Multi-Port Wireless Charging Architectures for Sustainable and Decarbonized Waterborne Transportation

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Abstract—Battery electric vehicles, harbor craft and autonomous vessels mandate high-power charging in a saltwater environment where they are moving, corroding and in contact with humans; while all of these technologies exist, to date no one has conquered the challenge of power connectors in that environment. This survey covers multiple-port wireless dock-and-charge schemes for waterborne transportation focusing particularly on inductive/capacitive wireless power transfer (WPT), multiple-port modular topologies, interaction with on-port energy systems, dock sensors for alignment and scheduling at the vessel level. This review focuses on charging at close distances – either docked or quasi-docked – and not long-range docking via microwave or laser transmission. The literature is split into the following categories: Coupling Hardware, Compensation and Control, Multi-port Power Sharing, Port Energy Management and Maritime Safety Validation. The discovery is that while single vessel wireless charging is the closest to being deployed, multi-port wireless charging docks still remain largely in the research & prototype phase.

Keywords: Wireless power transfer, electric vessels, multi-port charging, inductive power transfer, capacitive power transfer.

1. Introduction

The switch from diesel to electric and hybrid-electric powered waterborne transport is most pronounced in ferries, as well as in inland water and harbor work boats and autonomous surface vessels performing on-demand transportation with repeatable missions over fixed routes with controlled docking locations. Battery-electric ships have lower local emissions, lower noise levels and no on-board fuel handling, while the availability of shore-power and berths and charging time all have a significant impact on the economics of operation. More recent techno-economic analyses, however, suggest that under certain conditions a number of different battery-electric shipping alternatives are viable [1], [2]. The charging interface has turned out to be a major design challenge, therefore. Mechanical connectors are susceptible to corrosion, arcing potential, insulation stress, wear, attack from salt water, splash, tidal variation and repeated connection when high power is being transferred via conventional plug-in shore charging.

Automatic conductive charging arms may minimize the need for manual handling, but may add moving parts and maintenance needs. Contactless options are available such as inductive power transfer (IPT) or capacitive power transfer (CPT). It has been suggested that high power marine IPT can be used in ferries and plug-in hybrid ferries [3]. Due to the peculiarity

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of the water medium, coil spacing, magnetic leakage and parasitic losses, maritime WPT is different from road-vehicle charging. In this paper, the emerging multi-port wireless dock-and-charge infrastructure for waterborne transportation is discussed. In practice, a port may have multiple wireless pads on one quay, have multiple berths having the same shore-side direct current (DC) bus and have multiple vessels charging at the same time. Multi-port operation brings down the idle time of the chargers and also helps reduce the oversizing of the batteries, but it also results in the challenges associated with cross-coupling, power-sharing, scheduling, electromagnetic compatibility and safety of the system. The issue is not just in coupler design, but also pertains to power electronics, control and port-energy management. The summarized literature reviews still show a wide degree of fragmentation. The reviews refer to ship electrification concerning converters, shipboard DC microgrids, hybrid fuel-cell systems and onboard power architectures [4]–[10]. Compensation topologies, interoperability, coil misalignment and standards are covered in electric vehicle (EV) wireless-charging reviews [11]. For multi-receiver WPT, power allocation, frequency selectivity and modular transmitter–receiver configurations are studied [12]–[17] and [18]. But these streams seldom are included in a maritime-port context. So, it is important to add to a complete multi-port wireless dock charging review vessel dwell time, shore-grid limitations, coupler movement, wet insulation, power sharing, berth scheduling and safety validation.

The review is organized in topical, not chronological, order. Six questions were asked to filter literature from 2015 to 2026: What type of vessels are taken into consideration? What is the kind of coupling used? Which power level and gap does the study consider? Does the work involve experiments/simulations? What about interaction between multiple ports / multiple loads? Is it accounted for that they may be restricted by port-grids? According to these questions, literature existing on the subject is categorized into six groups, the first being maritime electrification and port energy systems, the second near field WPT couplers, the third compensation and conversion, the fourth control, the fifth multi-port and multi-receiver WPT and the last implementation evidence. The taxonomy aids in direct comparisons to deployable approaches and mathematically promising concepts. The identified central research challenge is multi-port wireless charging that is capable of overcoming motion, while also being aware of the queue. Waterborne charging docks are subject to a variety of issues such as the lateral drift, the tidal level difference, the wave-induced heave, the changing draft and uncertain arrival times. Meanwhile, the port operators should strive to reduce peak demand and minimize the delay of vessels. Hence, the crux of the issue is not to maximize the energy efficiency of a system for a specific air gap but to ensure safe, stable and equitable service of energy to multiple ships that undergo changing energy demands and coupling conditions during a short docking time.

The rest of this Review is framed as follows. The survey boundary and taxonomy are defined in Section 2. Section 3 is an analysis of the literature by the different categories of the techniques. The system level framework and mathematical relationships between energy, coupling, scheduling and safety are presented in Section 4. In Section 5, a comparative critical analysis between implementation oriented and simulation-oriented methods is done. Open challenges and future directions are discussed in Section 6 and the conclusion of the review is given in Section 7. Figure 1 depicts the conceptual architecture, an overview summary.

2. Survey Boundary and Review Positioning

2.1 Exact Boundary of the Survey

This review focuses on near field charging of waterborne vehicles (WBVs) at a vehicle docking point (VDP) including a dock, berth, quay, pontoon, floating platform or controlled charging station. The charger can be on top of the water, partially in the water, attached to a dock wall or as part of a floating solar or a port mega grid platform. The receiving side is supposed to be on-board ferries, small passenger vessels, autonomous surface vessels, workboats, electric yachts or harbor craft. When maritime gap and installation constraints dictate a single mode, power transfer is based on IPT, CPT or hybrid couplers. The review is limited to cases of long-distance beaming, laser beaming, purely wired charging at shore, and generic EV wireless charging research not focused on maritime factors. With regard to this, there are two related meanings for the word “multi-port”. First, it is the designation for several physical charging interfaces - all electrically linked to a single shore-side platform of power-electronic components.

Second, it means that more than one vessel/receiver module is receiving power from the same energy source or family of energy sources or transmitter. These are both significant interpretations in ports. Once the price of high-power infrastructure equipment becomes higher, having shared wireless charging infrastructure will become more valuable, particularly in the context of multiple vessels that need a specific turnaround time in the same berth area. Since 2015, research efforts for underwater WPT, multi-receiver WPT, maritime CPT, DC seaport microgrids and electric-vessel charging have gradually risen, and a few commercial trials of marine wireless charging are on the rise. There is currently no full design methodology that explains how to size, control, verify and certify a wireless docking system for multiple vessels for either sequential or parallel docking applications.

2.2 Review Questions

This review will be organized around five research questions (RQs). RQ1: What are the most appropriate coupling technologies which can be used for docked waterborne charging under wet-insulation and misalignment conditions? RQ2: What is the compensation/cv topologies that are capable of constant-current/constant-voltage (CC/CV) charging without significantly high reactive stress? RQ3: What are some of the ways that are being used to enable fair power sharing between several transmitters and receivers without inducing cross-coupling instability? RQ4: What are sensible scheduling problems for wireless charging at ports considering grid limits, renewables and vessel dwell times? RQ5: What approaches have moved from Simulation to Lab & Field validation?

2.3 Main Taxonomy

The classification taxonomy, which is presented in Table 1, is used to classify the literature. The studies are not presented chronologically since this would put an impediment to the identification of design gaps that transverse different research communities.

Table 1. Classification taxonomy

Taxonomy group	Main design concern	Typical methods	Evidence maturity
Maritime electrification and port microgrids	Battery size, shipboard DC distribution, charging demand, emissions, and port-grid limits	Powertrain modelling, DC microgrid control, voyage scheduling, techno-economic assessment	High for wired charging and shipboard converters; medium for wireless integration
Coupler and medium modelling	Air/water gap, misalignment, seawater conductivity, parasitic capacitance, insulation, leakage field	IPT coils, CPT plates, dual-medium couplers, FEM, equivalent circuits	Medium for IPT; low-to-medium for maritime CPT
Compensation, converters, and control	Efficiency, constant-current/constant-voltage charging, ZVS/ZCS operation, thermal limits	SS/SP/PS/PP, LCL/LCC, bidirectional DC-DC, SiC/GaN inverters, phase-shift control	High in road EV WPT; medium in marine prototypes
Multi-port and multi-receiver WPT	Power allocation, random receiver access, cross-coupling, interoperability, modular expansion	Segmented transmitters, frequency-selective receivers, MTMR optimization, scheduler-based power sharing	Mostly laboratory and simulation; limited maritime validation
Dock operation and safety validation	Berth queue, vessel drift, foreign object detection, EMI/EMC, emergency stop, crew safety	Alignment sensing, BMS/EMS coordination, probabilistic dwell-time models, cyber-physical monitoring	Low; standards and field test protocols remain incomplete

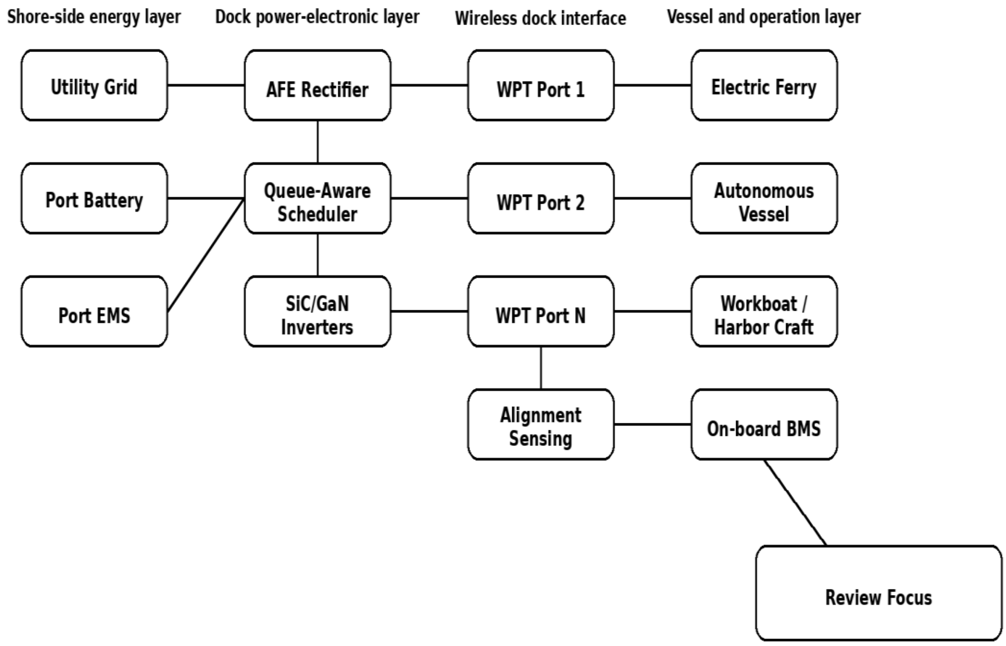

Figure 1. Multi-port wireless dock-and-charge architecture for decarbonized waterborne transport. AFE, active front end.

3. Literature Synthesis by Technical Category

3.1 Electric Marine Transportation and Port Energy Systems

The first section deals with the lit of wireless docks, and why that is important. Electric vessels are not stand-alone products; they are an element of a shore–ship energy system. Space and weight are limiting factors and compact, efficient and fault tolerant onboard power systems are required [4]. Reviews of shipboard DC microgrids show that batteries, fuel cells, photovoltaic sources, and propulsion drives can be integrated effectively, although protection and stability remain challenging [5], [7], [19]. For wireless docking, this means the charger cannot be designed as a standalone pad. It must communicate with the vessel battery management system (BMS), the shore-side DC bus, the protection layer, and the port energy management system. Battery-electric vessels are especially sensitive to these integration requirements. There may be just a few minutes in which to load passengers on a ferry. Harbor craft can remain longer but will arrive randomly. The decision about practical battery sizing is determined by studies on ship electrification economics, where the availability of charging and adaptation of a route is of utmost importance. During normal docking, a wireless charger will be able to add energy without increasing crew workload. However, for several vessels using a terminal or for the need of multiple receiver modules on a single high-power vessel, multi-port design is necessary. The research in the microgrid in ports has direct relevance. A study of the impact of voltage control on a seaport where the voyage navigation is planned reveals that these two functions can be optimized simultaneously [20].

Research on electric-vessel charging stations shows that port-side charging infrastructure can support vessel charging while also improving local power quality [21]. Although not all of these studies use wireless interfaces, they provide supervisory-control concepts relevant to wireless docks. They also show that peak demand, berth delay, and renewable utilization are important evaluation metrics in addition to coil efficiency. Reviews of battery-only craft [8],

[10], hybrid marine power systems, and fuel-cell/battery integration further broaden the design space. Accordingly, a future wireless dock may serve battery-powered, fuel-cell-powered, or hybrid vessels. Such a charger must accommodate multiple charging profiles, state-of-charge windows, and safety limits. A multi-port wireless dock can therefore be viewed as a contactless node within a maritime microgrid.

3.2 Wireless Coupling Systems for Docked Marine Vessels

IPT is the most advanced technology for high power charging underwater. It is based on an apparatus using a magnetic coupling between the transmitter and receiver coils and working with resonant compensation in order to ensure larger air gaps as compared to the conventional inductive coupling. For marine applications, high-power IPT charging of a battery electric ferry (BEF) in a short dwell time has already been proposed in [3]. Environmental factors can also impact the coupling, losses and heating as in underwater IPT studies [22]. The motion that occurs in maritime receivers during mooring activities increases the nominal misalignment tolerance, compared to road-vehicle charging. Although CPT is less developed than IPT, attractive form factors can be achieved for some maritime applications such as plates in bankside structures in proximity to the sea-level or plates in dockwalls. Shore-to-ship and underwater CPT studies [23], [24] have shown that the water, insulation layers and parasitic capacitances should be taken into consideration separately in the model. It is noteworthy that the problem is a dual medium in that the coupler might interact with air, fresh water, sea water, coatings, fenders, biofouling, and hull materials. Although CPT can, in theory, have a high-power density, more evidence regarding safety, leakage current and aging of the insulation is required before widespread use. Another direction that shows potential is floating-solar wireless charging. Contactless charging of electric ships is a practical possibility thanks to recent laboratory studies carried out with the connection of local renewable generation [25].

It applies to islands, marinas, fishery harbors, and other remote locations where it is too expensive to extend the grid. The floating platforms add further issues to deal with, as well as motion and cable management. As such, this is not a complete multi-port berth solution but instead, a laboratory demonstration of the concept. Hybrid (IPT–CPT) or modular designs could be effective in ports that host different ships. Some dock-face designs are segmented, which allows only those transmitter segments that are near the receiver to activate – thus increasing tolerance to docking errors. It comes at a cost and adds to the control complexity as the main trade-off. For multi-port setups, there needs to be some coordination with the scheduler, inverter rating and vessel detection.

3.3 Power Electronic Converters and Control Architectures

The coupler is loosely coupled, and is highly reactive, so the function of the compensation network is necessary for high power WPT cases. There are several structures in wireless charging of EVs widely used: classical SS, SP, PS, PP, LCL and LCC [26], [27]. The review of compensation methods and bidirectional WPT indicates that the appropriate topology needs to be chosen that corresponds to the inverter, rectifier, desired output characteristic, and load range [28]. The simplest charging profile that is usually followed in practice is a two-stage charging process with constant current followed by constant voltage. A fixed-frequency network supporting a given gap may perform poorly when the vessel moves to modify the gap and/or alignment. Consequently, research on power converters for ship electrification, which can be connected to medium-voltage alternating current (AC), port DC grid, renewable DC or buffer battery [4], [7] is also relevant.

Requirements for insulation and thermal management and maintainability of the equipment are even higher in a maritime setting, while silicon carbide (SiC) and gallium nitride (GaN) devices can improve the power density and switching speed. It is vital to be able to isolate a fast fault in the wireless dock, to prevent propagation of an AC-side charger fault to the ship's DC bus or to the port's DC bus. There are also issues related to interoperability. Interoperability is another practical concern. EV wireless-charging reviews discuss standards, frequency selection, communication, alignment, and safety [29], [30], but equivalent maritime standards are still limited. Because a port may serve many different vessels with different receiver geometries, a wireless dock cannot scale as a public-port service unless an interoperability layer is defined. Mechanical docking envelopes, electrical compensation classes, communication protocols, and emergency-stop behavior are therefore all key elements of interoperability. Control must be considered at both local and supervisory levels. Local control regulates inverter frequency, phase shift, output current, and soft-switching behavior. Supervisory control distributes power among ports, limits peak demand, accounts for vessel departure times, and incorporates renewable-generation forecasts. These layers are not independent. In a multi-port dock, supervisory scheduling changes resonant-network loading, while coupling disturbances at the port level may require rescheduling of power allocation. Consequently, local and supervisory control should be co-designed.

3.4 Multi-Node Wireless Power Transfer Networks

Multi-receiver WPT provides the closest technical background for multi-port dock charging. Frequency-selective WPT can route power to intended receivers through differentiated resonant frequencies [12]. Miniature multi-receiver systems demonstrate smart power distribution at small scale [13]. Random-access WPT enables load connection and disconnection without redesigning the full system [14]. Multiple-transmitter/multiple-receiver modular structures can improve field uniformity and misalignment tolerance [15]. Although these concepts are highly relevant to ports, they have not yet been validated under seawater exposure, high-power marine insulation requirements, or realistic boat motion. Multi-port charging is more complex than simple parallel charging because one receiver can alter the effective impedance seen by another when several receivers are magnetically or capacitively coupled to the same transmitter family. This interaction can reduce efficiency, distort sharing, and generate overvoltage in compensation elements.

Recent designs include single-transmitter/multi-receiver systems and exceptional-point methods that target efficient power allocation under receiver movement [16], [17]. Capacitive WPT with frequency bifurcation may also reduce sensitivity to receiver distance. Although these are important theoretical advances, high-power validation and safety margins are still required before maritime deployment can be considered. Multi-port scheduling remains underdeveloped in the WPT literature. Most studies optimize coil dimensions or equivalent-circuit parameters and test only one or two loading points. A practical port-level scheduler should answer four questions: Which vessel should be charged first? Which wireless interface should be activated? How much power should each vessel receive? How should peak demand be limited? Berth time, state of charge, required departure energy, coupling quality, thermal state, and shore-grid price are all inputs that should be available to the scheduler. Queue-aware power sharing therefore represents a key unresolved gap in waterborne wireless docks.

3.5 Performance Evaluation and Evidence Assessment

Table 2 summarizes the evidence types found in the literature and their value for a practical multi-port marine dock. The table is intentionally critical because similar reported efficiencies can hide very different implementation readiness.

Table 2. Performance evaluation

Evidence type	What it proves	Main weakness for maritime multi-port charging	Implementation value
Equivalent-circuit analysis	Explains resonance, load matching, compensation stress, and receiver interactions	Often assumes fixed coupling, dry environment, ideal sensors, and known load	Necessary but not sufficient
FEM / field simulation	Shows leakage field, coil/plate geometry, medium losses, and misalignment trends	Material aging, biofouling, thermal cycling, and metallic dock structures are hard to model fully	Useful for design screening
Small laboratory prototype	Verifies power transfer and control under limited voltage/current	Usually low power, short test duration, and limited vessel-motion emulation	Medium value if measurements are transparent
High-power laboratory prototype	Tests thermal behavior, soft switching, insulation, and fault response	Expensive; still may not include port queue, tide, salt spray, or real docking impact	High value for technology readiness
Field demonstration	Shows operator acceptance, maintenance, safety, and berth integration	May be proprietary and may not publish detailed data	Highest value but rare
System-level optimization	Quantifies peak demand, delays, renewable use, and fleet energy cost	Can become unrealistic if charger efficiency and coupling limits are assumed constant	High value when coupled to hardware constraints

4. Proposed Survey Framework and Mathematical Connection

4.1 Docking-Time Energy Requirements

A vessel arriving at berth *i* has a required departure energy that depends on propulsion energy, hotel load, reserve margin, and battery health limits. The wireless dock must deliver this energy inside the available dwell time. The required energy balance is expressed in (1):

$$E_i^{req}=E_i^{route}+E_i^{aux}+E_i^{reserve}-E_i^{arr} \tag{1}$$

Here, i identifies the vessel, and E_i^{req} is its required charging energy. In (1), E_i^{route} is the expected route energy after departure, E_i^{aux} is auxiliary load energy, E_i^{reserve} is the mandatory reserve, and E_i^{arr} is the usable battery energy at arrival. The energy transferred wirelessly through port j is given by (2):

$$E_{ij}^{\text{ch}}=\int_{t_i^{arr}}^{t_i^{dep}} \eta_{ij}(t)P_{ij}^{tx}(t)u_{ij}(t)\, dt \quad (2)$$

In (2), $\eta_{ij}(t)$ is the time-varying WPT efficiency, $P_{ij}^{\text{tx}}(t)$ is transmitter-side power, and $u_{ij}(t)$ is a binary connection variable. This expression shows why a constant-efficiency assumption is weak for waterborne charging. Efficiency changes with lateral offset, vertical gap, vessel motion, and receiver temperature. Here, j identifies the charging port, t denotes time, E_{ij}^{ch} is the energy transferred to vessel i through port j, and t_i^{arr} and t_i^{dep} are the arrival and departure times, respectively.

4.2 Coupling-Aware Power Transfer

For near-field WPT, the coupling coefficient k is the main bridge between mechanical docking accuracy and electrical performance. A practical misalignment-sensitive approximation is given in (3):

$$k_{ij}(t)=k_0\exp\left[-\left(\frac{\sqrt{\Delta x_{ij}^2(t)+\Delta y_{ij}^2(t)}}{r_c}\right)^2\right]\left(1-\frac{|\Delta z_{ij}(t)|}{z_c}\right) \quad (3)$$

Here, $k_{ij}(t)$ is the coupling coefficient for vessel i and port j at time t, and k_0 is its value at zero offset. In (3), Δx, Δy, and Δz represent lateral and vertical offsets; r_c is a characteristic horizontal tolerance; and z_c is a vertical tolerance. This expression is not a universal coupler law, but it is useful for scheduling because it converts docking quality into an estimated power-transfer limit. A simplified efficiency indicator is given in (4):

$$\eta_{ij}(t)\approx\frac{k_{ij}^2 Q_t Q_r}{1+k_{ij}^2 Q_t Q_r+\phi_{\text{loss}}} \quad (4)$$

In (4), Q_t and Q_r are transmitter and receiver quality factors, and φ_{loss} represents converter, copper, core, medium, and shielding losses. This equation explains why high-Q resonant operation can improve efficiency but may also increase sensitivity and overvoltage stress. Here, Q denotes a quality factor.

4.3 Multi-Port Scheduling Objective

A multi-port dock must decide the power allocation $p_{ij,t}$ between vessel i and port j at time step t. The scheduling objective is formulated in (5):

$$\min_{p,u}\left[\sum_i \alpha_i D_i+\beta P_{\text{grid}}^{\text{peak}}+\gamma\sum_t c_t P_{\text{grid},t}-\delta\sum_t P_{\text{ren},t}^{\text{use}}\right] \quad (5)$$

In (5), α_i, β, γ, and δ are objective weights; $P_{\text{grid}}^{\text{peak}}$ is peak grid power; $P_{\text{grid,t}}$ is grid power at time step t; and $P_{\text{ren,t}}^{\text{use}}$ is utilized renewable power. The decision variables p and u denote power allocations and binary connection states, respectively. In (6a)–(6c), $P_j^{\max}$ is the maximum port power, P_i^{BMS} is the vessel power limit imposed by the BMS, and $P_{\text{grid}}^{\max}$ is the maximum grid power. The terms represent vessel delay D_i, grid peak power, energy cost or carbon intensity c_t, and renewable energy utilization. The charger, vessel, and grid power constraints are specified in (6a)–(6c):

$$\sum_i p_{ij,t} \le P_j^{\max} \tag{6a}$$

$$\sum_j p_{ij,t} \le P_i^{\mathrm{BMS}} \tag{6b}$$

$$P_{\mathrm{grid},t} \le P_{\mathrm{grid}}^{\max} \tag{6c}$$

The corresponding energy-delivery, thermal, and leakage-field safety constraints are given in (7a)–(7c):

$$E_i^{\mathrm{arr}} + \sum_{j,t} \eta_{ij,t}\, p_{ij,t} \Delta t \ge E_i^{\mathrm{dep}} \tag{7a}$$

$$T_{\mathrm{coil},j,t} \le T_j^{\max} \tag{7b}$$

$$\left| B_{\mathrm{leak},t} \right| \le B^{\mathrm{lim}} \tag{7c}$$

Equations (5), (6a)–(6c), and (7a)–(7c) show that the open problem is not only WPT efficiency. It is the joint feasibility of energy delivery, berth time, thermal limits, leakage-field limits, and grid constraints. A charging method that is optimal for one vessel may be poor when several vessels compete for one dock. In (7a)–(7c), $\eta_{ij,t}$ is WPT efficiency at time step t, Δt is the time-step duration, E_i^{dep} is required departure energy, $T_{coil,j,t}$ is the coil temperature at port j and time step t, T_j^{max} is its maximum permitted temperature, $B_{leak,t}$ is the leakage magnetic field at time step t, and B^{lim} is its limit.

4.4 Novel Challenge: Queue-Aware Wireless Power Allocation

The central research challenge identified in this review is motion-tolerant, queue-aware power sharing. Coupler design and motion-compensation control have been studied extensively on their own, and queue-aware charging has been examined in port energy management and EV charging. However, their integration remains weak. Poor coupling at one vessel may require greater shore-side power to deliver the same battery energy, which can influence the charging order across a multi-port dock. In such cases, the scheduler may need to prioritize another vessel first, subject to operational deadlines that cannot always be delayed. Energy demand, departure priority, coupling quality, and thermal condition should therefore all be considered in fair power allocation. A feasible practice would involve two layers of controllers. The lower layer is for estimating, in real time, the coupling, alignment and thermal state at each wireless port. The upper layer is a rolling-horizon problem that takes into account predicted departures, electricity price, renewable generation, and required energy. This will overcome a typical deficiency of current literature: laboratory operation is optimized with the laboratory coupling set, but the operational queue is neglected.

5. Comparative Tables and Critical Analysis

Table 3 compares the main technical approaches. It distinguishes realistic implementation paths from methods that are still mostly simulation-based or early-stage laboratory ideas.

Table 3. Comparison of the main technical approaches

Approach	**Strengths**	**Limitations**	**Realistic implementation level**
Single-port high-power IPT	Most mature; contactless; suited to ferries with repeatable docking; corrosion-free interface	Needs accurate mooring, magnetic shielding, high-power thermal design, and standardized vessel receiver	High for fixed-route ferries and selected harbor routes
Underwater IPT	Can hide coupler below deck or waterline; useful for autonomous craft and protected stations	Seawater loss, maintenance, marine growth, insulation monitoring, and retrieval access are difficult	Medium; suitable first for controlled low-to-medium power
CPT / underwater CPT	Flat plates can fit dock walls; potential for high power density and low magnetic leakage	Parasitic capacitance, leakage current, insulation aging, and safety certification remain challenging	Low-to-medium; promising but needs field evidence
Segmented transmitter array	Improves misalignment tolerance and allows modular multi-port dock faces	More switches, sensors, coordination, and fault points; higher capital cost	Medium when paired with robust sensing
Frequency-selective multi-receiver WPT	Can address multiple receivers and reduce unwanted loading	Sensitive to component drift and interoperability; may complicate standards	Low-to-medium; strong in lab, less proven in ports
Random-access multi-load WPT	Supports vessels connecting/disconnecting without complete redesign	Power sharing and protection become complex at high power	Medium for small autonomous craft; low for MW-class vessels
Port microgrid coordinated charging	Controls peak demand and renewable use; links voyage and berth decisions	Often assumes simple charger models and ignores coupling dynamics	High for wired ports; medium for wireless ports
Floating solar wireless charging	Useful for remote docks and clean-energy demonstration	Power density, motion, anchoring, maintenance, and weather exposure limit near-term scale	Low-to-medium; good for pilots rather than busy terminals

5.1 Critical Analysis

For a fixed-route ferry, it appears that single-port / two-port high power IPT is the most feasible solution in the near-term. This is because it has reliable docking trajectories, duration, and energy consumption. Despite this, there are still engineering risks due to the conditions of operation. Another realistic scenario is port-microgrid-coordinated charging with a wireless end interface. Several previous studies related to port energy management systems, DC distribution, battery buffers, and electric vessels' chargers [5]–[7], [19]–[21] support this pathway. In such a context, the wireless segment should start by being used as a pilot layer and not used to replace conductive charging completely. Both CPT and underwater CPT are more exploratory. They have a compact integration in a dock wall, which is an attractive feature, but there are still some of the problems to be resolved such as wet insulation, parasitic capacitance, leakage current and certification [18], [24]. Science wise, multi-receiver frequency-selective methods, and exceptional-point methods, take into account the cross-coupling and variable receiver position. But the vast majority of reported investigations are, to date, at lab or analytical scale and at power levels considerably lower than for commercial ferry charging.

Therefore, these should not yet be considered deployment ready. However, floating-solar WPT also holds potential, especially for non-grid or marina applications and although it is not at high throughput seaports yet, it is emerging as an option. As a whole, one can clearly see that there is a certain degree of maturity gradient regarding the different approaches in that the shipboard converter/port energy systems are mature, single-port IPT is approaching practice, multi-port IPT is emerging, and the maritime CPT and advanced multi-receiver physics are at the very early stage. Realistic hardware constraints, scheduling and safety validation are the most important considerations for the best directions of research. Many studies are carried out to optimise the electrical performance with few of them focused on the ability to depart at the planned time when the grid, thermal and alignment constraints are applied.

5.2 Deployment Readiness and Design Guidelines

A good survey should differentiate between the concepts that will be attractive and the engineering that will get deployed. Table 4 shows a readiness perspective of the most common approaches related to the literature. The ranking doesn't represent a commercial certification; rather, it's a research-based assessment based on five criteria: level of evidence, maturity of converter, docking tolerance, marine safety, and burden of integration. This perspective can be used to gain insight into starting points for near-term pilots and future areas for research.

Table 4. Deployment-readiness ranking derived from the reviewed literature

Approach	Best application	Evidence status	Implementation readiness	Main design rule
High-power single-port IPT	Fixed-route ferry or shuttle vessel	Field demonstrations and mature circuit base	High	Start with one berth, strong alignment guides, and conservative thermal margins.

Approach	Best application	Evidence status	Implementation readiness	Main design rule
Two-port shared DC-bus IPT	Two ferries or workboats with predictable timetable	Prototype-ready; needs port energy management	Medium-high	Use berth reservation and peak-power constraints before adding many ports.
Segmented multi-transmitter IPT	Autonomous surface vessel dock or mixed small craft	Mostly laboratory and simulation studies	Medium	Energize only the aligned segment and use receiver identification for selectivity.
Marine CPT dock wall or pontoon	Low- to medium-power vessels where plates can be integrated	Early research with limited marine validation	Low-medium	Control parasitic coupling, leakage current, and plate insulation before scaling power.
Floating renewable wireless dock	Remote marina, island port, aquaculture, inspection autonomous surface vessel (ASV)	Concept and laboratory-level evidence	Low-medium	Co-design renewable generation, buffer battery, mooring motion, and charger dispatch.
Queue-aware multi-port optimizer	Port with many short-dwell vessels	Strong optimization literature; weak hardware-in-loop evidence	Medium	Include battery limits, vessel priority, coupling uncertainty, and grid peak in one scheduler.

A multi-stage development phase can be deduced from the literature. The initial phase will be served by a fixed-electrics docked electric ferry that has a fixed route with known energy usage and dwell times. Magnetic alignment and thermal-protection are among the functions that may be included in this phase, as is emergency shutdown, and communication with the vessel battery-management system. The second phase involves the installation of a second charging point and a common electric bus, to then test the port power sharing option without being entangled in too many coordinating tasks. The third stage involves segmented / modular pads for hulls of various shapes and autonomous vessels. In all three stages, there should be coherence between the electrical, mechanical and scheduling considerations for the research progress. Only showing the coil efficiency does not show if the dock can be operated reliably throughout the berthing process.

If no coupling model is provided for a dispatch method, then the dispatch method only determines if a selected vessel can accept any more charging power. Similarly, if a port microgrid study does not consider electromagnetic stress in charging, it is not possible to determine if high-power wireless charging will be safe for passengers, crew, ropes and other metal structures at the port. Therefore, a meaningful benchmark should be expanded to cover arrival and departure times, battery state, disturbance of sea-state, coil temperature, leakage field, renewable outcomes and grid constraints in a singular test case. A potential research direction will be a pilot project of a digital twin supported dock. In this configuration, the physical charger is used economically and before and after is a digital twin that estimates the coupling coefficient, the thermal reserves and the queue pressure. The controller will then be able to prioritize safety limits and allocate power in order of departure priority, and carbon intensity. This stepwise charging process allows for learning and incrementally increases from one charging port to many charging ports according to docking statistics.

5.3 Future Benchmarks

The other significant gap that exists in the literature is that there is a lack of uniformity in how to define success across metrics and research fields. The studies of wireless-power commonly include a single point of maximum efficiency. Typically, coupler physics is not considered in port-energy studies. Studies about vessel-electrification normally only cover the size of the batteries and the energy on the ship on the route and not the docking interface. These stand-alone metrics are not adequate for a multi-port wireless dock. A meaningful benchmark is one that can be related to energy generation or a vessel queue at least in the context of realistic maritime motion while also satisfying safety constraints from the same design. Table 5 also clarifies the scope of an implementation-oriented contribution. A concept paper proposing a new coupler, resonant network, or scheduling model should report the evidence items listed there. Studies that ignore degraded operating modes provide limited practical guidance. For example, a useful paper should show how available charging power is curtailed when a receiver is misaligned, when a vessel departs early, when thermal limits are approached, or when the shore grid approaches its load limit. Evidence of this type would strengthen future comparisons among wireless charging, plug-in charging, pantograph charging, and battery-swap approaches.

Table 5. Future multi-port wireless dock-and-charge studies

Evidence item	Required report	Why it matters	Minimum acceptable form
Electrical transfer	Input power, output power, efficiency map, coil or plate temperature	Separates real energy delivery from ideal circuit response	Measured or hardware-in-loop map over several misalignment points
Marine motion	Lateral, vertical, angular, and time-varying offset	Shows whether the dock survives normal berthing conditions	Recorded or replayed motion profile, not only a fixed air gap
Port coordination	Arrival time, dwell time, departure energy, and priority rule	Tests whether multi-port charging improves service quality	At least two vessels and two ports in one scheduling case
Safety boundary	Leakage magnetic/electric field, emergency stop, insulation, and wet-environment protection	Protects passengers, crew, electronics, and metallic dock structures	Limit-aware controller and documented shutdown logic

Evidence item	Required report	Why it matters	Minimum acceptable form
Grid and renewable link	Transformer limit, peak power, carbon signal, and storage state	Connects electrification with decarbonization rather than only charging speed	Microgrid model or measured shore supply profile
Reproducibility	Parameters, controller code, and vessel-duty cycle	Allows comparison across methods	Open parameter table and repeatable test sequence

6. Open Challenges and Future Directions

There are a number of open challenges yet to be addressed. First, there is a lack of available high-power maritime WPT experiment related data such as misalignment, tide, saltwater exposure, coil temperature, electromagnetic leakage and repetitive docking cycles. Second, multi-port interoperability should be defined prior to shared infrastructure investments; whether this be a simple geometry, communication, a safety-state, a compensation-class, or some other piece of information, should not be the property of just one receiver. Third, to study queue-aware power sharing, realistic schedules of vessels need to be used instead of laboratory-based load profiles. Fourth, there is a need for improved data relating to the aging of CPT insulation and leakage current of WPT when underwater. Fifth is that port-grid constraints should be directly considered while designing the chargers. Electrification can create either a reduction in emissions or an increase in emissions, depending on the level of peak demand, local buffers of batteries and the availability of renewables, as well as carbon aware scheduling. Therefore, future research should shift the focus of single-coupler efficiency studies into the hardware-in-the-loop simulation of entire docks, field pilots, reliability models and safety testing for certification. Transfer efficiency, grid peak demand, thermal margin, delivered battery energy and berth delays can be the core evaluation metrics.

7. Conclusion

The multi-port wireless dock-and-charge architectures for decarbonized transportation by water have been discussed. The literature highlights that the enabling technologies have made their own progress; there is still no maturing of alliance between two or more enabling technologies in the context of a shared wireless dock. Single-port IPT is probably the most likely technology for near term deployments particularly on fixed ferry routes. Maritime validation of CPT, floating solar WPT and multi-receiver techniques is yet to be performed, but these techniques are still promising. The review introduces a taxonomy and addresses a narrowed research challenge – motion-tolerant, queue-aware power sharing in the context of vessel, charger, grid and safety constraints. Future studies should correlate high power prototypes with berth scheduling, in-field information and certification supporting information.

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