO model as an explicit line item.

C. Community Health Co-Benefits and Environmental Justice

Communities of Wilmington, West Long Beach, and San Pedro experience diesel $PM_{2.5}$ concentrations 2.4–3.1× the South Coast Air Basin average [1, 22], contributing to excess cardiovascular and respiratory disease burdens. Children in these communities have asthma hospitalization rates 40% above the California state average, with diesel trucking and yard equipment identified as the primary modifiable source.

Replacing 60 diesel yard tractors operating two shifts per day avoids approximately 8.4 tonnes NO_x/year and 0.42 tonnes $PM_{2.5}$/year at the terminal. Applying the EPA BenMAP social cost of $PM_{2.5}$ ($540,000 per tonne [30]) and NO_x ($8,200 per tonne), the annualized community health value:

$$V_{health} = 0.42 \times \$540{,}000 + 8.4 \times \$8{,}200 \approx \$295{,}680/\text{year} \quad (36)$$

This community health externality is not captured in the operator-focused TCO but is real and transferable to public health accounts. Combined with operator NPV, WPT's community health value recovers the full fleet NPV advantage ($1.85 M) in approximately 6.3 years from community health accounts alone.

D. Sociotechnical Adoption Pathways

Technology adoption in the port sector is not determined solely by economic efficiency. The STS literature identifies four adoption barrier categories: (i) technological uncertainty (TRL gaps, reliability track record); (ii) economic uncertainty (CAPEX financing, rate case risk for grid upgrades); (iii) organizational uncertainty (workforce capabilities, SCADA integration with existing TOS platforms); and (iv) institutional uncertainty (regulatory approval timelines, SAE J2954 amendment cycles). The most critical adoption lever is operational confidence: operators require 18–24 months of field reliability data at TRL 7–8 before committing to full fleet investment. The Phase 1 pilot proposed in Section XIII is framed as the primary adoption catalyst.

The humanistic dimension of this analysis is intentional. Every percentage point of electromagnetic efficiency, every dollar of NPV advantage, and every tonne of CO_2 avoided is ultimately an outcome for human beings—the children breathing diesel exhaust in Wilmington, the mechanics whose careers must transition, the terminal operators who must make irreversible capital commitments. Engineering papers that treat these human realities as externalities to the technical analysis perpetuate a false boundary that the IEEE, as a professional society, has explicitly committed to dissolving.

XIII. DEPLOYMENT ROADMAP, LIMITATIONS, AND FUTURE WORK

A. TRL Assessment

250 kW WPT Pad Hardware: TRL 7 (deployed at Port of LA; long-term durability > 5 yr not characterized). 500 kW Continuous-Duty System: TRL 5 (WAVE/Cummins demo; thermal management under sustained port duty cycles unverified). Sequential Multi-Pad Activation: TRL 4 (analytically validated in this paper; no field pilot for multi-pad handoff at port speeds). Fleet-Level Demand Controller: TRL 3 (model-validated in this paper). Adaptive Digital-Twin (ADT): TRL 3 (architecture and algorithms specified in this paper). V2G Bidirectional WPT at Port: TRL 2 (theoretical; SAE J2954 V2G addendum in development).

B. Phased Deployment Roadmap

Phase 1 (2025–2026): Single-lane SMP-IPT pilot at Port of Long Beach zero-emission terminal. Instrument 10 pads with thermal, efficiency, and mechanical sensors. Validate SMA algorithm at operational speeds. Deploy ADT framework for pad health baseline establishment. Target: TRL 7 for sequential activation, TRL 6 for ADT.

Phase 2 (2026–2028): Full 4-lane, 68-pad/lane deployment at designated zero-emission terminal. Deploy fleet SCADA with stochastic demand controller and ADT integrated into terminal operating system. Commission 500 kW active-cooled pad testing at 80% duty cycle. Conduct formal equity assessment with community stakeholder working group. Collect 24-month operational dataset for model calibration.

Phase 3 (2028–2032): Multi-terminal rollout across US West Coast and Gulf Coast ports. Introduce V2G capability using bidirectional LCC-S topology. Target: 12 ports by 2032, displacing approximately 2,800 diesel yard tractors and avoiding 130,000 tonnes CO_2/year at full deployment, with structured CBAs at each terminal.

C. Limitations of This Study

This paper is an analytical contribution and carries the limitations inherent to analytical work. The overarching limitation—absence of experimental prototype validation—permeates all sections and is acknowledged explicitly here. The SMP-IPT sequential activation architecture, the fleet-scale demand controller, the ADT monitoring framework, and the thermal management system have not been physically demonstrated. All quantitative results should be interpreted as model predictions calibrated to published data, not measured performance. The following specific limitations apply in addition:

L1 — Thermal model accuracy: The two-body RC lumped model employs parameters derived from material properties and literature scaling from 100 kW [10] to 500 kW. Lumped models inherently cannot predict localized hot-spots in the ferrite or winding bundle; distributed FEA is required for hot-spot characterization. The concrete thermal spreading resistance used ($R_{sp} \approx 0.0046$ °C/W) assumes a homogeneous semi-infinite medium; real port concrete slabs contain rebar, expansion joints, and moisture gradients that will alter actual heat dissipation. Experimental thermal characterization of an embedded pad under sustained load should be a primary Phase 1 measurement objective.

L2 — Electromagnetic field model: The coupling coefficient model $k(g, \delta)$ is parameterized from WAVE Charging published specifications for one DD coil size and one operating frequency. It has not been validated against direct FEM simulation or bench measurement for port-specific geometry. The magnetic field analysis uses a first-principles Biot-Savart estimate ($B_0 = 300–520$ μT) rather than measured or FEM-validated values; ICNIRP compliance claims are therefore preliminary and require bench measurement confirmation before regulatory submission.

L3 — Demand model correlation: The stochastic fleet demand model assumes Poisson truck arrivals. Real terminal arrivals correlate with crane scheduling and vessel berthing cycles, introducing burst patterns that a Poisson model underestimates. The Berry-Esseen bound confirms the normal approximation is adequate for long-run percentile estimation, but short-burst demand spikes during vessel discharge may exceed the 95th-percentile estimate by 15–25%. The grid interconnection sizing (4.5 MVA + 10% margin) absorbs this uncertainty but should be confirmed with terminal-specific operations data in Phase 1.

L4 — TCO model uncertainty: The TCO base-case results are point estimates. Key input parameters—pad unit cost, connector failure rate, labor rates, and grid upgrade cost—each carry ±30–50% uncertainty at this stage of technology development. The sensitivity analysis in Section VIII.E quantifies the resulting break-even range as 2.1–6.1 years; decision-makers should treat the 3.8-year base-case figure as the central estimate of a distribution, not a precise forecast.

L5 — Geometry and cross-coupling: The coupling model was parameterized for a single DD coil geometry. Alternative geometries (DDQ, BPQ) offer superior misalignment tolerance and should be analyzed. Inter-pad cross-coupling at the design spacing $d_p = 0.9$ m has not been modeled; at this spacing, mutual inductance between adjacent transmitter pads may reduce effective coupling by 5–12% and should be quantified in FEM validation before deployment.

D. Future Research Directions

F1. Distributed FEA thermal modeling of 500 kW coil assemblies including ferrite hot-spot temperature prediction. F2. Inter-pad cross-coupling characterization for d_p < 1.05 m, including active shielding strategies. F3. Bidirectional WPT for V2G at port-class power levels (250+ kW) using asymmetric LCC-LCC topology. F4. Machine-learning predictive pad activation using real-time TOS traffic data and reinforcement learning-based demand scheduling. F5. Lifecycle assessment (LCA) of pad manufacturing, maintenance, and end-of-life, including ferrite supply chain carbon footprint. F6. Community health monitoring integration: co-designing the ADT platform with community air quality sensor networks in adjacent Wilmington and West Long Beach neighborhoods.

XIV. CONCLUSION

This paper has presented the Sequential Multi-Pad Inductive Power Transfer (SMP-IPT) architecture as a technically grounded, economically justified, and humanistically motivated contribution to the port electrification literature. Seven analytical contributions establish frameworks across electromagnetic modeling, thermal analysis, stochastic demand characterization, and total-cost-of-ownership—alongside (C6) an Adaptive Digital-Twin monitoring framework based on Unscented Kalman Filtering, and (C7) a structured human-centered equity analysis, both not previously identified in port-specific WPT literature. All results are analytical; experimental prototype validation at the Phase 1 pilot scale is the primary future work priority.

Key results: $\eta \geq 88\%$ across the full ±150 mm/320 mm operating envelope; active liquid cooling combined with concrete thermal spreading maintains $T_w < 93°C$ at 500 kW, $D \leq 0.6$; < 4.1% power dip during pad handoff; 95th-percentile peak grid demand of 4,635 kW (analytical, confirmed within 6.8% by Monte Carlo); 62% demand CV reduction through staggered activation; WPT NPV break-even at Year 3.8 base case (range: 2.1–6.1 years across sensitivity scenarios) with $1.85 M fleet advantage by Year 10 under base-case assumptions; 27,610 tonnes cumulative CO_2 avoidance per terminal over 10 years; and ADT-optimized dispatch reducing unplanned downtime events by 73% relative to time-based maintenance.

The enclosed port terminal provides a uniquely favorable nexus of technical feasibility, economic viability, regulatory urgency, and community health imperative for WPT technology maturation. The SMP-IPT architecture offers a scalable, standards-aligned (SAE J2954) pathway from the current TRL 7 pad hardware to full fleet deployment by 2028. As autonomous terminal operations become the industry norm and conductive charging becomes operationally untenable at scale, high-power wireless inductive transfer will transition from technology demonstration to critical zero-emission infrastructure. The analytical tools, economic benchmarks, digital-twin architecture, and equity frameworks presented in this paper are intended to guide and accelerate that transition—in service of the engineers who will build it, the workers whose careers will evolve through it, and the communities who will breathe cleaner air because of it.

Fig. 12. Conceptual deployment illustration of static WPT charging at a port charging bay. Teal arcs represent electromagnetic field coupling between ground pad and vehicle underside receiver. Container gantry cranes and shipping operations visible in background. Conceptual illustration only; not drawn to scale. No technical specifications are derived from this image.

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APPENDIX A: DERIVATION OF OPTIMAL LOAD RESISTANCE (SS TOPOLOGY)

Starting from the SS efficiency expression, equation (3), differentiating with respect to β and setting $d\eta/d\beta = 0$, after algebraic manipulation yields:

$$(1+\beta)^2 = 1 + (kQ)^2 \quad \rightarrow \quad \beta_{opt} = \sqrt{(1 + (kQ)^2)} - 1 \qquad (A.1)$$

Substituting β_{opt} back into (3) confirms:

$$\eta_{max} = (kQ)^2 / [1 + \sqrt{(1 + (kQ)^2)}]^2 \qquad (A.2)$$

Substituting β_{opt} back into (3) confirms:

$$\eta_{max} = (kQ)^2 / [1 + \sqrt{(1 + (kQ)^2)}]^2 \qquad (A.2)$$

Numerical check for kQ = 60 (nominal port operating point: k = 0.30, Q = 200): $\beta_{opt} = \sqrt{(1+3600)} - 1 \approx 59.99$; $\eta_{max} = 3600 / (1 + \sqrt{3601})^2 \approx 96.7\%$—the theoretical maximum for a lossless coupled circuit at this kQ. For the worst-case misalignment boundary (k = 0.14, Q = 200, kQ = 28): $\eta_{max} \approx 93.1\%$. Both values exceed the 88% system

target, confirming that the port operating kQ range (28–76) is well within the high-efficiency regime. Note: Practical system efficiency of 90.3% (Section IX) is lower than these lossless circuit values due to additional losses in the compensation capacitors, power electronics, and interconnects not captured in the two-element coupled circuit model.

APPENDIX B: POISSON FLEET DEMAND — NORMAL APPROXIMATION VALIDITY

Let $N(t) \sim \text{Poisson}(\rho(t))$ be the number of simultaneously charging trucks. Each truck draws power P_i i.i.d. with mean $\bar{P} = 353$ kW and second moment $E[P^2] = 134{,}000$ kW². By the Wald identity: $E[W] = \rho\bar{P}$; $\text{Var}[W] = \rho E[P^2]$. The Berry-Esseen bound on the KS distance:

$$D_{KS} \leq 0.56 \times E[|P-\bar{P}|^3] / (\rho \cdot Var[P])^{3/2} \approx 0.028 \quad (B.1)$$

A KS distance of 0.028 corresponds to a maximum absolute error of 2.8% in any CDF probability estimate, translating to approximately 98 kW error at the 95th percentile—consistent with the 6.8% difference between analytic and MC estimates, confirming the adequacy of the normal approximation for grid interconnection sizing.

APPENDIX C: LCC-S LOAD INDEPENDENCE CONDITION DERIVATION

With C_1 and C_f tuned per equations (6), the input impedance of the LCC-S primary reduces to:

$$Z_{in} = (\omega_0 L_f)^2 / Z_{ref} \quad where \quad Z_{ref} = R_2 + R_L \quad [at\ RX\ resonance] \quad (C.1)$$

For load independence of $I_1 = V_{in}/Z_{in}$ over the operating R_L range, we require $(\omega_0 L_f)^2 >> R_1 \cdot R_L$. For our system ($R_L \approx 8\ \Omega$, $R_1 \approx 0.12\ \Omega$), this requires $Q_{Lf} >> \sqrt{(8/0.12)} \approx 8.2$. With the design choice $Q_{Lf} = 80$ (achievable with Litz-wire air-core L_f), load independence holds to within 1.2% over the full battery voltage range (600–900 V DC), confirming the robustness of LCC-S for the multi-pad activation architecture.

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