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To cite this article: Xiaohui Li *et al* 2026 *Prog. Energy* **8** 042009

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TOPICAL REVIEW

Port electrification: definitions, pathways, and grid impact assessment

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Keywords: port electrification, onshore power supply, port operation, power-to-X, grid impact

OPEN ACCESS

RECEIVED
14 May 2026

REVISED
4 September 2026

ACCEPTED FOR PUBLICATION
4 November 2026

PUBLISHED
13 November 2026

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Abstract

Ports are increasingly central to decarbonization strategies, but port electrification is defined inconsistently across academic and policy literature. This ambiguity matters because different definitions imply different electricity-demand profiles, peak loads, connection requirements, and grid-upgrade needs. We examine how port-electrification pathways emerge under different combinations of contextual dynamics, policy signals and technological development, and how these differences matter for grid planning. Organizing the literature around electricity end use and the location of port activity, we identify three pathways—electrification at berth, electrification of terminal operations and electricity-based fuel supply in ports—ordered analytically by an expanding system boundary. Each pathway is mapped through a structured Scopus search supplemented by policy and technical reports. The comparison reveals uneven evidence maturity: shore-power research is relatively well grounded in port-specific operations, whereas terminal electrification and Power-to-X (PtX) studies more often draw on fragmented evidence or developments beyond the port sector. The pathways also exhibit distinct policy dynamics. Shore power has evolved through interactions among technological development, local air-quality measures and increasingly binding infrastructure requirements; terminal electrification remains shaped largely by domestic regulation, port initiatives and equipment investment; and port-based PtX is embedded in broader energy, industrial and geopolitical policy agendas. Correspondingly, the principal grid-planning problem shifts from managing coincident high-power vessel connections, to coordinating spatially distributed terminal loads, and ultimately to securing large-scale interconnection capacity for fuel production. When pathways are deployed together, however, they may share connection capacity, create coincident demand and provide complementary flexibility through managed charging, storage and schedulable electrolysis. By connecting the scope of port electrification to its policy, operational and grid-planning consequences, the review provides a structured basis for scenario design, coordinated port–grid planning and future research on integrated port energy transitions.

1. Introduction

Ports handle more than 80% of global trade by volume and are increasingly recognized as critical intervention points for climate mitigation and air-quality improvement, given their direct and indirect contributions to carbon emissions across logistics activities [1, 2]. Port operations, including auxiliary ship engines at berth, cargo handling, and drayage trucking, remain heavily dependent on fossil fuels, generating substantial greenhouse gas (GHG) emissions and local air pollutants in densely populated coastal areas [3–6]. Globally, ports and ships account for approximately 3% of CO_2 emissions [7] and a significant share of NO_x, SO_x, and particulate emissions in coastal cities [8]. For example, global shipping emitted approximately 9.2% of SO_x, 16.8% of NO_x and 4% of $PM_{2.5}$ from all anthropogenic sources in 2018 [9]. About 70% of ship activity and thus emissions occur within 400 km of the coast, with

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Table 1. Illustrative definitions of port electrification and the extent to which existing studies discuss grid impacts.

		Grid impact discussion	
Study	Scope of port electrification	Aspects	Brief (B) or substantive (S)
Clean Maritime Plan (UK) [16]	Shore-side power; Hybrid/fully electric vessels; Port operations (e.g. cranes)	Peak demand	B
Port Electrification Handbook (U.S.) [17]	Electrifying CHE; Light-duty electric vehicles and charging; Vessel shore power; Microgrid; Distributed wind and solar; On-port fuel production	New loads	S
Port as an energy hub (Sweden) [18]	OPS; Electrified cranes	Overloaded circuits; Voltage deviations; Frequency instabilities	S
[19]	Electrification of port equipment (e.g. electric cranes, trucks or forklifts); OPS; Alternative energy sources	Not explicit	/
[20]	Electrifying CHE, vehicles; Shore power; Microgrids	Increased demands; Grid outage	B
[15]	Shore power; Electrification of CHE	Overloading.	S
[21]	Shore-side electricity-OPS; Electric/hybrid cranes, support vessels, vehicles	Grid capacity; Peak demand	S
[4]	OPS; Microgrid	Grid peak period	B
[22]	OPS	Demand fluctuations	S
[23]	OPS	Power quality	B
[24]	Port equipment and vehicles (CHE, yard tractors)	Hourly electricity consumption	B

particularly high ship density in main shipping lanes and near major ports [10]. In response, port decarbonization is increasingly driven by international and regional policy initiatives, including the IMO's GHG strategy, FuelEU Maritime, and AFIR, while net-zero commitments in the United States, China, and the European Union have accelerated investments in shore power, electric port equipment, and zero-emission fuels [11–13]. As a result, port electrification is now widely framed as a key pathway for reducing emissions across the maritime supply chain, improving local air quality, and enabling compliance with emerging zero-emission requirements at berth [4, 14, 15].

Port electrification can be broadly understood as the transition from fossil-fuelled port operations to zero-emission, electricity-based systems. Despite its growing prominence, however, the term is used inconsistently across the academic and policy literature. Different studies adopt markedly different scopes, technologies, and system boundaries under the same label. As summarized in table 1, electrification is alternately treated as a single technology, a set of end-use conversions, or a broad energy-system transformation. In some cases, electrification refers narrowly to onshore power supply (OPS) for berthed vessels; in others, it includes the electrification of cargo handling equipment (CHE) and port vehicles; more recent work extends the concept further to renewable generation and storage, port microgrids, and even on-port fuel production.

This lack of terminological and conceptual consistency makes it difficult to compare findings across studies, aggregate evidence, or translate research insights into actionable infrastructure planning. These ambiguities are not merely semantic: they have direct implications for power-system analysis and investment decisions. The electricity demand associated with OPS for container vessels differs fundamentally from that of fully electrified terminal operations or power-to-X (PtX)-based production. Whether electrification is defined as an intermittent berth load, a fleet of fast-charging electric tractors, or a multi-hundred-megawatt electrolyser strongly affects projected peak demand, load variability, grid-connection requirements, and reinforcement timelines. In practice, many ports are located on the edge of distribution or transmission systems originally designed for legacy industrial loads. Overly narrow definitions risk underestimating grid constraints and upgrade costs, while overly broad or ill-specified definitions obscure where and how grid impacts arise, thereby increasing uncertainty for utilities, port authorities, and investors.

The review makes three contributions. First, it clarifies what should be counted as port electrification by organizing the literature around electricity end use and the location of port activities. On this basis, it proposes a three-pathway typology covering electricity use at berth, electrified terminal operations, and electricity-based fuel supply in ports, which makes the scope of port electrification explicit and supports consistent comparison across studies that currently use the term in divergent ways. Second, it systematically maps how these pathways are represented in academic literature and policy documents,

showing that port electrification is a heterogeneous and context-dependent transition, in which technologies, operational structures, and policy instruments jointly determine electricity-demand characteristics and grid impacts. This mapping provides a foundation for consistent analysis, scenario design, and coordinated port–grid planning. Third, the review investigates how grid impacts are assessed across the literature and synthesizes these fragmented approaches into a standardized analytical framework covering load characterization, voltage performance, network capacity and power flow, and power quality. By linking electrification scope to grid-assessment practice, the review bridges definitional ambiguity with actionable port–grid planning and provides a structured basis for scenario design, demand forecasting, and coordinated infrastructure development.

2. Review design and analytical framework

The review adopts a stepwise methodology consisting of exploratory scoping, concept development, typology-guided systematic search, thematic coding, and synthesis on how different electrification pathways are represented in the literature and how their grid implications are treated.

2.1. Scope and boundary logic

An exploratory scoping review of academic publications, policy documents, technical reports, and port-electrification guidance was first conducted to identify the definitions and technologies associated with the term 'port electrification'. Our review finds that definitional ambiguity largely stems from inconsistent treatment of electricity end-use consumers and system boundaries. To improve clarity and comparability, we therefore organized the review of port electrification from the perspective of electricity end-use, i.e. the downstream end of the energy value chain where electrification is ultimately realized through consumption, while anchoring the grouping of different port electrification activities in the location where they occur. This yields three port-electrification pathways, ordered analytically by an expanding system boundary—from electricity use at individual berths, to the electrification of terminal operations, and finally to electricity-based fuel production and supply linking the port to the wider energy system, as shown in figure 1:

- **1: Electrification of shore-to-ship connections.** It focuses on direct electricity use at the interface between the port and calling vessels. Shore-to-ship electrification is primarily achieved through OPS, also referred to as cold ironing. OPS enables berthed vessels to switch off their fossil-fuel auxiliary engines and use shore-supplied electricity to meet onboard hotel and service loads [25]. Where technically applicable, the same shore-side connection or dedicated charging infrastructure may also supply electricity to charge the onboard batteries of battery-electric and hybrid vessels.
- **2: Electrification of port-side operational equipment and vehicles.** It covers the electrification of all on-terminal operations including stationary CHE, such as quay cranes, yard cranes, and straddle carriers, and mobile assets such as terminal tractors, forklifts, and drayage trucks.
- **3: Electricity-based fuel supply via PtX processes.** Electrical energy is converted into various energy carriers or products (X = gas, heat, mobility, etc) to supply zero- or low-carbon fuels for maritime and other applications [26, 27]. A central pathway is hydrogen production via water electrolysis [28], which can substantially increase electricity demand. PtX deployment is often coupled with large-scale integration of renewable energy, extending beyond direct electrification to the energy, mobility, industrial, and residential sectors through hydrogen-based energy carriers.

Within this framework, port microgrids and RESs integration are enabling architectures that coordinate supply, storage, and flexible demand across multiple electrification pathways, because they do not represent distinct electricity end uses. Treating them as cross-cutting infrastructure avoids category overlap, preserves comparability across end-use pathways, and clarifies their role as systems for managing electrification demand.

2.2. Hierarchical keyword-search strategy

The proposed typology was operationalized through pathway-specific search strings in the Scopus database. The search terms and category boundaries were iteratively refined through screening of retrieved records, identification of recurrent false positives, and examination of relevant studies and reports for alternative terminology or omitted applications. After the search terms had been stabilized, a hierarchical keyword-search strategy was adopted, as illustrated in figure 2. First, pathway-only search

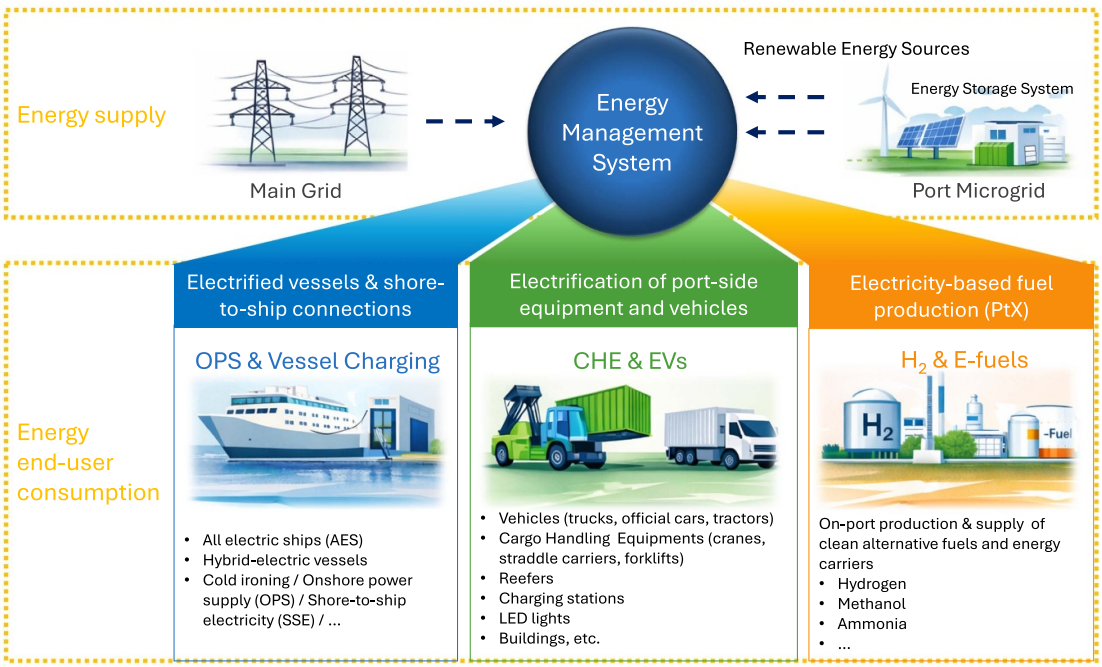

Figure 1. Three-pathway typology of port electrification and associated technologies.

strings were defined for each of the three electrification pathways in order to capture the broader literature associated with each electrification category. Second, these search strings were narrowed by adding port-related terms (e.g. port, seaport, maritime, harbo(u)r, terminal) to identify studies explicitly situated in port and maritime contexts. Third, a further grid-related filter (e.g. grid, power system, distribution network) was added to the port-related queries to isolate the subset of literature addressing electricity system and grid integration issues. Boolean operators ('AND', 'OR') were used to constrain the search. Random samples of returned studies were then reviewed, so that terms associated with recurrent irrelevant results were excluded from the search strings. In addition to peer-reviewed publications, some authoritative technical and project reports were included to strengthen coverage of practice-oriented developments, including reports from Lighthouse (Swedish maritime competence centre) [18], U.S. Maritime Administration [29], Pacific Northwest National Laboratory [17], and Port of Los Angeles [30]. The review protocol is documented in appendix A.

2.3. Thematic coding, synthesis, and analytical lens

The studies retained within the port-related scope were imported into NVivo software to support a structured qualitative synthesis of how port electrification is operationalized across the literature and of how drivers, technologies, methods, and barriers vary across contexts. A hybrid deductive–inductive coding strategy was adopted. First, an *a priori* coding frame was specified to reflect the review questions, including port function types and ship types, policy/drivers, methods, challenges/barriers, and relevant technologies. Second, additional subthemes were coded inductively as new concepts emerged during reading, ensuring that novel framings and underrepresented topics were captured. Coding was also applied to the contextual statements surrounding text-search hits, not just for the keywords. Individual excerpts could be assigned to multiple nodes when they contributed to several analytical dimensions (e.g. a container terminal vehicle scheduling paper could be coded simultaneously as 'Port function–container terminal' and 'Methods–simulation and optimization'). After coding, the NVivo codebook and coded references were exported and synthesized to map thematic distributions, compare methodological patterns, and relate these patterns to the three electrification pathways identified in the review. The number of studies identified with the specific thematic keyword is also recorded. These outputs constitute the evidentiary basis for the subsequent analysis.

In addition to thematic coding, the review compares the three electrification pathways in terms of contextual dynamics, policy signals, and technological development as reflected in the literature. Policy instruments are treated as contextual drivers and as markers of regulatory recognition, while publication patterns are interpreted as exploratory indicators of literature response and pathway-specific technological development rather than as direct measures of deployment or market uptake.

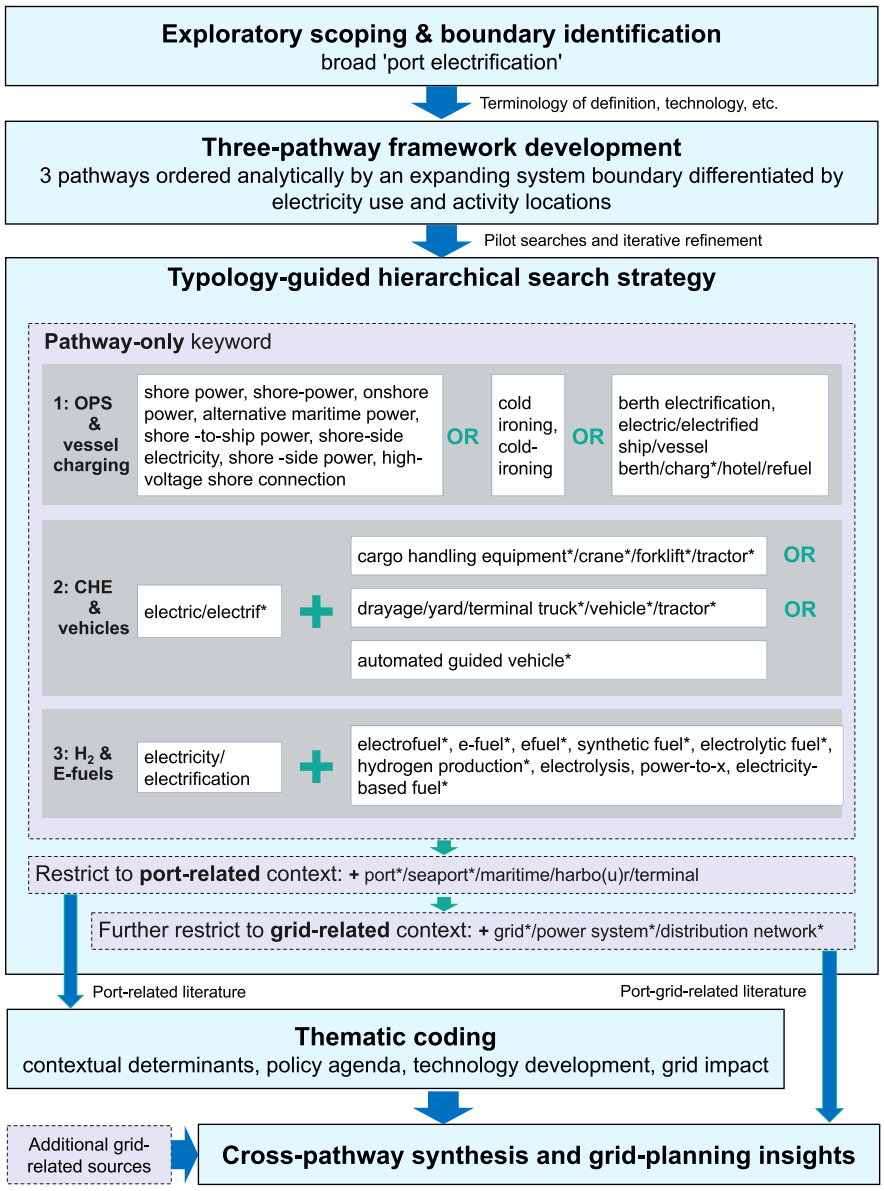

Figure 2. Review design and analytical methods with hierarchical keyword-search strategy used for Scopus queries.

2.4. Focused review of grid-assessment methods

Finally, studies captured under the grid-related scope were reviewed in greater depth to identify how grid impacts are described, which analytical dimensions are emphasized, and which methods recur across the literature. To strengthen this synthesis, additional technical sources on grid-impact assessment were also examined where needed. This focused review provides the methodological basis for the four-part framework developed later in the paper, linking electrification pathways to load characterization, voltage effects, network capacity and power flow, and power quality.

3. Pathway development across the literature

3.1. Literature distribution across the three pathways

The hierarchical search results reveal substantial differences in the size, maturity, and port- and grid-specific relevance of the literature across the three electrification pathways. As shown in figure 3(a), for all three pathways, the literature retrieved using pathway-only keywords is substantially larger than the

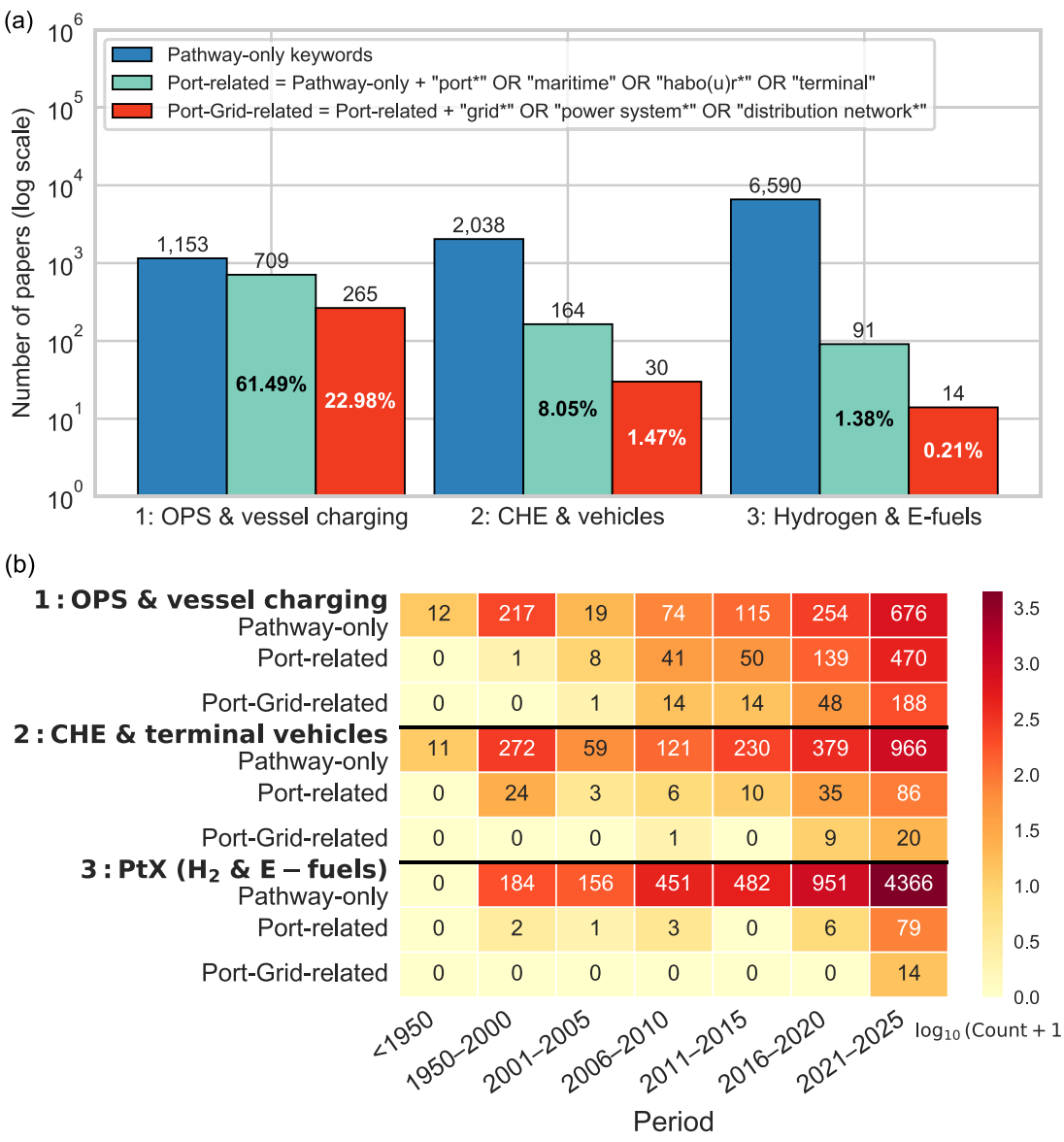

Figure 3. (a) Number of the reviewed literature. (b) Temporal distribution across three electrification pathways under progressively narrower keyword scopes.

subsets obtained after adding port-related and the further port-grid-related terms. The port-related subset of OPS and vessel charging literature accounts for a relatively large share of the pathway-specific literature (61.49%), whereas the port-grid-related subset is markedly smaller (22.98%). This contraction intensifies in CHE and terminal vehicle literature, where the port-related and port-grid-related shares fall to 8.05% and 1.47%, respectively. The divergence is most pronounced in PtX literature: despite the large body of general literature, only 1.38% is explicitly port-related, with just 0.21% relating to grid- or power-system terminology. This imbalance is not only structural but also temporal. Across all three pathways, publication activity is concentrated overwhelmingly in the post-2000 period, with the strongest accumulation in 2021–2025, as shown in figure 3(b). However, the port-grid-related subset remains consistently limited.

Taken together, the publication counts point to a clear asymmetry in research attention across the three pathways. OPS and vessel charging literature is the most port-specific and the most strongly connected to grid discussions; CHE and terminal vehicle literature is operationally important but conceptually fragmented across adjacent literature; and P2X literature is expanding rapidly but remains weakly anchored in port-specific and grid-specific analysis. This asymmetry suggests that port electrification is a composite domain in which different pathways occupy very different stages of conceptual and analytical development. And the significant imbalance between pathway-only and port- and further

Table 2. How port context matters across electrification pathways in the literature.

Pathway	Primary contextual dimension	Typical contexts in the literature	Why the context matters
1: OPS & vessel charging	Ship type (with port function as a secondary contextual factor)	Cruise ships, ferries, container ships, Ro–Ro vessels, bulk carriers, tankers, reefers, etc; Primarily cargo port/terminals, cruise terminals, etc.	Berth configuration, traffic regularity, vessel hoteling load, berth duration, voltage/frequency requirements, etc.
2: CHE & terminal vehicles	Port function	Primarily container terminals; Limited from Ro–Ro terminals and other terminal types	Terminal processes, equipment mix, operational layout, role of cranes, reefers, yard trucks, tractors, etc.
3: PtX (H_2 & E-fuels)	Cross-sector energy integration linkages	Port's extended role in the wider energy system linking to RESs, hydrogen, e-fuels, and CCS, etc.	Access to renewable resources, surrounding industry, land availability, storage needs, bunkering logistics, grid capacity, etc.

port-grid-related studies highlights the need for a synthesis that clarifies the scope of port electrification and consolidates its grid impacts.

The temporal evolving pattern of index keywords is also examined in appendix B. The analysis identifies three different thematic trajectories: berth and vessel electrification has broadened toward energy management, optimization, renewable-energy integration, and economic assessment; terminal-equipment and vehicle electrification has increasingly focused on mobile assets, charging, fleet scheduling, and operational coordination; PtX-based production and supply has expanded toward renewable-energy sourcing, hydrogen systems, and decarbonization.

3.2. Contextual determinants of electrification pathways

Around one quarter of the reviewed studies explicitly relate electrification to port function type or ship type. Port function type refers to the dominant operational and logistical role performed by a port or terminal, such as container handling, bulk cargo, Ro–Ro operations, cruise and passenger traffic, fishing activities, or multipurpose logistics functions. Ship type refers to the categories of vessels calling at the port, including cruise ships, ferries, container ships, Ro–Ro vessels, bulk carriers, tankers, and fishing vessels. Across the reviewed literature, the relevance of these two dimensions varies markedly by electrification pathway, as summarized in table 2.

Among the three pathways, berth and vessel electrification (OPS and vessel charging) is the pathway whose technical and regulatory relevance is most directly conditioned by who calls at the port and what the port does. Port function shapes berth configuration, traffic regularity, and the likely utilization rate of OPS infrastructure. This port-specificity across studies is especially evident at the terminal level. Some studies explicitly distinguish between cargo- and passenger-oriented terminals, showing that electrification cannot be treated as a single load category. For instance, cargo terminals and cruise terminals are differentiated in digital-twin applications [31]: cargo terminals are associated with berth allocation, cargo throughput, reefer monitoring, and shore-power sharing, whereas cruise terminals are characterized by passenger-centric activities and intermittent but high-intensity loads linked to cruise vessel hoteling demand [32–34].

As ship type determines auxiliary load, voltage and frequency requirements, and vessel berthing duration [35], studies show that the technical parameters for OPS vary significantly across container, bulk carrier, Ro–Ro, tanker, passengers, reefer and support vessels etc in terms of average berthing power, voltage, and maximum design loads [4, 36–39]. Regularity of calls also appears to be an important differentiating factor. For instance, passenger ships and Ro–Ro/passenger vessels accounted for the majority of arrivals in the case study, with regular schedules dominating traffic [22]. This regularity can improve the predictability of OPS demand and may make infrastructure utilization more attractive from a planning perspective. By contrast, ports serving a more heterogeneous mix of cargo segments may face greater uncertainty in simultaneity, load coincidence, and vessel-specific compatibility requirements.

Terminal CHE and vehicles electrification is shaped mainly by terminal function. Research on electrified CHE and terminal vehicles is concentrated overwhelmingly in container terminals, where electrified RTG cranes, reefers, and yard trucks account for a large share of electricity demand and where operational optimization has long been a research focus [40–43]. The literature on non-container operational contexts is much more limited but points to potentially different electrification priorities. Alternative powertrains and hydrogen-fuelled yard trucks are widely examined in Ro–Ro terminal operations

[44, 45], suggesting that port electrification in this setting may be more closely tied to terminal tractor fleets and horizontal transport, and the kinds of cargo-handling and logistics functions they perform.

PtX-based electrification is far less frequently mapped against port function. Where it does appear, it is typically associated with ports that are evolving into broader energy hubs in the context of port decarbonization [14, 46]. Researchers point out that most studies on port decarbonization were devoted to either large cargo ports, especially container terminals, or on cruise and ferry ports, and emphasize that port case studies should not be classified only by size or ship traffic, but by a broader typology including port activities, surrounding industries, grid capacity, ownership, geographical location, and ambition level for energy transition [47]. It is further noted that PtX is often coupled with renewable resources and, in some cases, carbon capture and storage (CCS). However, alternative fuels require additional storage space, safety infrastructure, and more complex bunkering logistics [48], which may pose greater challenges for smaller ports with limited land and operational flexibility. This suggests that Pathway 3 is technologically distinct from Pathways 1 and 2 and may only be viable under particular port functions and spatial conditions, while its integration into broader decarbonization transition packages could both reflect and reshape the role of ports over time.

Overall, the literature indicates that port electrification is a context-specific system transformation shaped by port function, infrastructure readiness, traffic composition, regulatory drivers, and fleet characteristics. Berth and vessel electrification is the most port- and ship-specific and the most operationally mature pathway; terminal CHE and vehicles electrification is shaped mainly by terminal function and remains concentrated in a relatively narrow set of port contexts; and PtX-based electrification is the least port-specific in the existing literature but potentially the most transformative, as it repositions ports as nodes of sector coupling and industrial decarbonization. Port electrification should therefore not be treated as a single category of technology adoption or electricity demand, but as a context-dependent set of pathways whose practical meaning varies across maritime settings [14]. Recognizing this heterogeneity is essential for realistic grid-impact assessment, infrastructure planning, and the design of effective decarbonization strategies.

3.3. Policy dynamics and literature-response patterns

This section examines how policy signals have shaped academic attention across the three pathways of port electrification and investigates whether discernible temporal gaps exist between the emergence of binding policy instruments and the growth of academic output. The four regions or countries examined–Europe (mainly the EU), the United States, China, and the United Kingdom–collectively account for approximately 73%, 70%, and 64% of the literature identified in Pathways 1, 2, and 3 respectively. Major policy milestones are summarized in table C1 in appendix C and figure 4.

OPS and vessel charging literature has developed alongside an increasingly specific regulatory framework at international, regional, and national levels. Figure 4(a) presents the annual publication counts for this pathway across the four focal regions from 2004 to 2025. Indicated by the relative timing of technical studies, policy milestones, and subsequent changes in publication counts, berth and vessel electrification appears to follow a long-cycle sequence of early technology development followed by stronger policy attention and deployment requirements. Before 2010, the US was the principal source of publications. Driven by near-port health concerns, early studies and practices such as the Port of Los Angeles" first commercial "cold ironing" application in 2004 existed several years ahead of the introduction of major binding at-berth requirements. This suggests that the early US policy in this field may act as a "first-mover validator" rather than the original driver of innovation. Globally, IMO's MARPOL Annex VI entered into force to address air pollution from ships, with significant later amendments tightening emission limits within designated Emission Control Areas (ECAs). OPS is a primary compliance method approved under this regulation [49]. The 2005 implementation of MARPOL Annex VI did not trigger an immediate spike in literature. Stronger publication growth became visible after the late-2000 s and early-2010 s amendments. This timing may be consistent with a lag between regulatory development and research activity, although it may also reflect technology maturation, port demonstrations, funding availability, and growing concern about local air quality. After 2010, China exhibits a much more recognizable policy-led pattern, and the EU also shows a strong rise in publication counts during the adoption of AFID and the subsequent AFIR and FuelEU Maritime. Overall, these trends might suggest that OPS and vessel charging research has evolved through interactions among technical development, local demonstrations, air-quality regulation, maritime policy, and later infrastructure mandates.

As shown in figure 4(b), the temporal sequence of CHE and terminal vehicles publication volumes across all regions exhibits high volatility without a clear, continuous growth trajectory. Globally, landside port equipment and vehicles falls outside the direct jurisdiction of the IMO and is governed exclusively by domestic environmental policies. Policy interventions are driven by local port authorities. Major

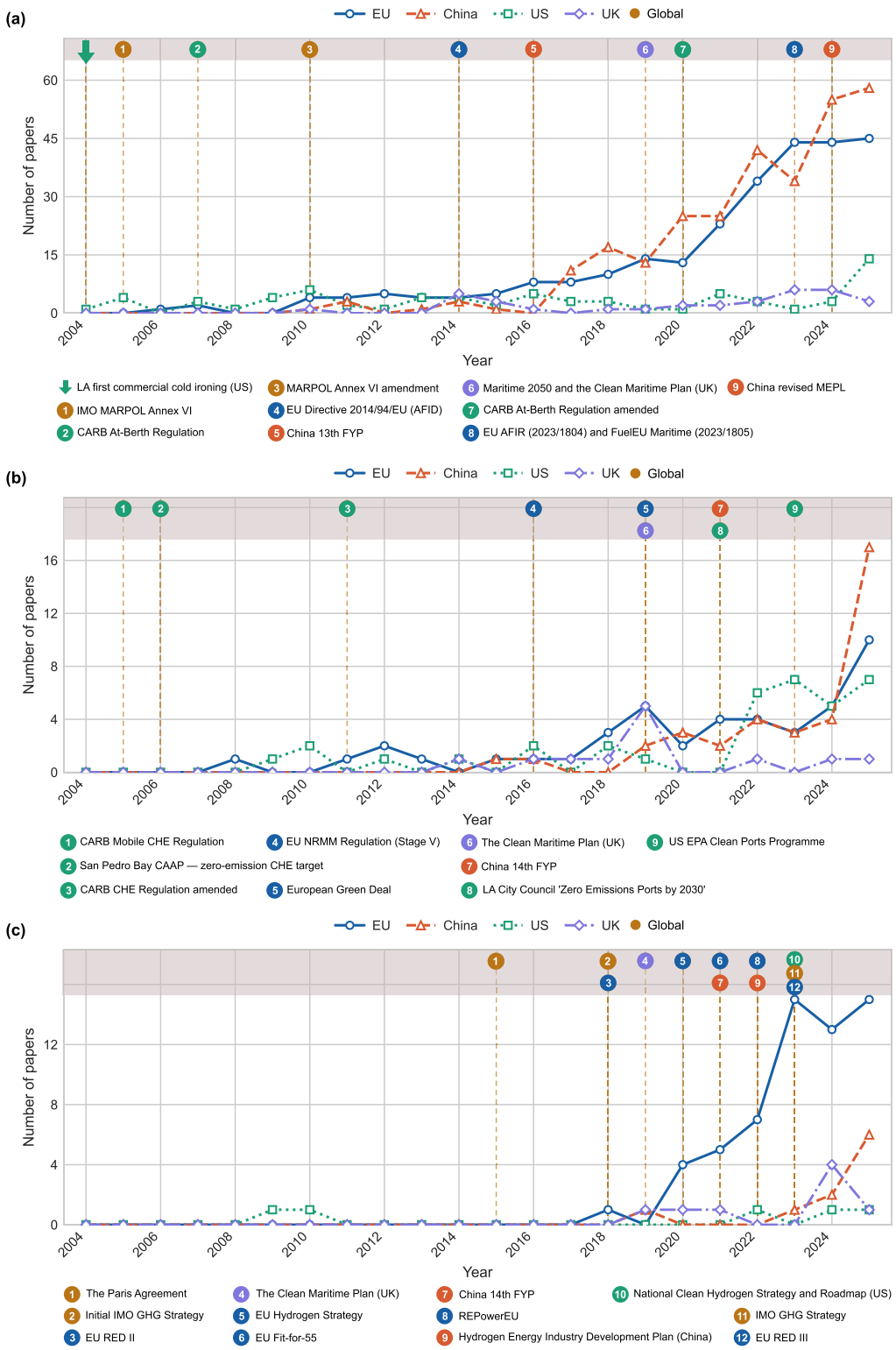

Figure 4. Publication counts in the dominated regions/countries with policy milestones: (a) 1: OPS & vessel charging; (b) 2: CHE & terminal vehicles; (c) 3: Hydrogen & E-fuels. The *y*-axis location of policy labels is for legibility only and carries no quantitative meaning.

global hubs like Rotterdam, Singapore, and Shanghai have established internal net-zero terminal targets for 2035–2060, where zero-emission solutions, including electric cranes and vehicle fleets, are proposed together with shore power utilization. As early as 2005, CARB's Mobile CHE Regulation was adopted to reduce toxic emissions and launched at the Ports of Los Angeles and Long Beach, which set targets for zero-emission CHE by 2030 and drayage trucks by 2035. Although these initiatives provided early policy

signals, the corresponding academic literature remained limited for several years. One possible explanation is that early knowledge development occurred primarily through equipment procurement, operational trials, manufacturer-led development, consultancy, and port demonstration projects rather than through academic publication. Publication activity increased more visibly during the past decade. This growth coincided with stronger financial and industrial support, including China's 14th Five-Year Plan subsidies and the US EPA's $3 billion Clean Ports Program, as well as broader European decarbonization and air-quality policies. However, external technological and economic factors such as supply-chain constraints, charging standards, electricity prices, grid-connection lead times, and access to capital may also affect implementation and research attention. Terminal CHE and vehicles electrification should therefore be understood as a field shaped by the interaction of environmental regulations and broader influencing factors.

Hydrogen and e-fuels policies mainly operate through fuel governance, market formation, and industrial transition strategies. Figure 4(c) shows that PtX publication activity was limited before the 2015 Paris Agreement but increased substantially during the late 2010 s and early 2020 s, particularly in Europe. REPowerEU, presented by the European Commission in May 2022, was explicitly framed as a response to the energy-market disruption caused by the Russia's invasion of Ukraine. This policy signal links the phase-down of Russian fossil-fuel dependence with energy savings, diversification of supply, accelerated renewable-energy deployment, electrification, biomethane, and renewable hydrogen. The sharp increase in European PtX publications after 2022 may therefore reflect the combined influence of climate-policy ambition, maritime-fuel regulation, energy-security concerns, natural-gas supply disruption, and public investment. At the international level, the 2023 IMO GHG Strategy sets the global benchmark, and it introduces a specific mandate for zero or near-zero GHG emission technologies in shipping energy. This does not require ports to build PtX plants, but it materially strengthens the future demand signal for hydrogen and electrofuels. Within the EU, PtX-based electrification is addressed by layered policy stack that provides a framework for renewable energy and strategies for hydrogen-based fuels. National strategies have also been established in countries such as Denmark, Germany and the Netherlands, linking port-side PtX with maritime demand. This policy stacking over the last decade may have contributed to a strong research response, but the publication data cannot isolate the effect of any individual instrument. The UK, China, and the US have also released national hydrogen strategies and roadmaps to create a stronger signal for alternative energy, but they lack specific policies for port-side PtX infrastructure. Based on the literature and the observations from the publication counts and policy signals, the evidence suggests that PtX-based electrification is generally embedded in a broader energy and industrial transition in which maritime decarbonization interacts with renewable-energy policy, hydrogen strategy, energy security, and geopolitical developments [17, 50, 51].

4. Grid implications and assessment framework

Port electrification fundamentally reshapes a port's energy profile. It can add from several megawatts to well over 100 MW of new electricity demand depending on scale and pathway (table 3), and grid impacts can range from feeder-level loading to bulk-system interconnection and reinforcement, which result in different grid impact assessment (table 4) and planning framework (table 5). Even ports with ample capacity today may face future constraints as electrification accelerates, risking operational disruption due to insufficient supply. Although the reviewed port-electrification literature often frames grid impacts primarily in terms of electricity demand and peak loads, the interconnection and operational feasibility of converter-intensive electrification also depend on voltage performance, thermal constraint violations over time, and power-quality compliance at the point of common coupling (PCC).

Different electrification pathways imply different load characteristics and therefore raise different grid questions. Each produces a distinct profile of network impacts, which in turn determines the analytical priorities for assessment and the planning outputs required.

OPS and vessel charging typically creates berth-based loads that depend on stochastic vessel calls, at-berth demand characteristics attributed to vessel type, berth allocation, and simultaneity. OPS operation can draw 25%–40% of rated connection capacity [12, 78], and demand is strongly seasonal [62, 79]. The literature accordingly often emphasizes grid peak periods, demand fluctuations, overloaded circuits, voltage deviations, and power-quality concerns [4, 18, 22, 23].

CHE and terminal vehicles creates more distributed and operationally driven loads tied to equipment use, charging windows, and working schedules. Here the emphasis falls on aggregate demand growth, hourly electricity consumption, feeder overloading, grid capacity, and local outage or reinforcement risks associated with electrified equipment and vehicles [20, 21, 24]. An optimal power flow analysis of a

Table 3. Evidence of indicative magnitudes of electricity demand and connection capacity by pathway.

Pathway	Sub-domain	Scope	Indicative magnitude	Basis of quantitative evidence	References
1: OPS & vessel charging	OPS	Per berth	Small vessels: 1–2 MW; Medium vessels: 2–8 MW; Large vessels: ⩾ 20 MW.	Review	[52]
	OPS	Per ship	Cruise ships: ≈4–12 MW; Container ships: ≈1–3 MW; Tankers: ≈1–2 MW; General cargo: ≈0.5–1.0 MW; Bulk carriers: ≈0.3–1.0 MW; Other (mostly small) ships: ≈0.1–2.0 MW.	Review	[53]
	OPS	Per berth	4 MVA per berth connection for container and car/RoRo vessels; 19 MVA handled by the station (7 berths).	Design rating, Port of Gothenburg	[54]
	OPS	Per berth	7.5 MVA per berth for mega-ships.	Design rating, Port of Hamburg	[55]
	OPS	Per connector	2.5 MW	Modelled, Port of Los Angeles	[30]
	OPS	Port-level	Installed: ⩾ 43 MW (⩾ 100 connections); Planned: 100 MW in total for 3 container terminals.	Measured/Design, Port of Rotterdam	[56]
	OPS	Port-level	Up to 60 MW	Measured, Port of Los Angeles	[8]
	OPS	Port-level	288.8 MW capability (23 berths) across major container hubs.	Measured, Port of Shanghai	[57]
	OPS	Per berth; port-level	12 MW × 2 connection points; 7.5 MW × 3 connection points.	Measured/Design, Port of Vancouver	[58]
	OPS	Port-level	5.95 MW peak power demand; 7.1 GWh annual demand.	Modelled, Port of Plymouth	[59]
	OPS	EU-wide	3.5–10.7 TWh yr^{-1}	Modelled	[60–62]
	Vessel charging	Per-ship	100 kW–10 MW	Review	[63]
	Vessel charging	Per-ship	MF Ellen (Denmark): 4 MW at 1000 V; Go Vakker Elen, Fredrikstad (Norway): 80 kW; MF Tycho Brahe and MS Aurora (Denmark–Sweden): 10.5 MW at 10 kV; MV Hallaig (Scotland): 50 kW.	Measured/Design	[64]
	Vessel charging	Per-ship	EVM200 (New Zealand): up to 2.2–3.75 MW.	Measured/Design	[65]
	Vessel charging	Per-ship	E-HC (Singapore): 150 kW DC	Measured/Design	[66]
	Vessel charging	Per-ship	MF Bastø Electric (Norway): 9 MW at each docking rating	Measured/Design	[67]
2: CHE & terminal vehicles	Drayage truck	Per-truck charging; port-level	350 kW assumed peak charging; Full drayage truck electrification demand peak: 3.5 MW for Fleet 1; 10.3 MW for Fleet 2; 10.8 MW for Fleet 3.	Modelled, Port of New York/New Jersey	[68]
	Drayage truck	Per-truck; port-level	25 × 360 kW charging units; ≈9 MW site: 44 trucks simultaneously; 200 trucks per day.	Measured/Modelled, Port of Long Beach	[69]
	CHE	Per equipment, port-level	6 kW–950 kW for RTG cranes, forklifts, reefers, top handlers, etc 128–277 MW additional distribution loading from full CHE electrification.	Design rating/Modelled, Port of Los Angeles	[30]
	RTG cranes	Port-level	≈800 kW peak demand for 2 electrified RTG cranes.	Measured, Port of Felixstowe	[70]
3: PtX (H_2 & E-fuels)	H_2 production	Port-level electrolyser	63 MW first phase; 300 MW (2028); 600 MW (2030).	Design rating, North Sea Port	[71]
	H_2 production	Port-level electrolyser	ELYgator: 200 MW hybrid PEM/alkaline	Design rating, Port of Rotterdam	[72]

(Continued.)

Table 3. (Continued.)

Pathway	Sub-domain	Scope	Indicative magnitude	Basis of quantitative evidence	References
	H_2 production	Port-level electrolyser	Uniper: 200 MW PEM within planned 1 GW facility	Design rating, Port of Wilhelmshaven	[73]
	H_2 production	Port-level electrolyser	HyTechHafen: 100 MW, expandable to 1 GW	Design rating, Rostock Port	[74]
	H_2 production	Port-level electrolyser	Power to Hydrogen: 0.5 MW (250 kW × 2 AEM electrolyser stacks)	Design rating, Port of Antwerp-Bruges	[75]
	E-fuel production	PtX plant-level	55.7–101.7 MW electricity consumption for 50,000 t methanol per year in different cases.	Modelled	[76]
	E-fuel production	Ports as e-fuel import/export node	81.65–231.84 GWh for 0.504 Mt e-methanol per year; 347.78–409.96 GWh for 0.556 Mt e-ammonia per year.	Modelled	[77]

Table 4. Grid impact assessment matrix across three port-electrification pathways.

Aspect	OPS & vessel charging	CHE & terminal vehicles	PtX (H_2 & E-fuels)
1. Load characterisation			
Electrical characteristics	Event-driven, vessel-call-dependent demand with operational load factors of 25%–40%.	Variable operational loads from CHE, reefers and drayage trucks charging with higher ramp effects.	Large continuous industrial PtX loads; planned expansion toward GW scale.
Assessment	Bottom-up co-occurrence modelling to estimate peak demand and required connection capacity.	Time-series operational assessment to derive terminal load profiles and feeder peak demand.	Bulk power-flow to assess required connection capacity and reinforcement assessment.
References	[4, 18, 59, 63, 90, 91]	[15, 20, 21, 24, 30, 92–94]	[80, 81, 95]
2. Power quality and voltage			
Electrical characteristics	Converter-induced harmonic distortion at the PCC and simultaneous berth loading can cause PCC undervoltage.	Feeder-voltage deviation under coincident heavy-duty truck (HDV) fast charging; harmonic distortion from variable-speed drives (VSDs).	High-power electrolyser rectifiers introduce reactive-power demand and harmonic distortion.
Assessment	At berth and PCC power flow and harmonic distortion assessment.	Feeder-voltage and converter-induced power-quality impacts.	Assessment focuses on PCC voltage regulation and reactive-power demand.
References	[18, 63, 95]	[92, 93]	[95]
3. Network capacity and hosting			
Electrical characteristics	Drives transformer and feeder loading, with connection ratings potentially exceeding operational demand.	Feeder hosting capacity is a primary constraint; voltage deviation under HDV fast charging	Transmission constraints for large PtX loads; extends to network reinforcement, N-1 security, and dynamic stability.
Assessment	Time-series power flow and concomitance modelling to assess transformer loading and network reinforcement.	Temporal hosting-capacity to binding constraints assessment.	Bulk-system capacity and stability margins.
References	[4, 18, 22, 90]	[15, 20, 30, 68, 92–94]	[80, 81, 95, 96]

major electrified UK port shows that the probability of a network constraint violation reaches 70% when operational uncertainty is ignored, and that reverting vessels to auxiliary engines in response to grid constraints results in a 150% increase in port-level emissions [15].

Hydrogen and e-fuels production and supply can introduce large industrial electricity demand at a scale that may exceed conventional distribution-level assumptions and place pressure on sub-transmission or transmission infrastructure. These implications are less often discussed in port-specific terms. However, the available evidence is drawn largely from adjacent literatures indicating that PtX

Table 5. Pathway-based grid planning framework for port electrification.

Pathway	OPS & vessel charging	CHE & terminal vehicles	PtX (H_2 & E-fuels)	Cross-pathway synthesis
Connection Layer	Port switchgear supply standardized at MV (6.6–11 kV)	Multiple radial feeders with LV charge points; MV (10–20 kV)	Transmission by large load interconnection; HV/EHV (66–132 kV+)	As pathway load scale increases, the network structure and capacity shifts higher
Binding Problem	How can current capacity serve concomitance within voltage and power quality limits?	How much operational flexibility is feasible and which feeder constraints do chargers add?	What extent of reinforcement needs are required for bulk power PtX loads?	Shifts from local peak loads to operational loads demand shifting and then bulk power capacity
Planning Variable	Co-occupancy of vessel categories per berth	Spatial and temporal placement of equipment and charging loads	Connection capacity agreed with network operator	Co-occurrence to coordination and interconnection
Flexibility Options	Vessel scheduling; ESS for peak shaving and load shifting; Shore-power allocation	Equipment scheduling; Managed charging; EMS; Local renewable integration.	Flexible electrolysis; Hydrogen storage; Price-responsive operation	Flexible network connection and grid enhancement across all three pathways

can substantially increase electricity demand and shift the planning challenge toward larger connection requirements and longer reinforcement timescales [17, 80, 81].

The uneven treatment of grid issues across the three pathways reinforces the need for pathway-specific grid assessment. Assessment depth should therefore be matched to both the pathway's connection voltage and the lead time required for reinforcement.

4.1. Load characterization methods

Accurately characterizing and modelling both the volume and the timing of electricity demand, i.e. the load profile, is essential for robust grid-impact assessment. This foundational step translates heterogeneous electrification measures into time-resolved electrical demand at defined connection points, such as berth substations, yard feeders, or the port's PCC. Existing methods used for modelling electricity demand can be grouped broadly into bottom-up, top-down, and hybrid approaches, depending on the availability of data [18, 41].

- Bottom-up approaches construct port demand by modelling individual end-use assets and aggregating their energy demands according to operational activity, which is especially useful where electrification is tied to discrete operations such as crane cycles, yard tractor duty cycles, or vessel hotel loads at berth [4, 35, 59, 82, 83].
- Top-down approaches infer and forecast future port electricity demand from historical aggregate measurements, often using statistical or machine-learning methods, and are particularly useful when equipment-level data are unavailable [84–87].
- Hybrid methods combine data-driven forecasting with operational reconstruction to improve both predictive accuracy and scenario interpretability [13, 88].

Most load-modelling studies tend to produce time-resolved load profiles because grid impacts are driven by peak demand, charging coincidence, and operational timing. In the port literature, this appears as hourly/day-ahead demand forecasting [41, 89], worst-case simultaneous peak estimation [30, 84], and quasi-static time-series grid studies [68]. Common outputs include total energy use, peak demand, and coincident/simultaneous peaks, because these determine contracted capacity and grid reinforcement needs [90]. Improving transparency and comparability in port-electrification research therefore requires standardized reporting of load modelling, at minimum specifying end uses included, temporal resolution, scenario assumptions, and resulting peak or coincidence metrics. A primary bottleneck remains the lack of high-granularity data [18, 41].

4.2. Power quality and voltage assessment

Once time-resolved load profiles have been established, the next question is whether those loads can be accommodated without violating technical limits. Power quality is a distinct concern because frequency converters, high-power rectifiers, variable-speed drives, and fast chargers inject harmonic and interharmonic currents that can distort supply voltages and interfere with sensitive equipment [97]. The assessments are therefore typically framed around compliance at the PCC and include metrics such as total

harmonic distortion and harmonic spectra in IEC/IEEE 80 005 [98]. Thyristor-based rectifiers, which remain the dominant topology for industrial alkaline electrolysers, have been demonstrated to produce substantial harmonic distortion and reactive power demand, with power factors ranging from 0.90–0.95 at full load [95]. Frequency conversion of shore-power converters from the utility 50 Hz or 60 Hz supply to a vessel's onboard standard and for direct-current fast charging inject harmonic and inter-harmonic currents into the local network [99]. A 24-pulse cold-ironing architecture has been reported to yield a grid-side current THD of 1.7%–2.1%, in contrast to the 5.3%–5.7% observed with a conventional static frequency converter supplying equivalent vessel loads [63]. Nevertheless, detailed harmonic studies remain less common in port-specific research than in adjacent microgrid and electric-vehicle literature. Voltage assessment addresses whether incremental electrified port loads can be supplied without violating voltage magnitude, unbalance, or event-performance expectations at critical nodes such as berth substations, yard feeders, and the PCC [18, 100, 101]. In converter-rich port electrification, the issue is not only coincident MW demand but also time-varying ramps alongside power factor and reactive power control [30, 96].

4.3. Network capacity and hosting analysis

Power-flow and hosting-capacity assessment identifies thermal overloads, voltage violations, and other steady-state feasibility issues across the relevant distribution network. In distribution planning and interconnection practice, these evaluations are often summarized through hosting capacity: the amount of new load or generation that can be accommodated under existing configurations without violating operational criteria or requiring infrastructure upgrades [102, 103]. In port planning practice, hosting capacity is best treated as a process rather than a single number, and decision-relevant outputs include the binding constraint by location and period, the hours of violation under time-series simulation, the upgrade options required to increase capacity, and the value of operational mitigation in deferring upgrades [30]. The relevance of this approach is substantial across all three pathways, particularly for terminal fleet charging. Uncoordinated megawatt-scale charging of heavy-duty vehicles is indicated to lead to network violations, with the effects influenced by the location of the charger and the simultaneity of charging activities [92]. Specifically at ports, the electrification of drayage trucks can also lead to concentrated stress on distribution networks, which requires integrated infrastructure planning [93].

4.4. Flexibility and mitigation options

A central integration question for port electrification is how to accommodate large, variable, and increasingly converter-intensive loads without destabilizing local distribution networks or triggering disproportionate costs. Not all pathway-specific impacts can or should be met through immediate grid reinforcement. The reviewed literature therefore points to a set of operational and infrastructure-based mitigation options that reshape demand, deploy distributed energy assets, and coordinate supply-side response while planning for long-term, asset-heavy grid upgrade.

4.4.1. Operational scheduling and forecasting strategies

Port electricity demand is determined not solely by equipment ratings but by the simultaneity of berth occupancy, crane assignments, and yard operations, so scheduling offers direct leverage. Coordinated berth and shore power allocation [104, 105], quay crane assignment [106, 107], and integrated yard scheduling [82, 101] reduce both consumption and coincident peaks by staggering operations across time and space rather than allowing multiple large loads to occur concurrently.

Smart charging, also referred to as controlled or managed charging, applies the similar logic to vessels and vehicle fleets [13, 94, 108]. In contrast to uncoordinated connection of vessels and electric vehicles upon arrival, managed charging schedules loads by prioritizing off-peak windows, sequencing equipment start-ups, and aligning demand with local network constraints or available renewable generation. In practice, many smart-charging schemes operate as forms of demand response [109, 110], shifting or curtailing flexible loads in response to time-of-use tariffs or other network signals [111, 112].

Both optimized scheduling and smart charging depend on accurate forecasting. Vessel arrivals, charging windows, operational routines, and renewable output should be predictable before proactive dispatch of flexible loads and local resources. Electrification planning is accordingly recommended to begin with a coordinated load forecast developed jointly with the serving utility [17, 18], as temporal visibility of both supply and demand underpins the reliable operation of every downstream mitigation strategy.

While system architecture typically orchestrates and amplifies the operational scheduling strategies described above, it is physically supported by on-site energy assets such as renewable generation and

energy storage systems (ESS) [3, 13, 31, 113–116]. ESS typically buffers fast load ramps, absorbs intermittent local generation, and provides short-duration backup during high-demand events, thereby reducing peak imports from the distribution network. Renewable integration reduces net grid imports by supplying low-carbon electricity from solar PV, wind, hydropower, etc and supports decarbonization objectives. Renewable generation delivers greater grid-integration benefits when combined with smart charging and energy storage, which improve the temporal alignment of renewable supply and port demand, increase local renewable-energy utilization, and reduce peak grid imports.

A port microgrid is a localized, controllable energy system comprising distributed energy resources, ESS, and controllable loads, and it is coordinated by an energy management system (EMS) with bidirectional grid interaction capability [17, 117, 118]. In normal operation, the EMS continuously balances generation and consumption in real time. In islanded mode, the microgrid maintains internal frequency and voltage regulation independently of the utility grid, providing resilience during supply disruptions. Smart port concepts extend this architecture by embedding Internet-of-Things sensors, real-time monitoring, and predictive analytics into the EMS, enabling condition-based maintenance, forecasting-assisted scheduling, and dynamic optimization across heterogeneous port assets [83, 101].

Integrated multi-energy systems extend the same coordination logic across longer timescales and multiple energy carriers such as electricity, hydrogen, and potentially heat or fuels [119, 120]. In these systems, electrolysers constitute a large, schedulable electrical load that can absorb surplus renewable electricity, while the stored hydrogen or its derivatives (e.g. ammonia, methanol) can provide long-duration energy reserves and zero-emission bunkering [121, 122]. This couples the operations and infrastructure of all electrification pathways together.

Overall, studies of port-microgrid, smart ports, energy-hub, and integrated energy system may combine some or all of the following: berth loads, terminal loads, renewable generation, storage, and hydrogen production and storage, and EMS. These studies therefore reveal several interlinkages across the identified electrification pathways: shared grid-connection capacity; coincidence or complementarity among loads; competition for renewable electricity; and cross-pathway flexibility through batteries, vessel charging, managed vehicle charging, hydrogen storage, and schedulable electrolysis. This cross-pathway synthesis therefore shifts the planning question from whether each pathway can be accommodated independently, to how their combined deployment alters the cumulative demand, flexibility and reinforcement requirements.

4.4.2. Utility-side and network strategies

Planning, permitting, and completing new grid infrastructure can take anywhere from 5 to 15 years [123], which creates a ‘chicken-and-egg’ dilemma for port electrification: ports hesitate to deploy electric assets without guaranteed grid capacity, while utilities withhold network upgrades until confirmed load commitments are in place. Resolving this requires early coordination among port authorities, terminal operators, and utilities through joint load forecasting, capacity reservation agreements, and phased infrastructure roadmaps to facilitate electrification while reducing capital commitments in early phases and preserving optionality for subsequent phases [17].

Localized network upgrades are often unavoidable, since high-power OPS connections, fast-charging infrastructure, and large electrolysers individually exceed the thermal capacity of existing feeders or distribution transformers. Compliance with IEC 80 005–1 and related IEEE standards requires the installation of active or passive harmonic filters at the PCC, adding both capital cost and design complexity to OPS projects. Targeted reinforcement for upgrading specific cables, transformers, or switchgear at bottleneck nodes identified through power-flow and harmonic studies would be more cost-efficient than uniform network upgrading.

When multiple ports within a region electrify simultaneously, competition for scarce distribution or transmission capacity can create adverse dynamics, including congestion, cost-shifting, and stranded asset risks [17]. Joint planning can make cumulative demand visible earlier, identify opportunities for shared infrastructure, and support more efficient sequencing of grid investment. Ports and terminals whose electrification projects depend on the same, or electrically interdependent, distribution or transmission infrastructure would benefit from coordinating load forecasts, connection requests, deployment timelines, and engagement with network operators. Depending on network topology and governance arrangements, this region may range from a geographically distributed but organizationally integrated port system, such as Ningbo-Zhoushan [124], to a concentrated neighboring-port complex, such as San Pedro Bay Ports [125]. At a larger scale, regional system-level planning, integrating port load growth into transmission network development plans, is increasingly relevant in corridors where port electrification coincides with broader industrial decarbonization demand, such as North Sea Hydrogen Ports and Maritime Community [126].

5. Discussion

A central implication of the review is that definition should come before assessment. Grid studies are only meaningful when the underlying electrification scope is explicit. Port electrification comprises a set of distinct but interacting pathways that differ in end use, scale, temporal profile, and grid-planning implications. Shore power creates berth-based loads that depend on vessel type, call frequency, and simultaneity. Electrified terminal operations create more distributed, operationally driven loads tied to equipment use, charging strategies, and working schedules. Electricity-based PtX process introduces large industrial loads that may operate continuously or flexibly, often at scales that exceed conventional distribution-level planning assumptions. These findings indicate that port electrification should be approached as a coordinated port–grid transition rather than as a sequence of isolated technology deployments. The system boundary should be clearly specified, including which assets are included, how they operate, where they connect to the network, and the adoption timeline.

The literature has not developed in a way that supports this. Research on shore power is relatively mature and closely connected to port practice. By contrast, research on electrified terminal operations is spread across equipment-level studies, logistics research, and energy-system analyses, limiting conceptual integration and slowing the emergence of a shared analytical framework for port electrification. Research on PtX in ports is expanding rapidly but still treats ports as generic industrial locations rather than as specific operational settings with traffic patterns, spatial limits, and grid constraints. Grid questions are consequently addressed inconsistently.

Our review further suggests that the port-grid assessment should go beyond simple annual energy estimates and single peak-load figures, with depth matched to the pathway. Time-resolved load modelling is necessary for all pathways to capture coincidence effects, but the binding question differs: OPS and vessel charging often raise voltage and power-quality concerns at specific connection points; terminal equipment and vehicle charging stresses feeder capacity and operational flexibility; hydrogen and e-fuel supply shifts attention from feeder adequacy toward sub-transmission or transmission access, which requires earlier coordination with network operators and longer project lead times. These differences widen as electrification becomes more converter-intensive, since high-power chargers, frequency converters, and rectifier-based loads introduce effects that annual energy totals cannot reveal.

Several technology trends and research directions emerge from the synthesis. First, data-driven and hybrid load-modelling approaches, combining operational data with machine-learning forecasting and optimization, represent a critical methodological frontier. Due to scarce port-specific measured load data, open challenges remain in uncertainty quantification, model transferability across ports of different scales and trade composition, and interpretability for non-specialist decision-makers such as port authorities and terminal operators. Second, flexibility-oriented electrification, including managed charging, schedulable electrolysers, and storage-coupled operations, is becoming central to limiting grid impacts, yet its value is insufficiently quantified in grid-planning terms. Third, port microgrids, advanced EMSs, and digital twins are increasingly positioned as enabling architectures for cross-sectoral port integration as multi-vector energy hubs. Future research should move beyond conceptual designs toward a comparative evaluation of control strategies, operational benefits, and interaction with utility planning under realistic uncertainty. Such work would enable efficiently coordinate supply, storage, and flexible demand across multiple electrification pathways. Finally, integrated port–grid governance models should be explored, as institutional misalignment among port authorities, terminal operators, utilities, and fuel developers remains a major barrier to coordinated infrastructure planning.

The review also has limitations that point to future work. The proposed framework should be tested using additional bibliographic databases and industry sources, while comparative analysis should be extended across different port archetypes. More importantly, future studies should combine measured operational data, time-resolved and spatially explicit network models, pathway-specific adoption scenarios, and consistent lifecycle boundaries. This would strengthen comparisons across port archetypes, improve the assessment of interacting pathway loads, and clarify when operational flexibility can defer grid investment and when network reinforcement remains necessary. Addressing these issues would strengthen both academic understanding and practical decision-making for port electrification.

6. Conclusion

How port electrification is defined has material consequences for electricity-demand estimates, grid-impact assessment, and infrastructure planning. By organizing the literature around electricity end use and the location of port activities, this review proposes a three-pathway typology ordered analytically

according to an expanding system boundary. This framework makes the scope of port electrification more explicit and comparable across studies. The comparative pathway synthesis reveals substantial differences in contextual dynamics, policy signals, technological development, demand characteristics, and treatment of grid impacts. The principal grid-planning problem therefore shifts across the pathways, from managing the coincidence of high-power vessel connections, to coordinating spatially distributed terminal and charging loads, and finally to securing large-scale interconnection capacity for PtX facilities. The synthesis also identifies important interdependencies across three pathways. Their combined deployment creates both cumulative-load risks and opportunities for shared flexibility, making integrated planning necessary. Building on these findings, the review organizes grid-impact analysis into pathway-specific load characterization, assessment of voltage and power quality, network capacity and hosting analysis, and further summarizes the flexibility and mitigation options for grid management. Overall, the framework connects the definition of port electrification to its operational, infrastructural, and grid-planning consequences. It provides a structured basis for consistent scenario design, network planning, and coordinated investment among different stakeholders. Such integrated port-grid planning will become increasingly important as ports evolve from transport and logistics nodes into wider hubs for electricity use, renewable-energy integration, fuel production, and industrial decarbonization.

Acknowledgments

This work is part of the Port as Energy Transition Hubs (POTENT-X) of the Clean Energy Transition Partnership (CETPartnership, Grant 10 106 9750 under HORIZON-CL5-2021-D3-01-04), with financial contributions from the Swedish Energy Agency, Danish Innovationfonden, and Ministerio de Ciencia, Innovación y Universidades. We thank the members of the Sustainable Transport & Energy Analytics and Modelling (STEAM) research group at Chalmers University of Technology, including Veronika Slakaityte, Kexin Yang, Yujia Shi, and Frans Libertson, for their insights and openness throughout the workshops and follow-up sessions. The author(s) used ChatGPT and Claude during the preparation of this work, in order to improve clarity and readability. After using the AI tool/service, the author(s) reviewed and edited the content and take(s) full responsibility for the content of the published article.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Appendix A. Search strategy and screening protocol

Table A1. Hierarchical search strings used in Scopus.

Pathway	Keyword scope	Search strings
1: OPS & vessel charging	Pathway-only	TITLE-ABS (``shore power'' OR ``shore-power'' OR ``onshore power'' OR ``cold ironing'' OR ``cold-ironing'' OR ``shore-side electricity'' OR ``shore-side power'' OR ``shore-to-ship power'' OR ``alternative maritime power'' OR ``high-voltage shore connection'' OR ``berth electrification'' ) OR ( TITLE-ABS ( ``electrified vessel'' OR ``electrified ship'' OR ``electric vessel'' OR ``electric ship'' ) W/15 ( berth OR charg* OR hotel OR refuel ) )5 AND ( LIMIT-TO ( DOCTYPE , ``ar'') OR LIMIT-TO (DOCTYPE , ``cp'' ) OR LIMIT-TO ( DOCTYPE , ``ch'') OR LIMIT-TO (DOCTYPE , ``re'')) AND PUBYEAR < 2026
	Port-related	TITLE-ABS (port OR ports OR seaport* OR maritime OR harbour* OR harbor* OR ((container OR roro OR bulk OR passenger OR cruise OR feeder OR inland) AND terminal*)) AND NOT TITLE-ABS-KEY (``inject*'' OR ``electrolysis pump'') AND {Pathway-only strings}
	Port-Grid-related	TITLE-ABS (``grid*'' OR ``power system*'' OR ``power network*'' OR ``distribution network*'') AND {Port-related strings}
2: CHE & terminal vehicles	Pathway-only	TITLE-ABS ((``cargo handling equipment*'' W/15 ( electrif* OR electric ) ) OR ( crane* W/15 ( electrif* OR electric ) ) OR ( forklift* W/15 ( electrif* OR electric ) ) OR ( tractor* W/15 ( electrif* OR electric ) ) OR ( ``automated guided vehicle*'' W/15 (electrif* OR electric)) OR ((drayage OR yard OR terminal) W/15 (electrif* OR electric) W/15 (truck* OR vehicle* OR tractor*))) AND (LIMIT-TO (DOCTYPE , ``ar'' ) OR LIMIT-TO ( DOCTYPE , ``cp'') OR LIMIT-TO (DOCTYPE , ``ch'' ) OR LIMIT-TO ( DOCTYPE , ``re'')) AND PUBYEAR < 2026
	Port-related	TITLE-ABS (port OR ports OR seaport* OR maritime OR harbour* OR harbor* OR ((container OR roro OR bulk OR passenger OR cruise OR feeder OR inland) AND terminal*)) AND NOT TITLE-ABS-KEY (airport* OR ``earth terminal'') AND {Pathway-only strings}
	Port-Grid-related	TITLE-ABS (``grid*'' OR ``power system*'' OR ``power network*'' OR ``distribution network*'') AND {Port-related strings}
3: PtX (H_2 & E-fuels)	Pathway-only	TITLE-ABS (electricity OR electrification) AND TITLE-ABS (electrofuel* OR ``e-fuel*'' OR efuel* OR ``synthetic fuel*'' OR ``electrolytic fuel*'' OR ``hydrogen production*'' OR ``power-to-x'' OR ``Power-to-X'' OR ``electricity-based fuel*'' ) AND ( LIMIT-TO ( DOCTYPE , ``ar'') OR LIMIT-TO (DOCTYPE , ``cp'' ) OR LIMIT-TO ( DOCTYPE , ``ch'') OR LIMIT-TO (DOCTYPE , ``re'')) AND PUBYEAR < 2026
	Port-related	TITLE-ABS (port OR ports OR seaport* OR maritime OR harbour* OR harbor* OR ((container OR roro OR bulk OR passenger OR cruise OR feeder OR inland) AND terminal*)) AND NOT TITLE-ABS-KEY (``inject*'' OR ``electrolysis pump'') AND {Pathway-only strings}
	Port-Grid-related	TITLE-ABS (``grid*'' OR ``power system*'' OR ``power network*'' OR ``distribution network*'') AND {Port-related strings}

Scopus was selected as the primary bibliographic database for this review because port electrification is an interdisciplinary topic spanning engineering, energy systems, transport, environmental studies, and policy. Compared with other selective databases, Scopus provides a broader multidisciplinary coverage including peer-reviewed journal articles, conference proceedings, and book chapters, which is important for an applied and emerging research field. Grey literature in this review was identified separately through targeted searches of institutional reports, agency documents, standards, port authority publications, and project deliverables. These sources were not merged into the main peer-reviewed review corpus but used selectively to contextualize industry practice, policy developments, standards, and infrastructure-planning issues that are not always fully represented in the peer-reviewed literature.

The Scopus search was conducted for studies published up to and including 2025 and is limited from peer-reviewed journal articles or reviews, conference papers, or book chapters. Studies were excluded if they were not substantively related to ports, port terminals, maritime logistics, or port-side energy systems. These included studies retrieved because of keyword overlap but not directly relevant to the review scope, such as studies on airport terminals, non-port transport electrification, or hydrogen systems without a clear port-side application. Ambiguous cases were retained for full-text assessment before a final inclusion or exclusion decision was made. Records were also excluded if they were duplicates or multiple indexed versions of the same publication. After screening, the port-related studies were further coded and used for the main analytical synthesis on keyword patterns, policy instruments, port function and ship type, and grid impact assessment to capture both the thematic development of the literature and the contextual factors shaping different electrification pathways. The full hierarchical search strings used in Scopus are reported in table A1.

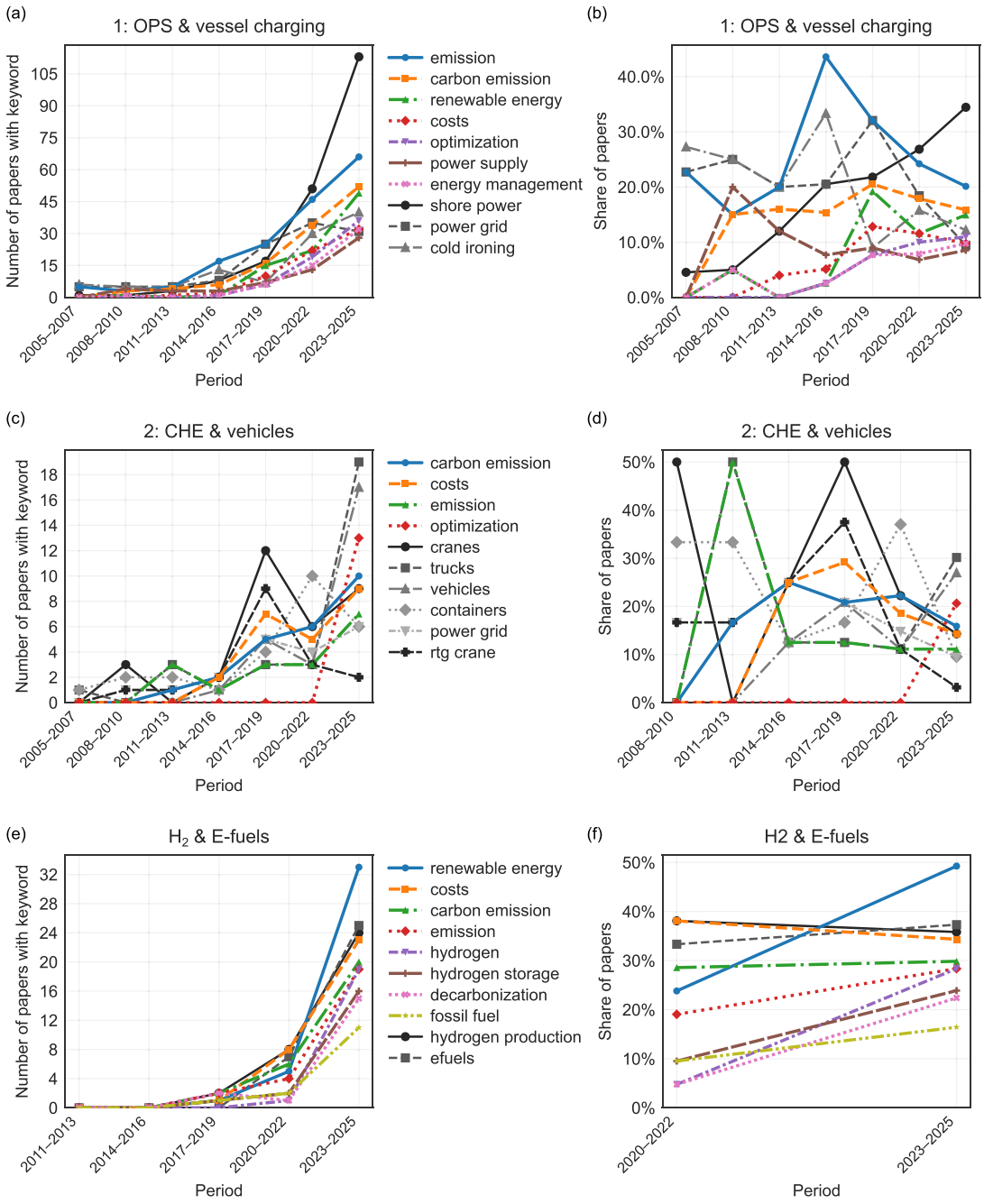
Appendix B. Conceptual framing and keyword evolution

The index keywords of the port-related literature are reorganized with a thesaurus list to avoid ambiguity and redundancy and are further analyzed. Figure B1 displays both the number and the prevalence of papers containing the selected keywords within every three-year periods from 2005. In addition to the benchmarked keywords derived from search strings, the concepts emerging within the screened literature demonstrate how each electrification pathway is framed in the literature and how these framings have evolved over time.

Early literature on berth and vessel electrification was organized primarily around the core technology *cold ironing* and its *emission* rationale. Over time, the broader term *shore power* became the more prevalent designation for this application. Grid attention increases in the early stage, but it does not keep pace with the rapid expansion of the literature in the most recent years, as indicated by a smaller share of the publications. In the contrast, themes related to *renewable energy*, *costs*, *optimization* and *energy management* have become more prominent. These trends suggest that the literature is evolving from a concentrated technology-and-emissions literature into a broader field concerned with renewable-energy integration, economic performance, optimization, and energy management related to the application of shore power.

The thematic development of terminal-equipment and vehicle electrification indicates a change in the principal analytical unit. Earlier studies focused mainly on individual cargo-handling technologies, particularly *cranes* and related equipment. More recent literature gives greater attention to mobile assets, including *trucks* and *vehicles*, and to the coordination problems created by fleet electrification. The growth of *optimization* is particularly notable, with its prevalence increasing from almost zero in the earlier periods to 20.6% in the most recent period. Whereas crane-electrification studies often evaluate the performance or energy consumption of an individual technology, mobile-fleet electrification requires the coordination of interdependent decisions regarding vehicle assignment, routing, charging schedules, fleet size, operating cycles, infrastructure location, and peak-load management. This change reflects that the literature is evolving from equipment-specific assessment toward fleet-level optimization and system-coordination problems. However, grid research expands much more slowly than the broader field. Environmental and economic considerations remain important all the time, but they are also increasingly embedded within a broader research agenda.

Research on electricity-based fuel production and supply expanded rapidly during the most recent periods and was accompanied by a widening conceptual scope. *Renewable energy* became the most prevalent contextual keyword, while *hydrogen* and *decarbonization* have also grown substantially. These changes indicate that the pathway is increasingly framed in relation to renewable-electricity sourcing, energy-system integration, and the role of hydrogen and derived fuels in decarbonization, beyond problems of fuel conversion and economic feasibility. Alongside the continued prominence of the search-derived terms *efuels* and *hydrogen production*, the increasing prevalence of the broader term *hydrogen* and the more specific term *hydrogen production* indicate that the analytical scope is increasingly extending. Nevertheless, grid-, network-, and power-system-related keywords do not appear among the most prevalent terms in the periods shown.



Notes: Scopus applies "emission" and "carbon emission" as distinct controlled terms with different scope — the former covers air pollutants generally (NO_x, SO_x, PM), the latter CO_2 specifically.

Figure B1. Number and prevalence of selected index keywords by three-year period in the retained port-related literature, with search-string keywords displayed in greyscale.

Appendix C. Policy milestones

Table C1. Key policy milestones governing the three pathways of port electrification across major regions.

Pathway	Region	Policy milestone	Relevance to port electrification
1: OPS & vessel charging	Global/IMO	MARPOL Annex VI (2005)	Established international framework for ship air-pollution control; OPS recognized as a primary compliance method within ECA.
		MARPOL Annex VI amendment (2008, eff. 2010)	Tightened ECA emission limits, significantly strengthening the regulatory incentive for shore power adoption.
		MARPOL Annex VI amendment on OPS reporting (eff. 2025/2026)	Requires vessels to report onshore power supplied (kWh), improving transparency and creating data infrastructure for compliance monitoring.
	EU	Directive 2014/94/EU (AFID, 2014)	First EU-level framework encouraging OPS infrastructure deployment at TEN-T ports.
		AFIR (EU 2023/1804)	Replaced AFID with binding mandate for OPS provision at core TEN-T maritime ports, converting encouragement into obligation.
		FuelEU Maritime (EU 2023/1805, applicable from 2025)	Obliges covered container and passenger ships to use OPS or equivalent zero-emission technology at berth by 2030, creating ship-side demand pull.
	US	CARB At-Berth Regulation (2007)	First mandatory shore power regulation globally; required 80% shore power usage by 2020 for designated fleets at California ports.
		CARB At-Berth Regulation amended (2020, eff. 2023)	Extended at-berth emission mandates to roll-on/roll-off vessels and tankers, broadening regulatory coverage.
	China	13th Five-Year Plan (2016–2020)	Set target of 400 new OPS connections at major ports; by 2022, 81% of eligible berths at 21 coastal ports had OPS access.
		Revised Marine Environmental Protection Law (MEPL, eff. 2024)	Shifted regulatory posture from incentive-based to mandatory compliance, compelling both shipping companies and port operators to utilize shore power.
	UK	Maritime 2050 & Clean Maritime Plan (2019)	Framed zero-emission shipping and port infrastructure as part of a long-term national transition strategy; strategic signal without prescriptive OPS mandates.
2: CHE & terminal vehicles	Global/IMO	/	Land-side port equipment and vehicles are governed exclusively by domestic environmental policies and local port authority initiatives.
	EU	NRMM Regulation Stage V (2016)	Tightened emission standards for non-road mobile machinery, indirectly pressuring electrification of port cranes, forklifts, and yard vehicles.
		European Green Deal (2019)	Established overarching decarbonisation and air-quality agenda that amplifies pressure on port terminal emissions.
	US	CARB Mobile CHE Regulation (2005; amended 2011; fully implemented 2017)	First regulation targeting toxic emissions from CHE; drove early adoption of cleaner CHE technologies at California ports.
		Clean Air Action Plan (CAAP, 2006) at Ports of Los Angeles and Long Beach	Set zero-emission targets for CHE by 2030 and drayage trucks by 2035; most prominent voluntary-plus-regulatory framework for port equipment.
	EPA Clean Ports Program		Provides $3 billion in federal funding for zero-emission port equipment, creating a major research opportunity window and accelerating fleet transition.
	China	14th Five-Year Plan (2021–2025)	Integrates green port certification standards that incentivize electric CHE through subsidy programmes; mandatory fleet timelines remain port-authority-level.
	UK	Clean Maritime Plan (2019)	Provides strategic signal for zero-emission innovation but does not include a dedicated statutory timetable for terminal-equipment electrification.

(Continued.)

Table C1. (Continued.)

Pathway	Region	Policy milestone	Relevance to port electrification
3: Hydrogen & E-fuels	Global/IMO	2023 IMO GHG Strategy	Sets global benchmark: ⩾20% shipping emission reduction by 2030, net-zero by 2050; mandates ⩾5% (striving for 10%) zero/near-zero fuels by 2030, materially strengthening port-side PtX demand signal.
	EU	RED II (2018) & RED III (2023)	Provide the renewable-energy framework underpinning eligibility criteria for green hydrogen and electrofuels.
		RFNBO delegated acts (adopted June 2023)	Define when hydrogen-based fuels qualify as renewable fuels of non-biological origin and how lifecycle emissions are calculated, enabling certification.
		EU Hydrogen Strategy (2020); REPowerEU (2022)	Set political targets and investment logic for renewable hydrogen production and infrastructure at scale.
		Fit-for-55 proposals (2021)	Introduce mandatory blending requirements, creating regulatory pull for low-carbon maritime fuels including electrofuels.
		FuelEU Maritime (EU 2023/1805)	Creates demand pull for low-carbon maritime fuels within shipping, linking fuel governance to port-side PtX viability.
	EU (national)	Denmark Energinet PtX (2019); Germany National Hydrogen Strategy (2020); Netherlands frameworks, etc	Establish the most advanced national frameworks coupling port-side PtX production with maritime fuel demand.
	US	National Clean Hydrogen Strategy & Roadmap (2023)	Creates a strong alternative energy demand signal but lacks specific mandates for port-side PtX infrastructure.
	China	14th Five-Year Plan (2021–2025)	Emphasizes green and digital infrastructure upgrading; green-port strategies increasingly incorporate multi-energy systems.
		Hydrogen Energy Industry Development Medium- & Long-Term Plan (2021–2035, released 2022)	Formally designates hydrogen as a key component of the national energy strategy, anchoring port-side hydrogen ambitions.
	UK	Clean Maritime Plan (2019) & clean-maritime innovation agenda	Supports clean-fuel innovation and demonstration but does not prescribe port-side PtX deployment timelines.

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