

Review

From Shore-Side Electricity to Sustainable Port Transformation: Emerging Technologies and Strategic Trends

Emin Güney ^{1,2,*}, Cüneyt Bayılmış ³, Yezhou Yang ², Erdeniz Erol ⁴, Özhan Atmaca ⁵ and Elif Bal Beşikçi ⁶

¹ Department of Computer Engineering, Sakarya University of Applied Sciences, Serdivan 54050, Türkiye

² School of Computing and Augmented Intelligence, Arizona State University, Tempe, AZ 85287, USA; yz.yang@asu.edu

³ Department of Computer Engineering, Sakarya University, Serdivan 54050, Türkiye; cbayilmis@sakarya.edu.tr

⁴ Elkon Marine and Electric Technologies Research and Development Center, Elkon Elektrik San. Tic. A.Ş., Istanbul 34953, Türkiye; erdeniz.erol@elkon-tr.com

⁵ Regbes B.V., Adriaan Kluitstraat 170, 3052 RJ Rotterdam, The Netherlands; ozhanatmaca@regbes.com

⁶ Department of Maritime Transportation Engineering, Istanbul Technical University, Istanbul 34940, Türkiye; bale@itu.edu.tr

* Correspondence: eminguney@subu.edu.tr

Abstract

Maritime transport, responsible for over 90% of global trade, is a significant contributor to greenhouse gas emissions due to its reliance on fossil fuels. Achieving international decarbonization targets set by the International Maritime Organization and the European Green Deal requires not only advancements in vessel technologies but also the sustainable transformation of port infrastructures. In this context, this study examines current trends in shore-to-ship (STS) charging technologies as a key enabler of sustainable port electrification. It provides a comprehensive review of AC, DC, and hybrid charging architectures, along with recent developments in robotic and autonomous charging systems. The study also explores industrial standards and energy management strategies for smart port applications, and identifies renewable integration and grid interaction models as key directions for future research. Furthermore, the study proposes an Onshore Power Supply (OPS) Readiness Index (OPSRI), a multi-criteria assessment framework that evaluates ship types based on their operational, technical, infrastructural, and regulatory suitability for onshore power integration. The main contribution of this review lies in integrating international standards, robotic charging technologies, and ship-type-specific readiness assessment into a unified analytical framework. The results indicate that ferries and tugboats are highly suitable for OPS deployment, while long-haul cargo vessels face greater limitations under current conditions. Overall, the findings offer practical insights for port authorities, policymakers, and energy planners, highlighting key challenges and future directions toward smart, sustainable, and low-carbon port ecosystems.



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1. Introduction

Maritime transport plays a central role in global logistics, accounting for more than 90% of world trade and ensuring the continuity of supply chains, passenger safety, and overall economic efficiency. Despite its strategic importance, the maritime industry is responsible for approximately 3–5% of total global greenhouse gas (GHG) emissions due to

its heavy dependence on fossil fuels [1,2]. The combustion of marine fuels releases harmful pollutants such as carbon dioxide (CO₂), sulfur oxides (SO_x), nitrogen oxides (NO_x), and black carbon, all of which significantly exacerbate the sector's impact on climate change. If the current trends continue and no effective climate policies are implemented, maritime emissions are projected to rise to 17–18% of total global emissions by 2050, threatening the long-term sustainability of the sector [3]. In response, the International Maritime Organization (IMO), aligned with the European Green Deal, has established ambitious decarbonization targets, aiming for net-zero greenhouse gas emissions from international shipping by or around 2050, with interim reduction targets for 2030 and 2040 [4–7]. As illustrated in Figure 1, achieving the IMO's 2050 decarbonization targets will require a substantial transition from conventional fossil fuels to low- and zero-carbon energy sources.

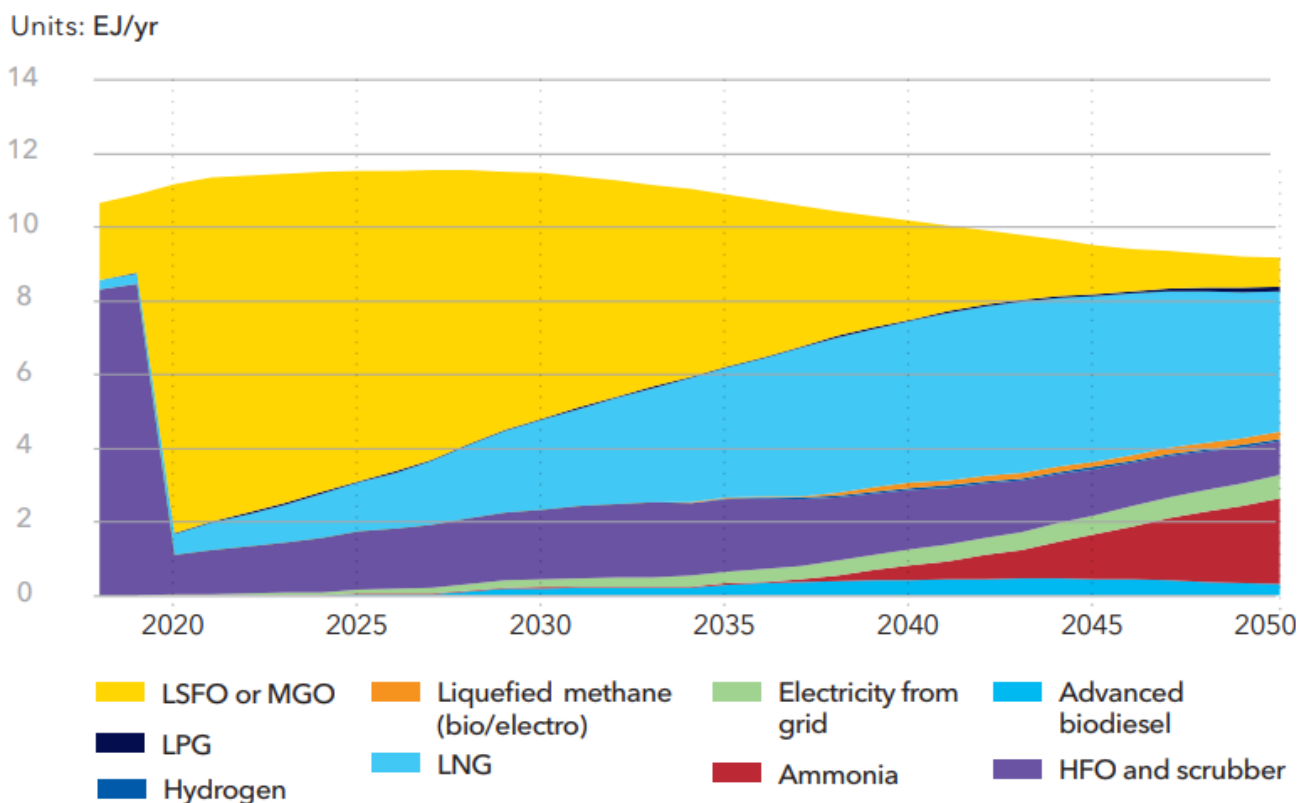


Figure 1. Projected fuel mix for the maritime sector between 2018 and 2050 [8] (IMO target scenario, reproduced with permission from DNV).

This transition particularly depends on port electrification and the large-scale deployment of onshore power supply (OPS) and shore-to-ship (STS) charging technologies [9]. As shown in Figure 2, a substantial emission gap remains between the IMO's GHG-reduction pathway and the business-as-usual (BAU) scenario, indicating that achieving the IMO targets will require approximately 50% reductions in absolute emissions and 70% reductions in emission intensity by 2050. These ambitious reduction targets cannot be achieved solely through cleaner fuels; port-side electrification and STS charging infrastructures are indispensable. In particular, the increasing deployment of electric and hybrid vessels has amplified the need for high-power, fast, and reliable STS charging systems capable of minimizing port emissions and reducing vessel idling times [10,11].

In recent years, autonomous and robotic shore-to-ship charging technologies have become a key component of smart-port initiatives [12]. These systems adapt EV charging automation principles to the maritime domain, where significantly higher power ratings and shorter connection–disconnection times are required. With the rapid growth of electric

vessel technologies, the need for fully autonomous and intelligent charging infrastructures has become more critical than ever [13,14]. By reducing human intervention and operational delays, robotic and automated STS systems increase safety and energy efficiency, playing a pivotal role in sustainable port electrification strategies [15]. These automated systems integrate robotic manipulators, perception algorithms, and real-time motion control to ensure precise connector–socket alignment under dynamic maritime conditions [16,17].

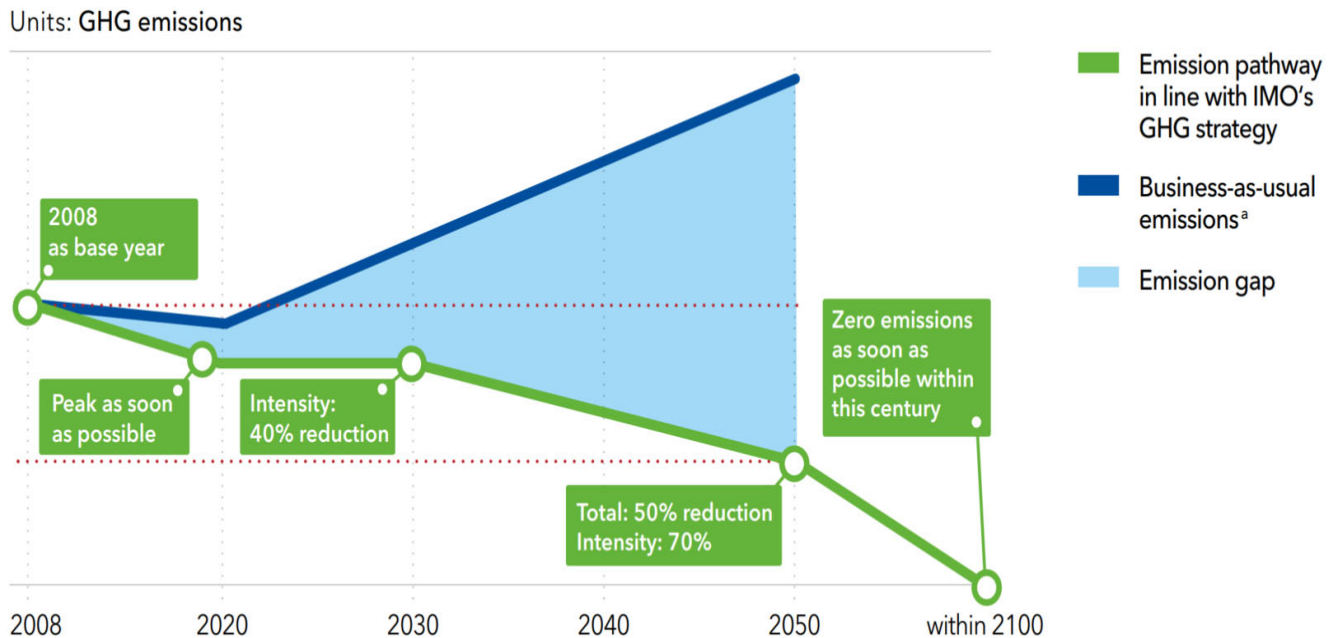


Figure 2. Comparison of the IMO GHG-reduction strategy with the business-as-usual (BAU) scenario. Reproduced with permission from DNV [8]. The upper and lower red dotted lines indicate the 2008 baseline emission level and the 50% absolute reduction target for 2050, respectively. ^a The BAU emissions are shown for illustrative purposes and differ from the emissions baseline used in DNV's detailed modelling.

Existing studies in the literature include various works and research on electric vehicle charging technologies. Among these studies, Walzel et al. [14] examined developments in automatic charging technologies in their proposed charging station prototype for electric vehicles. In their work, they focused on the design of sensor technologies and control algorithms that enable the charging connector to be connected to the vehicle socket completely autonomously via robotic arms. Guidi et al. [15] proposed a high-power inductive (wireless) charging system for battery-electric and plug-in hybrid vessels, offering significant advantages in terms of ease of use and safety. They also emphasized the potential of such systems to increase operational efficiency and contribute to sustainability in maritime applications. Kumar et al. [18] examined charging stations to enable easier charging of batteries; they discussed the practical applicability and technical challenges of these systems. Karimi et al. [9] provided an overview of current and future trends covering power system architectures, charging infrastructure, and charging management control systems. Guo et al. [16] proposed a complete automatic electric vehicle charging system based on vision–force fusion, integrating perception, motion planning, and control to enable a robotic manipulator to align and plug the charging connector into the vehicle's charging port with high precision. Mutarraf et al. [19] emphasized the fundamental roles of STS systems in integrated electric ship management by focusing on charging infrastructure requirements, energy demand management, and integrated system planning in the context of fully electric ship operations. A computer-vision-based autonomous control

approach has also been developed for shore robotic charging systems, addressing connector detection and guidance without operator intervention [17]. Zhang et al. [20] proposed the RoboCharger system for mobile energy distribution for electric ships in the Amsterdam canal network. This system aims to increase the flexibility of the charging infrastructure and improve operational efficiency. Bucher et al. [21] introduced an innovative charging robot that includes a low-cost camera connected to the Degrees of Freedom (DoF) and Combined Charging System (CCS) connector for electric vehicles. Behl et al. [22] proposed a robot mechanism that maps while avoiding obstacles and a new robotic system for the autonomous charging of parked electric vehicles.

To the best of our knowledge, existing studies either focus on general port electrification strategies or on robotic EV charging, without offering an integrated review that jointly examines STS charging architectures, automation levels, international standards, robotic connection systems, and a ship-type-specific OPS readiness assessment framework. In this study, a comprehensive review is conducted to examine the current state, challenges, and future directions of STS charging technologies as a key enabler of sustainable port electrification, and an OPS Readiness Index (OPSRI) is proposed to quantify ship-type-specific suitability for OPS deployment. The paper first outlines the regulatory background and standardization efforts governing onshore power supply systems, followed by an analysis of technological approaches, including AC- and DC-based charging architectures, hybrid configurations, and emerging wireless or robotic connection systems. Furthermore, the study investigates energy management strategies and infrastructure requirements necessary for large-scale deployment, and identifies integration with renewable sources as a key direction for future research. Compared with previous reviews, this paper provides a unified comparison of industrial standards (IEC/IEEE/ISO 80005 series [23–25]), automation technologies, and AI-based robotic charging solutions.

Finally, the study identifies research gaps and future opportunities in maritime electrification, emphasizing the need for interoperable standards, grid–port interaction models, and artificial intelligence-driven autonomous charging mechanisms. By offering a consolidated perspective on technological, environmental, and regulatory aspects of STS systems, this review contributes to the development of sustainable, low-emission port ecosystems aligned with global decarbonization goals.

The main contributions of this review are summarized as follows:

- Provides a systematic and structured review of existing shore-to-ship (STS) charging technologies, covering AC-based, DC-based, hybrid, and emerging wireless charging architectures.
- Offers a unified comparison of international standards and regulatory frameworks (IEC/IEEE/ISO 80005 series [23–25], AFIR, IMO), highlighting their impact on interoperability, safety, and port electrification strategies.
- Analyzes automation-driven and robotic STS solutions, including perception, pose estimation, alignment control, and autonomous connector docking.
- Proposes an OPS Readiness Index (OPSRI), a multi-criteria framework that evaluates ship-type-specific suitability for OPS deployment across operational, technical, infrastructural, and regulatory dimensions, offering a practical decision-support tool for port authorities and policymakers.
- Evaluates energy and power-management strategies in STS-enabled ports, including integration with microgrids, renewable sources, and energy-storage systems.
- Identifies existing gaps and future research directions, emphasizing the need for standardized interfaces, AI-based autonomous control mechanisms, and grid–port interaction models.

The remainder of this paper is organized as follows. Section 2 establishes the regulatory background and international standardization framework governing onshore power supply. Section 3 reviews current trends in maritime electrification. Section 4 introduces the OPS Readiness Index and its multi-criteria methodology for assessing ship-type suitability. Section 5 compares wired, wireless, battery-swapping, and fully robotic charging technologies. Section 6 examines robotic control and docking technologies, and Section 7 concludes with key findings and future research directions.

2. Background and Regulatory Framework

Ensuring the safe and efficient operation of shipboard electrical systems requires strict adherence to international industrial standards. These standards govern a wide range of technical requirements, including the design, construction, and operation of electrical subsystems. In particular, safety guidelines have been established for electrical installations, hazardous-area equipment, battery energy storage systems, and emerging fuel-cell and hydrogen-based technologies.

For clarity, the standards referenced in this review can be grouped into four categories: (i) shore-connection standards, most notably the IEC/IEEE/ISO 80005 series, which defines high-voltage shore connection systems (80005-1), their communication interfaces (80005-2), and low-voltage shore connection (80005-3) [23–25]; (ii) shipboard electrical-installation and protection standards (e.g., IEC 60092 [26], IEC 61363-1 [27], IEC 60947 [28]); (iii) energy-storage and alternative-fuel safety standards (e.g., IEC 62619/62620 for batteries [29,30], IEC 62282 for fuel cells [31], ISO 16110-1 for hydrogen [32]); and (iv) power-quality and grid-interaction standards (e.g., IEEE 519 [33], IEEE 1547 [34]). Among these, the 80005 series is the primary framework governing shore-to-ship power transfer and interoperability, and it therefore forms the regulatory backbone of the OPS readiness assessment presented in Section 4.

Alternative-fuel systems-such as ammonia and methanol reforming units for hydrogen production-must comply with ISO 16110-1, which defines safety requirements for fuel processing and decomposition [32,35]. To minimize operational risks, ISO/TR 15916 specifies general safety principles for hydrogen handling, storage, and ventilation system layout [36,37]. Hazardous areas where flammable gases may accumulate are classified according to IEC 60079-10-1 [38], and equipment operating in these zones must be periodically inspected under IEC 60079-17 guidelines [39]. Fuel-cell power systems are designed in accordance with IEC 62282, which specifies leak detection, thermal management, and emergency shutdown requirements to ensure safe operation of hydrogen-powered systems. For battery energy storage systems-particularly large-scale lithium-ion installations-IEC 62619 and IEC 62620 [30] define safety, test procedures, and life-cycle performance criteria, including over-temperature protection, charge/discharge limits, and cell balancing under maritime operating conditions.

Shipboard electrical distribution systems must also comply with standards such as IEC 60092-101 [26] (general electrical installation requirements) and IEC 61363-1 (short-circuit calculation). Low-voltage switchgear, converters, and protection devices follow IEC 60947, IEC 60439 [40], and IEC 60898 [41], ensuring reliable power conversion and protection coordination. Power quality and grid-interaction performance are further guided by IEEE standards, including IEEE 519 (harmonic control requirements) [33], IEEE 1100 (grounding for sensitive equipment) [42], and IEEE 1453 (voltage fluctuation limits) [43]. For hybrid and renewable-based port energy systems, distributed generation and grid connection requirements are regulated under IEEE 929 [44] and IEEE 1547 [34], covering synchronization, protection, and DER grid compliance. Table 1 summarizes the key industrial standards relevant to maritime electrification.

As summarized in Table 1, IEC standards primarily regulate equipment-level safety and performance, while IEEE standards address grid interaction and power quality. Together, these standards ensure safe, reliable, and interoperable shore-to-ship electrical interfaces. Major maritime classification societies—including DNV, Lloyd’s Register, and the American Bureau of Shipping (ABS)—require certification based on these standards before system deployment.

Table 1. Major industrial standards applied in maritime and port electrification systems.

Standard	Code	Standard Title
Battery Systems	IEC 62619	Secondary cells and batteries—Safety requirements for industrial lithium systems
	IEC 62620	Secondary lithium cells and batteries—Performance and life testing for industrial applications
Electrical Installations and Ship Systems	IEC 60092-101	Electrical installations in ships—General requirements
	IEC 61363-1	Electrical installations in ships—Short-circuit current calculations
	IEC 60076	Power transformers—General requirements
Switchgear and Inverters	IEC 60947	Low-voltage switchgear and controlgear
	IEC 60439	Low-voltage switchgear and controlgear assemblies—General requirements
	IEC 60898	Circuit breakers for overcurrent protection
	UL 1741-1999	Standard for Inverters, Converters, and Controllers for Use in Independent Power Systems
	IEEE 519-2022	IEEE Standard for Harmonic Control in Electric Power Systems
Power Quality (IEEE)	IEEE 493-2007	Recommended practice for the design of reliable industrial and commercial power systems
	IEEE 1100-1999	Recommended practice for powering and grounding sensitive electronic equipment
	IEEE 1250-1995	Guide for service to equipment sensitive to momentary voltage disturbances
	IEEE 1346-1998	Recommended practice for evaluating power system compatibility with electronics process equipment
	IEEE 1453-2004	Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems
Grid Connection and Islanding	IEEE 929-2000	IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems
	IEEE 1547-2018	IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

3. Trends in Maritime Electrification

The maritime industry is undergoing a rapid transition toward electrification as a response to the global decarbonization targets set by the IMO and regional environmental regulations. The adoption of electric and hybrid vessels has accelerated particularly in short-sea shipping, coastal transport, and port operations, where frequent docking enables convenient access to shore-based power infrastructure. Figure 3 illustrates the growth trend in the number of vessels already in operation compared with those currently on order.

The data clearly show a consistent year-on-year increase in electrically propelled ships, reflecting the industry's strong commitment to low-emission propulsion systems.

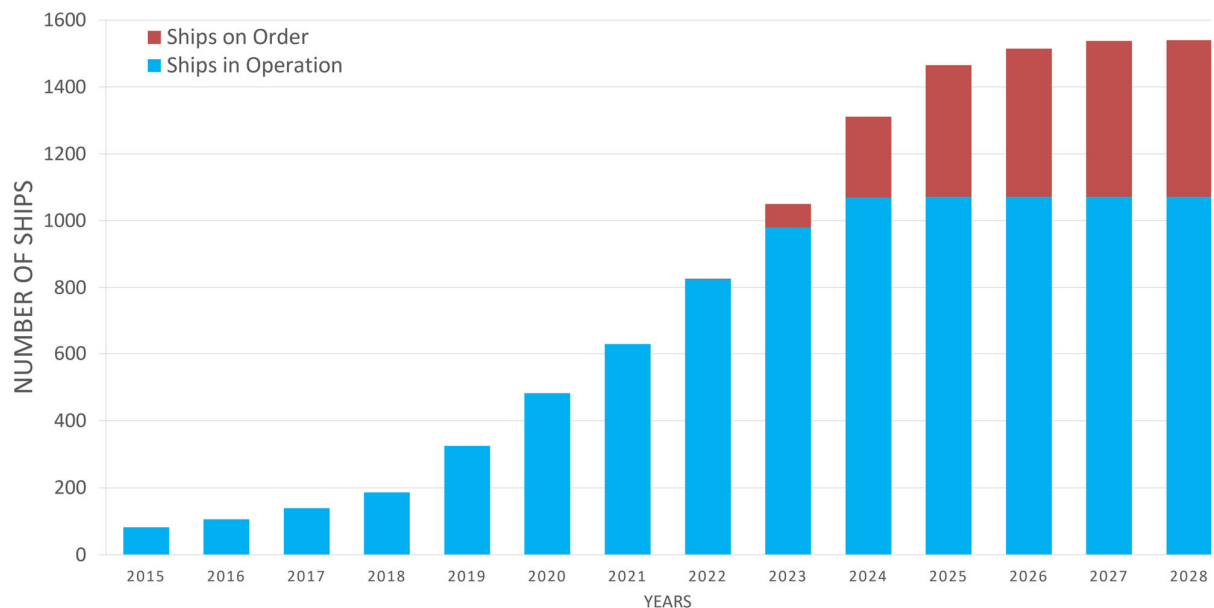


Figure 3. Number of operating and ordered electric vessels by year. Source: DNV Alternative Fuels Insight (AFI) platform (<https://afi.dnv.com>), accessed on 7 July 2026.

The number of orders for battery-powered vessels has surpassed historical averages, indicating that full-electric and plug-in hybrid configurations are becoming commercially viable for a wide range of maritime applications. Figure 4 shows that until today only 35% of battery-powered vessels are plug-in or full electric, which can be charged by an OPS. This is due to a lack of infrastructure in ports and the transition of battery-powered vessels to improved high-density batteries. A more detailed classification by vessel type is presented in Figure 5, showing the distribution and projected growth of battery-powered ships between 2022 and 2025. The data reveal that ferries, passenger ships, and offshore service vessels dominate the electrification landscape, largely due to their predictable routes, shorter voyage distances, and regulatory pressure to reduce emissions in coastal and urban waters. In contrast, deep-sea cargo and tanker segments are still in the early stages of adoption, with hybrid architectures being explored as transitional solutions.

Technological advancements in lithium-ion and solid-state batteries, coupled with improvements in energy density, safety, and charging efficiency, have been key enablers of this shift. At the same time, major classification societies such as DNV and Lloyd's Register have updated their guidelines to facilitate the certification of battery installations and hybrid propulsion systems in commercial vessels. Regional initiatives have further accelerated the adoption of electrification. Norway remains a global leader with its all-electric ferry fleets, supported by government subsidies and strict emission control areas (ECAs). While the number of battery-equipped vessels is projected to double by 2028, OPS peak power demand is expected to grow disproportionately faster due to the increasing share of fast-charging ferry and tug segments.

The Netherlands and China have followed with large-scale pilot projects for electric inland cargo and harbor vessels, while Singapore and South Korea are investing heavily in smart-port electrification programs. Overall, these trends signal a clear market transformation in which electrification, hybrid propulsion, and renewable energy integration are becoming the dominant pathways toward a sustainable maritime future [45,46]. The observed momentum forms the foundation for advanced shore-to-ship (STS) charging in-

frastructures, which are essential to meet the increasing power demands of next-generation electric vessels. According to DNV GL's Energy Transition Outlook, shore-based electricity delivered through batteries and cold ironing is projected to supply approximately 5–7% of total shipping energy by 2050, corresponding to 150–170 TWh, with the service and passenger segments showing the highest electrification share (close to 18%) [8].

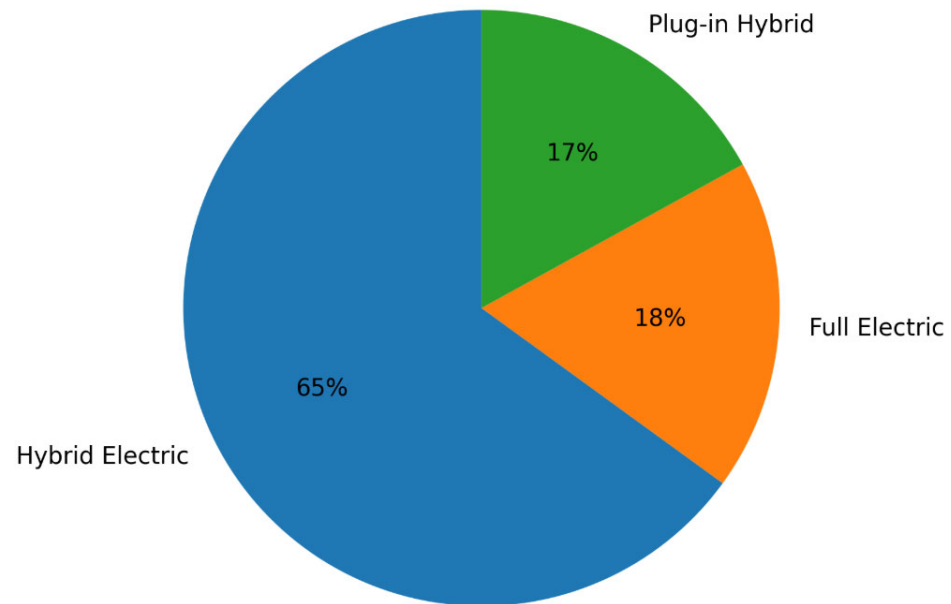


Figure 4. Percentage of battery electric vessels by their propulsion type. Source: DNV Alternative Fuels Insight (AFI) platform (<https://afi.dnv.com>), accessed on 7 July 2026.



Figure 5. Change in the number and orders of battery-powered ships by vessel type between 2022 and 2025. Source: DNV Alternative Fuels Insight (AFI) platform (<https://afi.dnv.com>), accessed on 7 July 2026.

4. OPS Readiness Index by Ship Type

The rapid expansion of Onshore Power Supply (OPS) infrastructure is widely recognized as a key enabler for reducing emissions during port stays and supporting the electrification of maritime transport [47]. On the other hand, the suitability of OPS and shore-to-ship charging solutions is highly heterogeneous across ship types, reflecting

differences in operational patterns, onboard energy systems, and regulatory exposure. While regulatory instruments such as FuelEU Maritime increasingly mandate OPS usage, ports and policymakers face a critical challenge in prioritizing investments under constrained grid capacity and infrastructure budgets [48]. In order to address this gap, this study introduces an OPS Readiness Index (OPSRI), a composite indicator designed to rank ship types according to their present suitability for OPS connection and shore-based charging, as summarized in Table 2 and illustrated in Figure 6. By integrating operational, technical, infrastructural, and regulatory parameters already implicit in the global battery-equipped fleet dataset, the OPSRI provides a structured and transparent framework to support evidence-based port electrification strategies. The index enables a comparative assessment of vessel segments and offers direct relevance for infrastructure planning, regulatory implementation, and investment prioritization. In particular, the technical-readiness and infrastructure-compatibility dimensions of the index draw directly on the shore-to-ship charging technologies compared in Section 5: the availability and maturity of wired, wireless, battery-swapping, and robotic charging options determine how readily each vessel segment can be served, thereby linking the technology review to the multi-criteria assessment.

Table 2. OPS Readiness Index (OPSRI) scores by ship type.

Ship Type	Operational Suitability	Technical Readiness	Infrastructure Compatibility	Regulatory Pressure	OPSRI
Ferries	5	5	5	5	5.0 (Very High)
Tugboats	4	4	4	4	4.0 (High)
Short-Sea Cargo	4	3	3	4	3.5 (Medium)
Cruise Ships	3	3	4	4	3.5 (Medium)
Long-Haul Cargo	1	2	2	3	2.0 (Low)

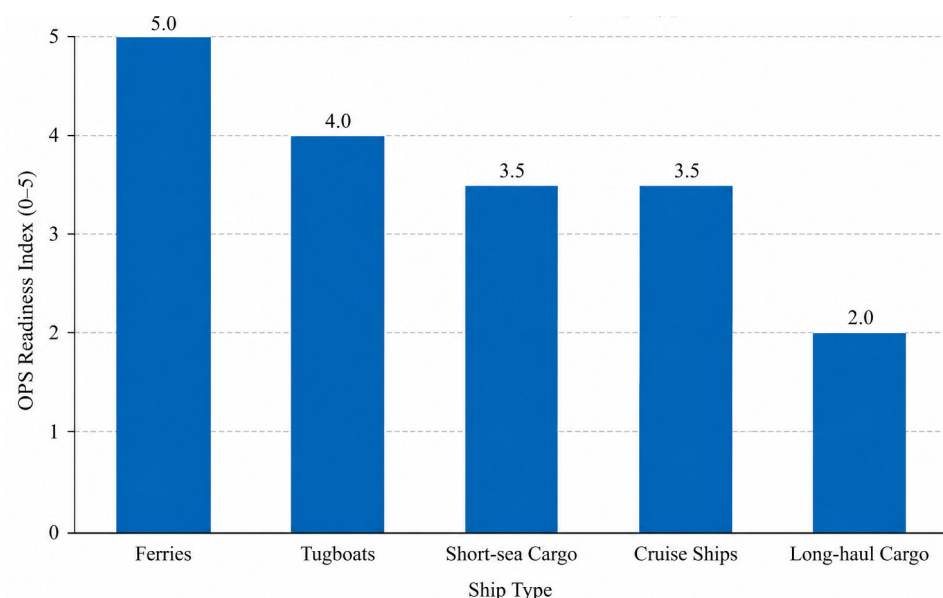


Figure 6. OPS Readiness Index (OPSRI) by ship type.

4.1. Methodology for OPSRI

The OPS Readiness Index (OPSRI) is constructed as a multi-criteria composite score combining four equally weighted dimensions, each evaluated on a normalized 0–5 scale, where higher values indicate greater readiness for OPS integration across different vessel types. Operational suitability reflects the compatibility of vessel operational profiles with

shore power usage and is assessed based on route length (short-sea versus long-haul operations), average port dwell time, and frequency of port calls. Vessels operating on short, repetitive routes with frequent port stays receive higher scores due to increased opportunities for shore connection and charging.

Technical readiness captures the maturity of onboard electrification and energy management systems, using indicators such as the share of battery-hybrid and fully electric vessels within each ship category, the presence of advanced Energy Management Systems (EMS), and the typical battery capacity ranges. Ship types with higher penetration of battery systems and established EMS architectures are scored more favorably.

Infrastructure compatibility evaluates the alignment between vessel power requirements and existing or deployable OPS infrastructure. This dimension considers the typical shore power levels required (low-, medium-, or high-voltage AC and DC fast charging) and the feasibility of providing such power within current port grid constraints. Ship types demanding extremely high peak power levels receive lower scores due to increased grid reinforcement requirements.

Regulatory pressure represents the extent to which vessel categories are exposed to OPS-related regulatory requirements, particularly under FuelEU Maritime. Factors include the likelihood of calling at regulated ports, duration of port stays, and sensitivity to local emission constraints in urban or environmentally regulated areas.

The final OPS Readiness Index for each ship type is calculated as the arithmetic mean of the four-dimension scores. The relative importance of the four dimensions may vary across vessel segments and geographical regions, depending on operational conditions, infrastructure availability, and regulatory requirements. The results are presented using a ranked table and visualized through a bar chart to facilitate comparison across vessel segments.

Formally, the index is expressed as $OPSRI = \sum_i w_i \cdot s_i$, where s_i denotes the normalized score (0–5) of dimension $i \in \{\text{operational suitability, technical readiness, infrastructure compatibility, regulatory pressure}\}$, w_i is the corresponding weight, and $\sum_i w_i = 1$. In the baseline configuration, all four dimensions are weighted equally ($w_i = 0.25$), so the index reduces to the arithmetic mean of the four dimension scores. Each dimension is rated on an anchored 0–5 rubric (0 = not suitable, 5 = fully ready) using the operational, technical, infrastructural, and regulatory indicators defined above. The dimension scores were derived from the operational characteristics, infrastructure requirements, regulatory exposure, and technological maturity reported in the reviewed literature and subsequently consolidated through expert assessment.

4.2. Policy and Investment Implications

The OPS Readiness Index provides a practical decision-support tool for port authorities: prioritizing OPS investments where utilization and emission reduction are highest; for regulators: targeting OPS mandates where compliance is technically realistic; and for electric grid planners: anticipating power demand growth driven by high-OPSRI vessel segments.

The results indicate that ferries and tugboats should be the primary focus of near-term OPS and fast-charging infrastructure, while cruise and short-sea cargo vessels represent secondary but growing markets. Long-haul cargo vessels, despite regulatory exposure, remain structurally constrained by power demand and limited battery integration. The OPSRI highlights pronounced differences in the suitability of ship types for shore-to-ship power integration under current technological and regulatory conditions. Short-sea segments, particularly ferries and tugboats, exhibit very high readiness due to favorable operational patterns, advanced battery integration, and strong regulatory incentives. Short-sea cargo

vessels and cruise ships demonstrate medium readiness, reflecting partial electrification potential and increasing regulatory pressure, but also higher infrastructure requirements.

To test the robustness of the resulting ranking, a sensitivity analysis was performed by varying the dimension weights around the equal-weight baseline. Under a regulation-emphasized scenario (regulatory weight raised to 0.40, the remaining dimensions 0.20 each), the scores become 5.0 (ferries), 4.0 (tugboats), 3.6 (short-sea cargo), 3.6 (cruise ships), and 2.2 (long-haul cargo); under an infrastructure-constrained scenario (infrastructure weight 0.40), they become 5.0, 4.0, 3.4, 3.6, and 2.0, respectively. Across all tested weightings, ferries and tugboats remain the highest-ranked segments and long-haul cargo the lowest, confirming that the overall readiness ordering is robust to weight selection. The only sensitivity appears in the relative ordering of short-sea cargo and cruise ships, which depends on whether regulatory exposure or infrastructure feasibility is prioritized. Scenario-based projections, such as future grid-capacity upgrades or tightening FuelEU Maritime thresholds, would predominantly raise the readiness of the medium-tier segments without altering the position of the extremes. This ranking is consistent with independent projections: DNV GL identifies the service and passenger segments as having the highest share of grid electricity and full-electric operation as currently most relevant for the short-sea segment [8], corroborating the high readiness scores assigned to ferries and short-sea vessels.

In contrast, long-haul cargo vessels show low OPS readiness, primarily due to limited battery integration, long voyage profiles, and substantial shore power demand, which pose challenges for both onboard systems and port grid infrastructure. These findings underscore the importance of differentiated OPS deployment strategies, rather than uniform mandates across all vessel types.

By providing a transparent and data-driven ranking framework, the OPSRI directly supports policy design, port investment prioritization, and grid planning decisions. The index enables stakeholders to focus near-term OPS investments where utilization, emission reduction potential, and economic efficiency are highest, while identifying segments that may require alternative decarbonization pathways or longer-term infrastructure development.

5. Comparison of Charging Technologies

5.1. Wired Charging Systems

Wired charging systems used in electric marine vessels are categorized into two main architectures: onboard charging systems and off-board charging systems. The differences between these systems are based on technical parameters such as the location of power conversion equipment, charging power, energy transfer efficiency, automation level, and maintenance requirements.

In onboard charging systems, the alternating current supplied from the port is converted into direct current through AC–DC converters integrated into the ship, and then transferred to the battery system. Typically, 230 V single-phase or 400 V three-phase configurations are used, making this architecture widely preferred in low-power applications such as passenger ferries and service boats. Since the converter hardware is integrated into the vessel, the system provides flexibility in terms of installation and operational mobility. However, it increases onboard system complexity, occupies valuable ship interior space, and requires periodic maintenance [8,49,50].

In off-board charging systems, power conversion equipment is installed on the port side, where AC power is converted into DC before being delivered to the vessel. This architecture is suitable for vessels requiring high charging power—such as ferries, Ro-Ro ships, and cargo vessels—and can provide DC output capacities of 500 kW and above. Faster charging, integration capability with automated connection mechanisms, and centralized energy control make this configuration ideal for operationally intensive maritime routes.

Additionally, off-board systems can be centrally monitored and managed, enabling remote diagnostics and maintenance functions, which reduces total cost of ownership [51]. (The key technical parameters of the wired shore-to-ship charging architectures are shown in Appendix A (Table A1)).

For wired systems to operate efficiently, additional design considerations such as automated cable-handling solutions, insulated connector systems, safety-locking mechanisms, and ship-port synchronization protocols must be integrated into the overall system. In high-current operations, reducing harmonic distortions, employing protection relay-based systems, and integrating smart energy management remain major research areas [52]. Figure 7 places these wired configurations within the broader classification of shore-to-ship charging methods, alongside wireless charging and battery swapping.

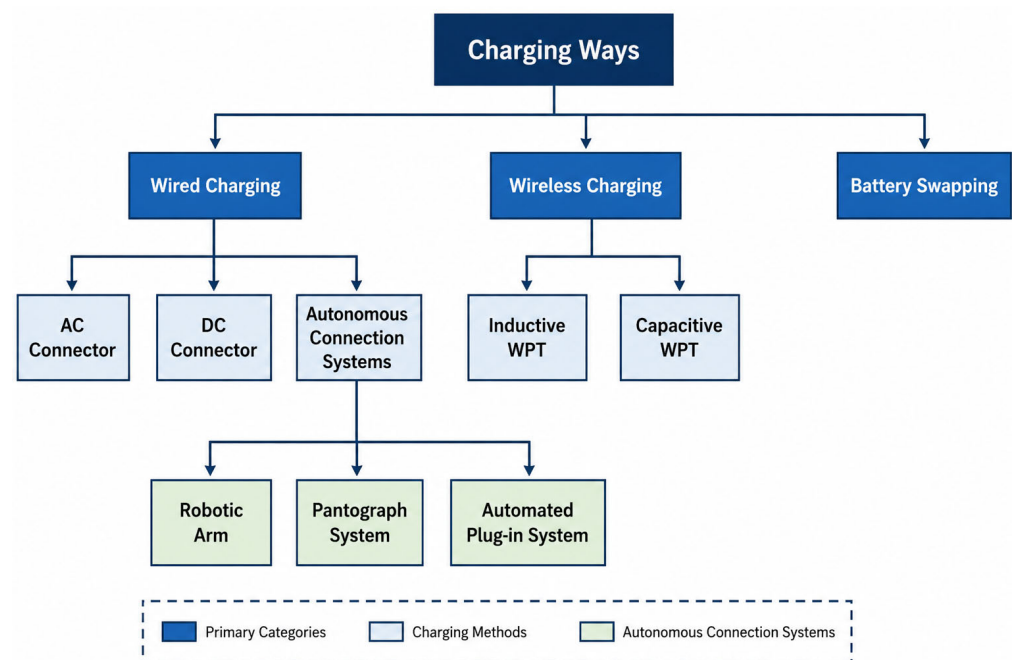


Figure 7. Classification of shore-to-ship charging methods: wired charging (AC connector, DC connector and autonomous connection systems, the latter comprising robotic arm, pantograph and automated plug-in systems), wireless charging (inductive and capacitive wireless power transfer) and battery swapping.

5.2. Wireless Charging Systems

Wireless Power Transfer (WPT) eliminates the risks of mechanical wear, corrosion, and connector failure associated with conventional plug-in systems, making it an attractive option for electric ships. WPT systems transfer energy without physical contact, using electromagnetic or electric fields, which makes them highly suitable for harsh marine environments such as salty and humid conditions [53]. Two main WPT technologies are being explored for maritime applications:

- **Inductive Power Transfer (IPT):** Operates via alternating magnetic fields between coils. It is notable for high-power transfer capability, alignment tolerance, and robustness against harsh marine conditions. Wärtsilä's IPT prototype has demonstrated power transfer up to 1 MW during field testing [51].
- **Capacitive Power Transfer (CPT):** Uses electric fields between conductive plates. While structurally simpler and free from magnetic interference, CPT suffers from lower efficiency, alignment sensitivity, and insulation challenges in salty water environments [54].

WPT systems enable fast charging during short docking periods, offering significant operational flexibility for vessels with frequent trips, such as ferries. Low maintenance requirements and reduced infrastructure wear are key advantages. Recent developments indicate potential integration with floating charging stations, enabling wireless charging in offshore and shallow-port applications. However, technical challenges such as electromagnetic interference, spatial constraints, and energy losses remain critical. Ongoing research focuses on optimizing coil design, improving alignment tolerance, and integrating WPT with smart port infrastructures.

5.3. Battery Swapping Systems

Battery swapping is proposed as a fast and efficient alternative to plug-in charging in time-critical maritime operations. It is particularly suitable for ferries and service vessels operating on short routes. During the docking process, depleted battery modules are replaced with fully charged ones, minimizing operational downtime. A major advantage is that it smooths the load profile of the port grid. Unlike high-power charging, battery modules can be charged gradually at lower power levels and during off-peak periods, facilitating integration with renewable energy sources. However, the sustainability of this method depends on maintaining a continuous stock of fully charged battery units. Otherwise, system interruptions may occur. Implementation also requires high-capacity robotic handling systems or crane mechanisms, leading to high initial investment costs and vessel design compatibility requirements. Therefore, the technical and economic feasibility of battery swapping must be carefully evaluated.

5.4. Automation Levels of STS Systems

The automation level of Shore-to-Ship (STS) energy transfer systems varies significantly depending on port infrastructure, vessel type, and operational requirements. In this section, current solutions are classified into three categories based on technical characteristics and alignment with port electrification strategies: manual systems, semi-automatic systems, and fully robotic systems.

Manual systems represent the conventional approach to STS power connection and involve direct human handling of cables and connectors. Typically designed in accordance with IEC/IEEE 80005-1 standards, they remain common due to low capital cost and compatibility with traditional port layouts [55]. However, sustainability challenges are increasing as these systems require intensive labor, are prone to alignment errors, and lead to extended connection times. Adverse weather and sea conditions accelerate the wear of system components, increasing maintenance costs. Additionally, manual handling of high-voltage cables introduces ergonomic and safety risks for operators [56].

Semi-automatic STS systems retain operator supervision but incorporate motorized components and sensor-based feedback mechanisms to reduce manual workload. Guided cable reels, telescopic arms, and assisted alignment systems improve connector precision and reduce operator fatigue [57,58]. While connection initiation and abnormal situation handling still require operator involvement, partial automation provides consistency in repetitive tasks and shortens overall docking time. Such systems are cost-effective for medium-scale ports or terminals undergoing phased transition toward robotic automation [59,60].

5.5. Fully Robotic Systems

Fully robotic systems aim to eliminate human intervention by utilizing robotic manipulators, computer vision, sensor fusion, and AI-based control algorithms. These systems automatically detect connector positions, compensate for vessel motion, and complete the connection without operator input [61]. Current implementations include manipulator

arms mounted on rail systems or autonomous ground vehicles (AGVs), capable of real-time alignment based on environmental feedback. These systems reduce human error, minimize connection time, and enable continuous 24/7 operation in high-capacity terminals [62]. However, challenges remain in system complexity, high initial cost, reliability in humid and saline environments, and integration into existing port logistics. With improvements in hardware durability and adaptive control algorithms, fully robotic systems are expected to become standard in next-generation green ports [63,64].

In terms of cost-effectiveness and commercial maturity, these emerging options occupy distinct positions. Wireless (WPT) charging currently carries a higher per-unit capital cost due to specialized coil infrastructure and power electronics, and its efficiency penalty relative to wired systems raises lifetime energy costs; commercially it remains largely at the pilot and demonstration stage. Battery swapping avoids high peak-power grid draw and enables off-peak, renewable-friendly charging, but its economics are dominated by the cost of maintaining a redundant charged-battery inventory and the robotic or crane handling infrastructure, and deployment is so far confined mainly to short-route ferry pilots. Wired off-board DC charging remains the most commercially mature and cost-effective option for high-power applications and therefore dominates current operational OPS installations. A full techno-economic comparison (levelized cost per kWh transferred, and capital and maintenance cost per berth) is identified as an important direction for future work.

6. Robotic Control and Docking Technologies

The first category of robotic alignment techniques relies on cameras and computer vision algorithms to detect the charging inlet on the vessel and guide the connector toward it. This approach aims to enable precise alignment without manual assistance or mechanical guidance fixtures. Early studies utilized geometric methods such as Hough transforms and Perspective-n-Point (PnP) algorithms. Subsequent systems employed 2D vision-based detection to guide robotic movements toward the socket. With the rise in deep learning, CNN-based models have achieved detection accuracies exceeding 98%, while hybrid CNN-SVM architectures and SIFT-based stereo matching methods have further improved robustness and precision. Compared with earlier geometric approaches (e.g., Hough transform and PnP) and classical feature-based methods (SIFT/SVM), CNN-based detectors offer substantially higher accuracy and greater tolerance to illumination changes and occlusion, whereas transformer-based and YOLO-family detectors trade a small accuracy margin for real-time inference speed. This indicates that hybrid pipelines, which combine CNN-level accuracy with the low latency of single-stage detectors, are best suited to the dynamic alignment requirements of maritime charging; a standardized quantitative benchmark of these models under identical maritime conditions remains an open research need. These methods demonstrate successful performance under maritime-specific challenges such as motion blur, illumination changes, and partial occlusions [65–67].

Recent research has shifted from fixed or low-DOF mechanisms toward multi-degree-of-freedom robotic arms, which offer improved adaptability to vessel motion and environmental disturbances. Cable-guided robotic arms and articulated plug-in mechanisms have been investigated for providing safe and repeatable connection with minimal operator involvement. Compact designs compatible with standardized maritime interfaces offer advantages in installation and maintenance, particularly in confined port spaces, and are being progressively adopted in commercial robotic charging solutions [68,69]. AI-assisted control systems use deep learning and reinforcement learning to estimate connector pose and dynamically respond to disturbances such as vessel motion, wave effects, and visual occlusions [17]. Object detection models-including YOLO variants, CNNs, and transformer-based architectures-are integrated into feedback control loops

to maintain accurate alignment even in complex environments [70]. Feature-matching algorithms and sensor fusion methods (e.g., Kalman filtering) enhance tracking stability and reduce latency. Embedded system implementations developed for congested port environments demonstrate that these control strategies are compatible with real-world operational constraints [46,71].

As STS charging increasingly relies on AI-driven robotic control, networked sensors, and remote monitoring, cybersecurity becomes a critical operational concern. Key attack surfaces include the perception and control pipeline (e.g., adversarial manipulation of camera or sensor inputs that could mislead pose estimation), the communication links between ship, shore, and port energy-management systems (susceptible to spoofing, man-in-the-middle, and denial-of-service attacks), and the high-power switching hardware, where a compromised controller could create safety hazards. Because these systems bridge operational technology (OT) and information technology (IT), they inherit vulnerabilities from both domains. Mitigation requires defense-in-depth measures such as encrypted and authenticated communication (consistent with IEC 62443 for industrial automation security [72]), intrusion detection tailored to robotic control loops, adversarially robust perception models, and fail-safe fallback modes that revert to a safe state upon anomaly detection. Standardized cybersecurity requirements for autonomous maritime charging remain underdeveloped and represent an important area for future research.

7. Conclusions and Recommendations

This review examined the role of shore-to-ship (STS) charging technologies in supporting the maritime sector's transition toward low-emission and electrified operations. The review integrated regulatory frameworks, charging architectures, battery-swapping concepts, robotic charging technologies, and AI-driven control systems into a unified perspective. In addition, the proposed OPS Readiness Index (OPSRI) provided a practical framework for evaluating the suitability of different vessel types for onshore power integration. The results indicate that ferries and tugboats currently represent the most suitable candidates for OPS deployment, whereas long-haul cargo vessels remain constrained by technical and infrastructural limitations.

The findings demonstrate that internationally harmonized standards, together with off-board DC fast charging and increasing levels of automation, will play a central role in future port electrification. Rather than adopting a uniform deployment strategy, ports should prioritize OPS investments according to vessel characteristics, operational profiles, and infrastructure readiness. By combining technological assessment with operational and policy perspectives, this review provides practical guidance for port authorities, policymakers, and researchers working toward sustainable and intelligent port ecosystems.

Future research should focus on enhancing interoperability beyond the current IEC/IEEE/ISO 80005 framework, developing grid–port interaction and demand-response models, evaluating the techno-economic performance of emerging charging technologies, strengthening cybersecurity for AI-enabled robotic charging systems, and validating the OPS Readiness Index using operational data from multiple ports. Furthermore, integrating renewable energy sources and energy storage into smart-port ecosystems remains an important step toward fully autonomous and low-carbon maritime infrastructure.

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Abbreviations

The following abbreviations are used in this manuscript:

ABS	American Bureau of Shipping
AC	Alternating Current
AFIR	Alternative Fuels Infrastructure Regulation
AGV	Autonomous Ground Vehicle
AI	Artificial Intelligence
BAU	Business-as-Usual
CCS	Combined Charging System
CNN	Convolutional Neural Network
CPT	Capacitive Power Transfer
DC	Direct Current
DoF	Degrees of Freedom
DER	Distributed Energy Resource
ECA	Emission Control Area
EMS	Energy Management Systems
EV	Electric Vehicle
GHG	Greenhouse Gas
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
IPT	Inductive Power Transfer
ISO	International Organization for Standardization
OPS	Onshore Power Supply
OPSRI	OPS Readiness Index
OT	Operational Technology
PnP	Perspective-n-Point
Ro-Ro	Roll-on/Roll-off
SIFT	Scale-Invariant Feature Transform
STS	Shore-to-Ship
SVM	Support Vector Machine
WPT	Wireless Power Transfer
YOLO	You Only Look Once

Appendix A

Table A1 consolidates the key technical parameters of the wired shore-to-ship charging architectures discussed in Section 5.1.

Table A1. Technical parameters of wired charging architectures (compiled from Section 5.1).

Parameter	Onboard Charging (AC)	Off-Board Charging (DC)
Location of power conversion	On the vessel	Port side
Typical voltage	230 V single-phase/400 V three-phase	DC output (post-conversion)
Typical power level	Low power	500 kW and above
Charging speed	Lower	Fast
Automation integration	Limited	High (automated connection mechanisms)
Monitoring & control	Local, onboard	Centralized, remote diagnostics and maintenance
Typical vessel types	Passenger ferries, service boats	Ferries, Ro-Ro ships, cargo vessels
Main considerations	Higher onboard complexity; occupies ship space; periodic maintenance	Higher port-side infrastructure cost; lower total cost of ownership at scale

References

1. Rony, Z.I.; Mofijur, M.; Hasan, M.; Rasul, M.; Jahirul, M.; Ahmed, S.F.; Kalam, M.; Badruddin, I.A.; Khan, T.Y.; Show, P.-L. Alternative Fuels to Reduce Greenhouse Gas Emissions from Marine Transport and Promote UN Sustainable Development Goals. *Fuel* **2023**, *338*, 127220. [CrossRef]
2. Fang, S.; Wang, Y.; Gou, B.; Xu, Y. Toward Future Green Maritime Transportation: An Overview of Seaport Microgrids and All-Electric Ships. *IEEE Trans. Veh. Technol.* **2020**, *69*, 207–219. [CrossRef]
3. Mahmud, K.K.; Sheikh, W.; Chowdhury, M.M.H. Decision Framework for Sustainability Assessment of Alternative Fuels to Achieve Shipping Decarbonization. *Ocean Coast. Manag.* **2025**, *265*, 107637. [CrossRef]
4. Joung, T.-H.; Kang, S.-G.; Lee, J.-K.; Ahn, J. The IMO Initial Strategy for Reducing Greenhouse Gas Emissions and Its Follow-Up Actions Towards 2050. *J. Int. Marit. Saf. Environ. Aff. Shipp.* **2020**, *4*, 1–7. [CrossRef]
5. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Alternative Fuel Options for Low Carbon Maritime Transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
6. Zhu, M.; Shen, S.; Shi, W. Carbon Emission Allowance Allocation Based on a Bi-Level Multi-Objective Model in Maritime Shipping. *Ocean Coast. Manag.* **2023**, *241*, 106665. [CrossRef]
7. Pietzcker, R.C.; Osorio, S.; Rodrigues, R. Tightening EU ETS Targets in Line with the European Green Deal: Impacts on the Decarbonization of the EU Power Sector. *Appl. Energy* **2021**, *293*, 116914. [CrossRef]
8. DNV GL. *Energy Transition Outlook 2019: Maritime Forecast to 2050*; DNV GL: Høvik, Norway, 2019; Available online: <https://www.dnv.com/maritime/maritime-forecast/> (accessed on 27 February 2026).
9. Karimi, S.; Zadeh, M.; Suul, J.A. Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture, Infrastructure, and Control. *IEEE Electr. Mag.* **2020**, *8*, 47–61. [CrossRef]
10. Frkovic, L.; Cosic, B.; Falkoni, A.; Pukšec, T.; Vladimir, N. Shore-to-Ship: Enabling the Electrification Sustainability of Maritime Transport with the Nexus Between Berthed Cruise Ships and Renewables in Isolated Energy Systems. *Ocean Eng.* **2024**, *302*, 117537. [CrossRef]
11. Zis, T.; North, R.J.; Angeloudis, P.; Ochieng, W.Y.; Harrison Bell, M.G. Evaluation of Cold Ironing and Speed Reduction Policies to Reduce Ship Emissions Near and at Ports. *Marit. Econ. Logist.* **2014**, *16*, 371–398. [CrossRef]
12. Yau, K.L.A.; Peng, S.; Qadir, J.; Low, Y.C.; Ling, M.H. Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology. *IEEE Access* **2020**, *8*, 83387–83404. [CrossRef]
13. Karimi, S.; Zadeh, M.; Suul, J.A. Evaluation of Energy Transfer Efficiency for Shore-to-Ship Fast Charging Systems. In *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE 2020)*, Delft, The Netherlands, 17–19 June 2020; IEEE: New York, NY, USA, 2020; pp. 1271–1277.
14. Walzel, B.; Hirz, M.; Brunner, H. *Robot-Based Fast Charging of Electric Vehicles*; SAE Technical Paper 2019-01-0869; SAE: Warrendale, PA, USA, 2019.
15. Guidi, G.; Suul, J.A.; Jensen, F.; Sorforn, I. Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-In Hybrid Vessels. *IEEE Electr. Mag.* **2017**, *5*, 22–32. [CrossRef]
16. Guo, D.; Xie, L.; Yu, H.; Wang, Y.; Xiong, R. Electric Vehicle Automatic Charging System Based on Vision–Force Fusion. In *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO 2021)*, Sanya, China, 6–10 December 2021; IEEE: New York, NY, USA, 2021; pp. 405–410.

17. Güney, E.; Bayılmış, C.; Çakar, S.; Erol, E.; Atmaca, Ö. Autonomous Control of Shore Robotic Charging Systems Based on Computer Vision. *Expert Syst. Appl.* **2024**, *238*, 122116. [\[CrossRef\]](#)
18. Kumar, J.; Memon, A.A.; Kumpulainen, L.; Kauhaniemi, K.; Palizban, O. Design and Analysis of New Harbour Grid Models to Facilitate Multiple Scenarios of Battery Charging and Onshore Supply for Modern Vessels. *Energies* **2019**, *12*, 2354. [\[CrossRef\]](#)
19. Mutarraf, M.U.; Guan, Y.; Xu, L.; Su, C.L.; Vasquez, J.C.; Guerrero, J.M. Electric Cars, Ships, and Their Charging Infrastructure—A Comprehensive Review. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102177. [\[CrossRef\]](#)
20. Zhang, Z.; Yan, L. A Dispatching Strategy of Autonomous Robotic Charger Boats for Charging Electric Vessels. *IEEE Trans. Mob. Comput.* **2024**, *23*, 10429–10442. [\[CrossRef\]](#)
21. Bucher, J.; Knipschild, J.; Künne, B. Development and Evaluation of an Automatic Connection Device for Electric Cars with Four DOFs and a Control Scheme Based on Infrared Markers. *Int. J. Mechatron. Autom.* **2021**, *8*, 175–186. [\[CrossRef\]](#)
22. Behl, M.; DuBro, J.; Flynt, T.; Hameed, I.; Lang, G.; Park, F. Autonomous Electric Vehicle Charging System. In *Proceedings of the Systems and Information Engineering Design Symposium (SIEDS 2019), Charlottesville, VA, USA, 26 April 2019*; IEEE: New York, NY, USA, 2019; pp. 1–6.
23. IEC/IEEE 80005-1:2019; Utility Connections in Port—Part 1: High Voltage Shore Connection (HVSC) Systems—General Requirements. IEC/IEEE: Geneva, Switzerland, 2019.
24. IEC/IEEE 80005-2:2016; Utility Connections in Port—Part 2: High and Low Voltage Shore Connection Systems—Data Communication for Monitoring and Control. IEC/IEEE: Geneva, Switzerland, 2016.
25. IEC/ISO/IEEE 80005-3:2014; Utility Connections in Port—Part 3: Low Voltage Shore Connection (LVSC) Systems—General Requirements. IEC: Geneva, Switzerland, 2014.
26. IEC 60092-101:1994; Electrical Installations in Ships—Part 101: Definitions and General Requirements. IEC: Geneva, Switzerland, 1994.
27. IEC 61363-1:1998; Electrical Installations of Ships and Mobile and Fixed Offshore Units—Part 1: Procedures for Calculating Short-Circuit Currents in Three-Phase A.C. IEC: Geneva, Switzerland, 1998.
28. IEC 60947-1:2020; Low-Voltage Switchgear and Controlgear—Part 1: General Rules. IEC: Geneva, Switzerland, 2020.
29. IEC 62619:2022; Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes—Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications. IEC: Geneva, Switzerland, 2022.
30. IEC 62620:2014; Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes—Secondary Lithium Cells and Batteries for Use in Industrial Applications. IEC: Geneva, Switzerland, 2014.
31. IEC 62282-3-100:2019; Fuel Cell Technologies—Part 3-100: Stationary Fuel Cell Power Systems—Safety. IEC: Geneva, Switzerland, 2019.
32. ISO 16110-1:2007; Hydrogen Generators Using Fuel Processing Technologies—Part 1: Safety. ISO: Geneva, Switzerland, 2007.
33. IEEE Std 519-2022; IEEE Standard for Harmonic Control in Electric Power Systems. IEEE: Piscataway, NJ, USA, 2022.
34. IEEE Std 1547-2018; IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE: Piscataway, NJ, USA, 2018.
35. Duraiswamy, K.; Chellappa, A.; Smith, G.; Liu, Y.; Li, M. Development of a High-Efficiency Hydrogen Generator for Fuel Cells for Distributed Power Generation. *Int. J. Hydrogen Energy* **2010**, *35*, 8962–8969. [\[CrossRef\]](#)
36. Yang, Y.; Xu, H.; Lin, L.; Bao, W.; Zhang, B.; Ai, B. Development of Standards for Hydrogen Safety. *Proc. E3S Web Conf.* **2020**, *194*, 02013. [\[CrossRef\]](#)
37. ISO/TR 15916:2015; Basic Considerations for the Safety of Hydrogen Systems. ISO: Geneva, Switzerland, 2015.
38. IEC 60079-10-1:2020; Explosive Atmospheres—Part 10-1: Classification of Areas—Explosive Gas Atmospheres. IEC: Geneva, Switzerland, 2020.
39. IEC 60079-17:2023; Explosive Atmospheres—Part 17: Electrical Installations Inspection and Maintenance. IEC: Geneva, Switzerland, 2023.
40. IEC 60439-1:1999; Low-Voltage Switchgear and Controlgear Assemblies—Part 1: Type-Tested and Partially Type-Tested Assemblies. IEC: Geneva, Switzerland, 1999.
41. IEC 60898-1:2015; Electrical Accessories—Circuit-Breakers for Overcurrent Protection for Household and Similar Installations—Part 1: Circuit-Breakers for A.C. Operation. IEC: Geneva, Switzerland, 2015.
42. IEEE Std 1100-1999; IEEE Recommended Practice for Powering and Grounding Electronic Equipment. IEEE: Piscataway, NJ, USA, 1999.
43. IEEE Std 1453-2004; IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems. IEEE: Piscataway, NJ, USA, 2004.
44. IEEE Std 929-2000; IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems. IEEE: Piscataway, NJ, USA, 2000.
45. Inal, O.B.; Charpentier, J.F.; Deniz, C. Hybrid Power and Propulsion Systems for Ships: Current Status and Future Challenges. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111965.

46. Zhao, F.; Wang, Z.; Dong, B.; Li, M.; Ji, Y.; Han, F. Comprehensive Life Cycle Cost Analysis of Ammonia-Based Hydrogen Transportation Scenarios for Offshore Wind Energy Utilization. *J. Clean. Prod.* **2023**, *429*, 139616. [\[CrossRef\]](#)
47. Percic, M.; Jovanovic, I.; Fan, A.; Vladimir, N. Design of Alternative Power Systems for Ferries Operating in the Adriatic Sea. *Ocean Eng.* **2025**, *319*, 120246. [\[CrossRef\]](#)
48. Williamsson, J.; Costa, N.; Santén, V.; Rogerson, S. Barriers and Drivers to the Implementation of Onshore Power Supply: A Literature Review. *Sustainability* **2022**, *14*, 6072. [\[CrossRef\]](#)
49. Doğan, F. Türk Limanlarında Gemilere Kıydan Elektrik Sağlanması (Cold Ironing): Tanımlar, Uluslararası ve Ulusal Mevzuat, Uyum Eksiklikleri ve Stratejik Çözüm Önerileri [Shore-to-Ship Power Supply (Cold Ironing) in Turkish Ports: Definitions, International and National Regulations, Compliance Gaps, and Strategic Solution Proposals]. *Ulaştırma Altyapı* **2025**, *2*, 166–192. (In Turkish)
50. Aksöz, A.; Asal, B.; Golestan, S.; Gençtürk, M.; Oyucu, S.; Biçer, E. Electrification in Maritime Vessels: Reviewing Storage Solutions and Long-Term Energy Management. *Appl. Sci.* **2025**, *15*, 5259. [\[CrossRef\]](#)
51. Mohammed, S.A.Q.; Jung, J.W. A Comprehensive State-of-the-Art Review of Wired/Wireless Charging Technologies for Battery Electric Vehicles: Classification, Common Topologies and Future Research Issues. *IEEE Access* **2021**, *9*, 19572–19585. [\[CrossRef\]](#)
52. Fan, A.; Liu, H.; Wu, P.; Yang, L.; Guan, C.; Li, T.; Liu, Y. LSTM-Augmented DRL for Generalisable Energy Management of Hydrogen-Hybrid Ship Propulsion Systems. *eTransportation* **2025**, *25*, 100442. [\[CrossRef\]](#)
53. Dini, P.; Saponara, S.; Chakraborty, S.; Hegazy, O. System-Level Compact Review of On-Board Charging Technologies for Electrified Vehicles: Architectures, Components, and Industrial Trends. *Batteries* **2025**, *11*, 341. [\[CrossRef\]](#)
54. Van Mulders, J.; Delabie, D.; Lecluyse, C.; Buyle, C.; Callebaut, G.; Van der Perre, L.; De Strycker, L. Wireless Power Transfer: Systems, Circuits, Standards, and Use Cases. *Sensors* **2022**, *22*, 5573. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Guo, S.; Wang, Y.; Yue, M.; Dai, L.; Fang, S.; Zhang, S.; Hu, H. Optimization of Energy Replenishment for Inland Electric Ships Considering Multi-Technology Adoption and Partial Replenishment. *J. Mar. Sci. Eng.* **2025**, *13*, 2092. [\[CrossRef\]](#)
56. Hsu, S.H.; Tzu, F.M.; Chen, Y.D.; Huang, C.W. Navigating Safety and Compliance in High-Voltage Shore Connection Systems: A Comprehensive Exploration of IEC/IEEE 80005-1 Standards and the Guidelines of Ship Classification Societies. *J. Mar. Sci. Eng.* **2024**, *12*, 322. [\[CrossRef\]](#)
57. Sulligoi, G.; Bosich, D.; Pelaschiar, R.; Lipardi, G.; Tosato, F. Shore-to-Ship Power. *Proc. IEEE* **2015**, *103*, 2381–2400. [\[CrossRef\]](#)
58. Costa, N.; Ekholm, J.; Rogerson, S.; Janhäll, S.; Besker, T.; Linders, T. *Standards of Shoreside Charging for Battery-Powered Vessels: Technical Report*; SSPA Sweden AB, RISE, University of Gothenburg: Gothenburg, Sweden, 2022.
59. Marquart, K.; Haasdijk, T.; Ferrari, G.B.; Schmidhalter, R. Shore-to-Ship Power: ABB's Turnkey Solution Is Effectively Reducing Portside Emissions. *ABB Rev.* **2010**, *4*, 56–60.
60. World Business Council for Sustainable Development. *Shore-to-Ship Power*; WBCSD: Geneva, Switzerland, 2019.
61. Karimi, S.; Zadeh, M.; Suul, J.A.; Thieme, C.A. Reliability Analysis of Shore-to-Ship Fast Charging Systems. In *Proceedings of the IEEE Transportation Electrification Conference and Expo (ITEC 2021)*, Chicago, IL, USA, 23–25 June 2021; IEEE: New York, NY, USA, 2021; pp. 539–545.
62. Mahaadevan, V.C.; Narayanamoorthi, R.; Gono, R.; Moldrik, P. Automatic Identifier of Socket for Electrical Vehicles Using SWIN-Transformer and SimAM Attention Mechanism-Based EVS YOLO. *IEEE Access* **2023**, *11*, 111238–111254. [\[CrossRef\]](#)
63. Pruyn, J.; Willeijns, J. Cold Ironing: Modelling the Interdependence of Terminals and Vessels in Suitable Systems. *J. Shipp. Trade* **2022**, *7*, 17. [\[CrossRef\]](#)
64. Colarossi, D.; Principi, P. Technical Analysis and Economic Evaluation of a Complex Shore-to-Ship Power Supply System. *Appl. Therm. Eng.* **2020**, *181*, 115988. [\[CrossRef\]](#)
65. Wang, Z.; Liao, P.; Long, F.; Wang, Z.; Ji, Y.; Han, F. Maritime Electrification Pathways for Sustainable Shipping: Technological Advances, Environmental Drivers, Challenges, and Prospects. *eTransportation* **2025**, *26*, 100462. [\[CrossRef\]](#)
66. Xie, P.; Tan, S.; Bazmohammadi, N.; Guerrero, J.M.; Vasquez, J.C. A Real-Time Power Management Strategy for Hybrid Electrical Ships under Highly Fluctuated Propulsion Loads. *IEEE Syst. J.* **2023**, *17*, 395–406. [\[CrossRef\]](#)
67. Güney, E.; Şahin, İ.H.; Çakar, S.; Atmaca, Ö.; Erol, E.; Doğanlı, M.; Bayılmış, C. Electric Shore-to-Ship Charging Socket Detection Using Image Processing and YOLO. In *Proceedings of the 2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, Ankara, Türkiye, 20–22 October 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1069–1073.
68. Fayyazi, M.; Sardar, P.; Thomas, S.I.; Daghigh, R.; Jamali, A.; Esch, T.; Khayyam, H. Artificial Intelligence/Machine Learning in Energy Management Systems, Control, and Optimization of Hydrogen Fuel Cell Vehicles. *Sustainability* **2023**, *15*, 5249. [\[CrossRef\]](#)
69. Ren, Y.; Zhang, L.; Shi, P.; Zhang, Z. Research on Multi-Energy Integrated Ship Energy Management System Based on Hierarchical Control Collaborative Optimization Strategy. *J. Mar. Sci. Eng.* **2022**, *10*, 1556. [\[CrossRef\]](#)
70. Güney, E.; Bayılmış, C.; Çakan, B. An Implementation of Real-Time Traffic Signs and Road Objects Detection Based on Mobile GPU Platforms. *IEEE Access* **2022**, *10*, 86191–86203. [\[CrossRef\]](#)

71. El-Shahat, A.; Qian, J.; Kilaz, G. Challenges and Solutions Samples to Improve the Utilization of Electric Ships (Brief-State-of-the-Art). In *Proceedings of the 2022 International Conference on Electrical, Computer and Energy Technologies (ICECET), Prague, Czech Republic, 20–22 July 2022*; IEEE: New York, NY, USA, 2022; pp. 1–5.
72. IEC 62443-3-3:2013; Industrial Communication Networks—Network and System Security—Part 3-3: System Security Requirements and Security Levels. IEC: Geneva, Switzerland, 2013.

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