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REVIEW

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The floating future of ports: a systematic review of readiness, challenges, and pathways toward sustainable floating ports

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Abstract

This study investigates the emerging concept of floating ports, examining their applications, technological readiness, and future potential as transformative maritime infrastructure. Despite decades of isolated innovations in floating structures such as floating breakwaters, terminals, piers, berths, tourism platforms, shipyards, very large floating structures (VLFS) and renewable energy platforms, the literature remains fragmented with limited cohesive research addressing floating ports as integrated systems. By employing a systematic literature search combining bigram-based keyword analysis across Scopus and Web of Science, the study identified 142 relevant articles focused on floating ports and harbors. A Balanced Readiness Level Assessment (BRLa) across eight floating port applications revealed moderate to high technological maturity for most components however persistent gaps in market readiness, regulatory frameworks, organizational integration, and societal acceptance. While floating structures have been successfully deployed in niche, single-user contexts, no fully established multi-user floating port currently exists at a scale comparable to that of a conventional seaport. The findings highlight the necessity of integrated governance models, regulatory alignment, stakeholder engagement, and robust financial frameworks to support the transition of floating ports from isolated experimental structures to fully operational and sustainable maritime hubs. Such development is critical to addressing land scarcity, enhancing resilience, and managing evolving logistical challenges within global port systems.

Keywords Floating ports, Floating harbors, Floating future, Port governance, Maritime transportation, Ports and harbors, Floating structures, Port systems

Introduction

Global port systems are increasingly constrained by land scarcity, growing vessel sizes, environmental regulations, and the need to adapt to evolving environmental conditions, including sea level rise and extreme weather events (Kurt, 2024). Ports are increasingly exposed as critical yet vulnerable nodes in global supply chains, facing growing technical, environmental, and economic constraints on the expansion of conventional land-based infrastructure, alongside broader environmental changes such as sea level rise

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and extreme weather events (Kurt, 2024; León-Mateos et al. 2021). Within this context, floating ports are gaining attention as a potential alternative or complementary form of maritime infrastructure that can provide capacity expansion, flexibility, and climate resilience without permanent land reclamation (Kurt, 2024; Weerasinghe et al. 2025a, b).

This study examines the concept of floating ports within the broader Floating Future project (NWO, 2022), focusing on how floating port applications have evolved, how ready they are for wider deployment, and what pathways exist for their future development. By synthesizing fragmented research on floating maritime infrastructure, the paper positions floating ports not as isolated engineering experiments but as a potentially strategic response to systemic challenges facing contemporary port development.

Background of floating port as a concept

Floating structures have been explored and applied in maritime contexts for several decades, both in practice and in theory. Applications range from floating piers and terminals accommodating tidal variability and spatial constraints, to large scale conceptual studies on floating airports and very large floating structures intended to extend infrastructure capacity offshore (Kurt, 2024; Suzuki, 2001). Within port related contexts, floating solutions have been used for berthing, transshipment, logistics support, and auxiliary terminal functions, often in locations where fixed infrastructure is difficult to construct or expand (León-Mateos et al. 2021; Weerasinghe et al. 2025a, b). These applications demonstrate that floating ports (not floating terminals which are vessel types) are not a novel idea, but rather an evolving set of practices and concepts that have emerged across different operational, environmental, and geographical settings (Johansson 1986; León-Mateos et al., 2021).

Much of the existing work has evolved through isolated technical solutions rather than through a port system perspective. Early examples, such as the floating pier in Iquitos that adjusts to 10-meter river level variations and the transshipment solutions described for bulk commodities, demonstrate context-specific innovations but rarely link to broader systemic adjustments (Tanner et al. 1983; Lindemalm 1982). These early applications were primarily driven by local physical constraints, with limited consideration of broader logistical, institutional, or strategic port system implications.

Subsequent research, including the development of linkspan designs and foundational work on buoyancy and floating pier dynamics, provides essential technical insights, yet these are frequently disconnected from evolving logistical demands or environmental challenges (Johansson 1986; Tsinker 1986). However, these studies largely remained focused on technical performance, with limited attention to evolving port functions, environmental pressures, or governance arrangements. Later studies have highlighted the growing importance of floating structures in the face of increasing vessel sizes, space constraints, and climate resilience requirements (Ahn et al. 2013; Esteban et al. 2020). Nevertheless, the fragmented nature of this body of work ranging from case-specific engineering evaluations to exploratory infrastructure concepts reflects the absence of a cohesive vocabulary or integrated research framework (Joque et al. 1999; Cichanski et al. 2004; Baird and Rother 2013). This fragmentation may impede the adoption of floating ports as scalable, robust, and sustainable solutions in global port design. As a result, it remains difficult to compare applications across contexts or to assess their readiness beyond individual case studies.

Furthermore, while concepts such as modular hybrid piers and floating logistics hubs are increasingly being introduced, they remain under-theorized in the literature on port governance and economic geography (Zeck and Wernli, 2010; Assbrock et al. 2020). This imbalance suggests that technological innovation has advanced faster than understanding of regulatory alignment, organizational integration, and stakeholder coordination. A critical synthesis across technological, environmental, and policy dimensions is therefore urgently required to inform future research directions and support meaningful investment decisions.

Against this background of fragmented but expanding experimentation, floating ports have increasingly been explored in practical settings (León-Mateos et al. 2021). Building on these fragmented yet expanding advancements, floating ports are increasingly being considered in various cases as a viable solution to infrastructure challenges in confined or environmentally vulnerable settings. Large-scale prototypes, such as the floating terminal tested on Geoje Island, highlight efforts to solve land shortages, deep-draft vessel needs, and environmental constraints (Ahn et al. 2013).

The modular hybrid pier designed by the United States Navy shows a similar endeavor to provide berthing flexibility while avoiding the high capital expenditures associated with fixed infrastructure (Zueck and Wernli 2010). Floating structures have also been placed in places with significant tidal ranges and difficult site conditions, such as Puget Sound and also Juneau and Valdez in Alaska (Johnson et al. 2016; Joque et al. 1999). Conceptual frameworks such as the Floating Container Storage and Transshipment Terminal (FCSTT) suggest offshore options that could lessen dependency on traditional land-based terminals (Baird and Rother 2013). While these innovations demonstrate floating infrastructure's adaptability, they also highlight major concerns, particularly about long-term durability, environmental performance, and integration into larger logistical and governance systems. As a result, floating ports are often treated as experimental infrastructures that must be rigorously evaluated in context (Esteban et al. 2020).

In addition to technical and spatial considerations, economic feasibility has emerged as a key motivation in specific application contexts. Floating ports have been investigated for their potential to improve accessibility and logistical efficiency in areas where traditional infrastructure is scarce or prohibitively expensive. For example, the deployment of floating ports in tiny island environments such as Nias and Kisar in Indonesia has proved the potential of Floating Logistics Supporting Facilities (FLSFs) to improve local logistics and boost economic activity in remote places (Gurning et al. 2022). Similarly, research on floating port concepts such as the FCSTT suggests that such structures could provide transshipment and storage capacity at a lower capital expenditure than typical landside infrastructure, especially in limited areas (Baird and Rother 2013).

Furthermore, floating terminals designed for offshore oil and gas fields or rural coastlines have been proposed to address the logistical and environmental issues involved with building new land-based ports (Takagi et al. 2017). While these instances reveal potential pathways for improving regional economic integration and increasing local employment, the larger effects of floating ports on economic inclusion and development are mostly unknown and require additional empirical research. To determine their position in future trade networks, the economic feasibility, long-term maintenance costs, and integration with inland transportation and regulatory systems must all be carefully investigated.

Summarizing these developments, it can be concluded that although floating ports demonstrate increasing technical feasibility, their functional diversity, readiness for wider adoption, the integration within port systems remain insufficiently understood, and motivates the need for a structured and systematic analysis.

Aim of the study

The importance of this study stems from knowing the potential benefit that the concept of “floating” can offer to future port developments. Although floating ports were first proposed in the 1980s, their development has been slowed, allowing little opportunity to examine their governance using real-life instances. As a result, while floating ports are not a new concept, they remain underexplored and have unrealized potential (Abrams, 2020; Kurt, 2024; Weerasinghe et al. 2025a, b) .

The primary goal of this study is to investigate and evaluate currently accessible floating port applications which are not vessel types (see 3.1). We do so by analyzing available literature within the scope, we have determined how floating ports have been used in various situations, what functions they serve, and what problems or benefits they provide. To address this objective, we are answering two research questions; I) What types of floating port applications currently do exist, and what functions do they serve across different contexts? and ii) How ready are existing floating port applications for wider adoption, based on dimensions such as technical maturity, regulatory alignment, and market feasibility, and what patterns of evolution and potential synergies across application types are suggested in the literature?

This study identifies potential future applications by synthesizing observed evolutionary trends and complementarities across existing application types discussed in the literature. This investigation will bridge the current gap by consolidating and explaining an overview of the existing literature in the domain. It will provide a better understanding of the practical importance of these studies and help to shape future research and development in this field.

Although several floating port concepts have been developed, there has been limited academic research that evaluates their contemporary applications. Most of the available research focuses on specific case studies or technological designs. These frequently lack on follow-up assessments of long-term performances or operational consequences. There is very little discussion regarding how floating ports are tailored to specific regional demands or policy settings.

Projects like the Floating Logistics Supporting Facilities in Indonesia and the offshore PSV terminals in Brazil provide valuable insights, but they are rarely studied combined (Gurning et al. 2022; Ruggeri et al. 2017). As a result, there is no comprehensive understanding of how floating ports differ in design, function, and performance. Without this, it is difficult to determine their value or transferability. A systematic review is consequently required. It can assist organize existing knowledge, discover common patterns, and reveal what remains unknown. This will help to guide future research and practical decisions about where and how to use floating port solutions most effectively.

Structure of the study

This study addresses the fragmented nature of floating port research by first expanding the investigation lens to include all floating constructions and then gradually restricting

the focus to floating ports (see Sect. [Review method](#)). The study consolidates scattered discoveries into a coherent body of knowledge by conducting a controlled, multi-phase literature search that includes bigram-based keyword methods and systematic screening.

After identifying and classifying current floating applications, a Balanced Readiness Level Assessment (BRLa) is used to systematically examine their level of technological maturity and practical viability (see Sect. [Analytical synthesis of floating port studies](#)). This approach is applied to move beyond descriptive classification and to enable consistent comparison across diverse floating port applications that differ in function, scale, and context. By assessing multiple readiness dimensions in parallel, the BRLa helps identify strengths and gaps that are not evident from technical descriptions alone.

Building on this foundation, the study synthesizes how insights from existing applications and their observed evolution suggest potential roles for floating ports in future port systems, highlighting innovative uses such as offshore transshipment centers, floating dry ports, and renewable energy platforms (see Sect. [Potential applications for future developments of floating ports](#)). Finally, it identifies key future research areas in governance, management, and infrastructure resilience based on patterns and limitations observed in the analyzed applications (see Sect. [Findings](#)). Overall, this structured approach addresses the fragmented nature of existing studies by enabling systematic comparison and synthesis, rather than relying on conclusions drawn from dispersed literature, and supports the identification of directions for the future development of floating ports.

Review method

Systematic search phases

The purpose of this research was to identify the present applications of floating ports and to investigate future directions. Based on the few established work on this topic, this task is challenging because the concept of “floating ports” as a non-vessel based system remains relatively underexplored, with limited literature devoted exclusively to the topic (Kurt, 2024; Weerasinghe et al. 2025a, b). To address this, a systematic literature search process was developed and integrated into the structure of this study to identify and analyze floating port applications. The following diagram (see Fig. 1) depicts the phases involved in this process.

Exploring the broad concept “floating structures”

In the initial screening stage, the objective was to develop a robust keyword structure by identifying relevant terms associated with “floating ports” through an exploratory review of the broader concept of floating structures. Accordingly, the primary aim was to capture a comprehensive set of publications, including those addressing only specific components of the wider theme of floating structures and their roles or impacts in enabling large scale, multifunctional, and inclusive spaces on water (see Fig. 1- Step 1.1 & Step 1.2).

A range of search strategies employed in prior review studies was examined. The systematic search approach was identified as the most appropriate, given the poorly defined scope of the topic of “floating ports” within the broader and evolving field of “floating structures.” This approach also reduces selection bias by enabling a more consistent and transparent identification of studies relevant to floating ports within the wider floating

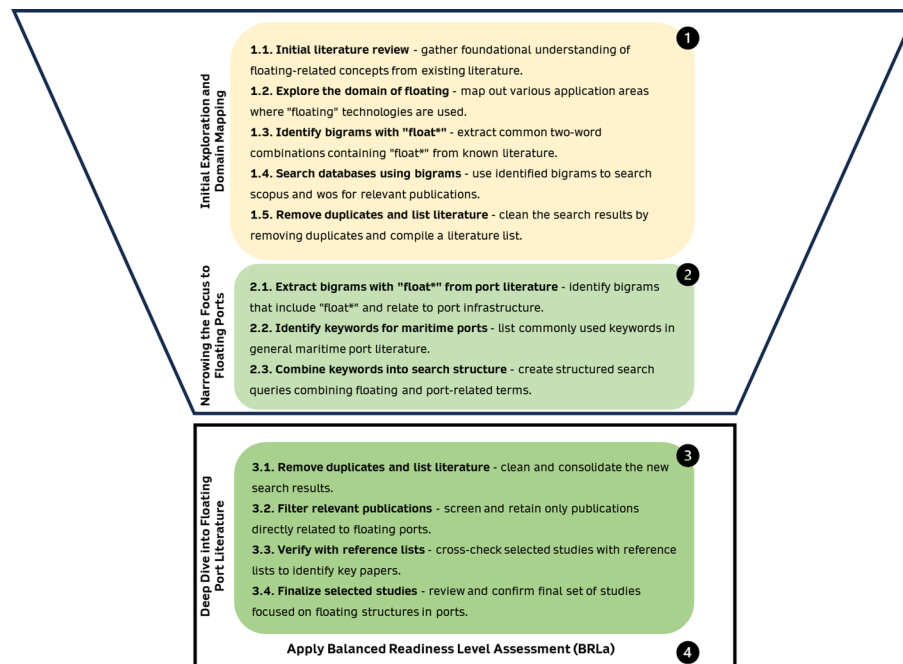


Fig. 1 Systematic Searching Process

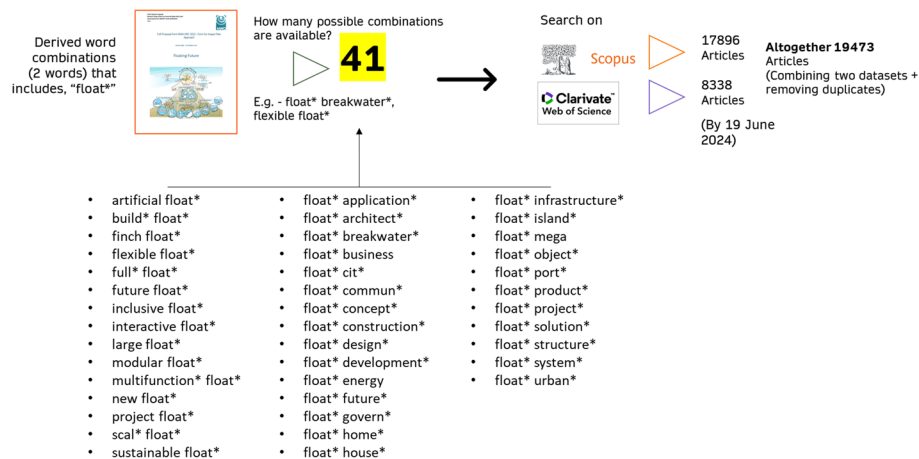


Fig. 2 Summary of initial searches including identified bigrams

structures domain (Weerasinghe et al. 2024). The next step involved identifying relevant keywords (see Fig. 2). However, the limited availability of well-defined keywords led to an underrepresentation of key concepts within the broader body of literature on floating structures. To address this, a bigram-based search approach was adopted, focusing on two-word combinations. For example, "Very Large Floating Structures (VLFS)" represents a well-established keyword typically used as a fixed term, whereas the broader bigram "floating structures" encompasses a wider range of related concepts, including established terms such as VLFS.

This approach not only identifies existing developments related to ports but also expands the scope of the search to include a broader range of solutions and applications associated with the concept of "floating." A key criterion in selecting bigrams was that at least one term contained either "floating" or "float*." Using Python 3.10 within the

Google Colab environment, a total of 41 such bigrams were explored (see Figs. 1- Step 1.3 and 2).

These bigrams were derived from an initial set of 13 papers identified through preliminary searches, supplemented by selected project reports associated with the “Floating Future” project (NWO, 2022). The resulting 41 bigrams formed the basis for subsequent database searches conducted in Scopus and Web of Science (WoS) (see Fig. 1, Step 1.4). This search yielded 17,896 records from Scopus and 8,338 from WoS; after removing duplicates, a total of 19,473 unique records remained as studies.

The results indicate that these bigrams appear across nearly 19,500 studies, highlighting the scale and relevance of the literature to be examined (see Fig. 1, Step 1.5). Notably, this step was undertaken to expand the initial keyword base, which was limited to 13 papers and related reports, thereby reducing potential bias and improving the comprehensiveness of the search strategy.

Bring back the focus “floating ports”

The 19,473 identified studies were subsequently screened based on titles, keywords, and abstracts. Applying the same bigram-based approach, additional “float*” or “floating” bigrams were extracted, resulting in the identification of 9,962 distinct bigrams. This outcome raised a critical question regarding how to effectively narrow the scope to the specific subject of “floating ports,” thereby enabling a more focused examination of relevant applications. In summary, we began with 41 bigrams derived from 13 studies and relevant reports associated with the broader concept of “floating.” Using these, a total of 19,473 studies were identified, from which 9,962 distinct “floating” bigrams were extracted.

We found only 22/9,962 bigrams uniquely linked to concepts, “floating ports,” “floating harbors” or “floating terminals”. That means only 22 bigrams of almost 9,962 matched what one might think to be the specific topic of floating ports (see Fig. 1 - Step 2.1). This is an interesting finding that reaffirms the relative lack of publications on floating ports, compared to those published in the broader area of applications related to floating structures. Based on this understanding, we created a keyword structure to search literature on floating ports (see Fig. 3). This stage marks the formal initiation of the search process for the studies included in the analysis. All preceding steps were dedicated to the systematic identification and refinement of relevant keywords to support this process.

This structure combines identified 22 bigrams (see Fig. 2) that are directly linked to “floating ports” (see Fig. 1 - Step 2.2 & Step 2.3) and it adds one more layer of keywords which together represent the wider context of “maritime ports” (Fadiga et al. 2024; Weerasinghe et al. 2024).

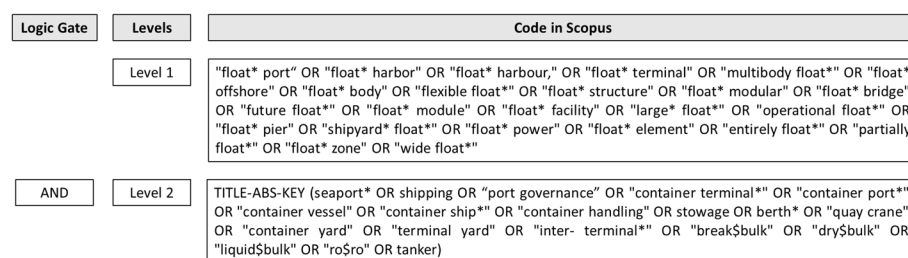


Fig. 3 Keyword structure – Floating ports and maritime ports

Such systematically derived and focused keyword cohorts (along with their respective combinations) facilitated a relatively structured and thorough exploration within the domain. By following this method, we got 453 results from Scopus and 477 from WoS, with a total of 821 (as per 26 January 2026) studies remaining after removing duplicates (Step 3.1). To ensure an extensive review, we examined the reference lists of the selected articles and also conducted additional searches on relevant external sources. Through this process, we identified 67 additional studies that met our inclusion criteria (keywords – Fig. 3, Step 3.2 & Step 3.3). The final number of studies considered thus was 888 which were finalized for comprehensive review in the analysis phase of the research. Figure 4 offers a visual summary of our search process.

In summary, we created a systematic search process to investigate the existing applications and future directions of floating ports. Given the scarcity of direct literature on floating ports, we began broadly exploring the idea of “floating structures” using a bigram-based keyword analysis. Using an iterative search and refining strategy, we first surveyed the larger terrain before restricting our attention to research related to floating ports. We then developed a targeted keyword framework that integrated floating port phrases with broader marine port concepts, resulting in thorough but concentrated research. This technique enables the identification of relevant research for in-depth evaluation and analysis.

First (Sect. [Exploring the broad concept “floating structures”](#)), a broad search was conducted using 41 “float”-related bigrams to identify relevant terminology and port-related concepts. This step was intended to explore and capture relevant bigrams from a wide range of studies, rather than to finalize a literature pool.

Second (Sect. [Bring back the focus “floating ports”](#)), 22 bigrams associated with port systems were combined with a port logistics keyword layer. This resulted in 821 studies, which were further expanded to 888 studies by incorporating relevant papers from reference lists and external sources. This stage represents the formation of the initial paper pool used for subsequent analysis.

In Sect. [Analytical synthesis of floating port studies](#), this initial pool was further refined by selecting studies that explicitly address floating ports as a central focus. This selection was conducted manually through abstract screening of the 888 papers identified in the previous phase. As a result, the dataset was reduced to 142 studies, which

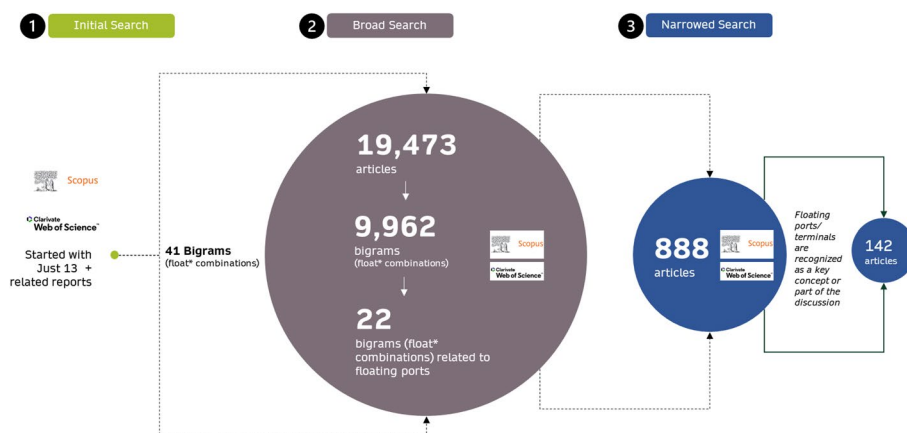


Fig. 4 Summary- systematic literature searching process

were then used to identify existing floating port applications and to support the subsequent analysis.

Analytical synthesis of floating port studies

Overview of identified floating port studies

Our analysis identified 142 studies indexed in Scopus or WoS that deal with the topic of floating ports and harbors. Nevertheless, a closer look reveals that not all these studies are solely focused on floating ports or harbors, with many addressing broader or related floating technology within floating ports. The overall trend in the appearance of publications on floating ports does not follow the normal exponential development pattern seen in other marine port research areas. In truth, the timeline appears disjointed, with inconsistent activity and little signs of continuous development (see Fig. 5).

While there are signs of a progressive increase in interest in related technologies, this expansion appears to be in its early phases and remains rather unfocused, particularly regarding floating ports and harbors. These findings indicate that, while some research is being conducted, concentrated and coordinated progress in the subject is still lacking.

Some studies attempt to position these developments within the broader concept of “floating ports” or “floating harbors”. However, the field remains at an early stage of development, with limited research conducted within each subcategory. This indicates a clear need for targeted research efforts to address existing gaps and to support innovation in this emerging but strategically important field.

We also looked at several types of floating port projects that have been covered in the literature. The categories we found are described in Sect. [Balanced readiness level assessment of floating ports applications](#). To comprehend the worldwide significance of these applications, we also investigated their geographic distribution. According to our research, most of the studies have a technological foundation and concentrate mostly on conceptual or testing-based advancements. As a result, the designated geographic areas

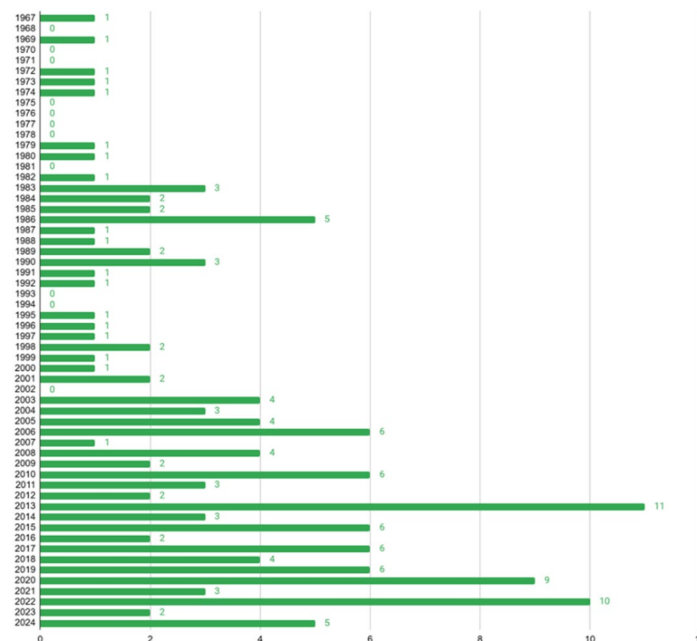


Fig. 5 Timeline – literature on floating ports

do not correspond to fully operational floating applications. We created a map that highlights 27 countries (major locations) that were cited in 63 of the 142 publications that were analyzed (see Fig. 6).

Southeast Asia and the North Sea were important regional clusters that went beyond specific countries. Among the countries identified, China, Japan, South Korea, the Netherlands, the United Kingdom, and the United States lead in the number of referenced studies.

Considering the different forms of floating port applications presented in the 142 studies selected for this research, we identified eight distinct application categories for further exploration in Sect. [Balanced readiness level assessment of floating ports applications](#). These applications include floating breakwaters, floating terminals (excluding vessel types), floating piers, floating berths, floating mega structures, floating tourism platforms, floating shipyards, and floating renewable energy platforms.

Balanced readiness level assessment of floating ports applications

This section presents an analytical overview of the collected literature on floating ports and their various forms. Through a comprehensive literature review, we find that no fully established floating port exists as an independent entity compared to a large seaport or dry port. Instead, floating structures are consistently integrated as extensions of seaports or river ports. Due to the wide range of applications, defining the term “floating port” remains challenging. Unlike well-established seaports and dry ports, which have been operational for decades and are supported by extensive expertise, floating ports largely remain conceptual.

After classifying floating port applications by structural type based on definitions found in the literature, we conducted targeted supplementary searches to clarify the technical characteristics, development status, and deployment contexts of specific applications where published academic evidence was limited or fragmented. In addition to these sources, expert consultations were used to validate and contextualize the BRLa values derived from the literature. These consultations were not used to generate new readiness scores but rather to confirm and interpret the results obtained from the literature review.

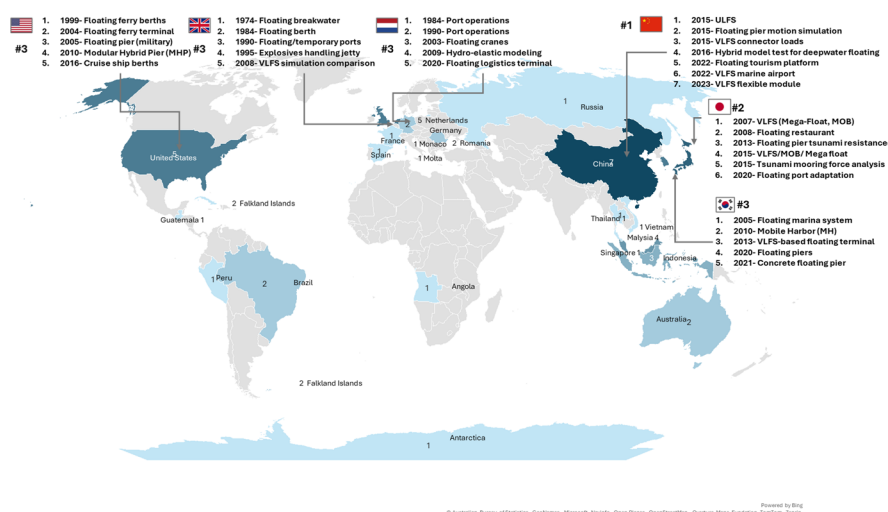


Fig. 6 Countries mentioned in studies

Interviews were held with eight specialists from relevant academic and industry communities, particularly those working on floating structures and port-related technologies. The experts were selected based on their direct involvement in the design, testing, or implementation of floating infrastructure, and their role was to verify whether the readiness levels identified in the literature were consistent with current engineering practice and development experience.

These eight experts represent a diverse set of roles relevant to floating developments. They include engineers specialized in energy terminals, floating energy production, startup driven innovations, and general floating initiatives, alongside also experts in terminal operations, system design, and applied research support for ports. In addition, one expert contributes from the perspective of government innovation support, linking policy instruments with technological development. Collectively, they bring extensive experience across engineering, design, operations, research facilitation, and public sector support related to floating energy systems, hubs, and port-based applications.

Building on these expert perspectives, the analysis shifts from roles and experiences to the identified functions of floating ports. When examined individually, the literature shows that many of these functions have already been extensively tested and have reached a level of technological maturity suitable for integration into core infrastructure. Accordingly, the following sections examine each floating application in detail, assessing its readiness across technology, market, legislation, and societal acceptance using the BRLa concept (Vik et al. 2021).

BRLa is regarded as relevantly balanced since it acknowledges that the success of new and developing technologies is dependent on more than simply technical functionality. While standard Technology Readiness Level (TRL) evaluations solely assess technological maturity, BRLa includes five additional factors to account for the broader reality of technology adoption. These five dimensions are: Technology Readiness Level (TRL), which assesses the development of the technology itself; Market Readiness Level (MRL), which evaluates market demand and commercialization status; Regulatory Readiness Level (RRL), which checks if laws and regulations enable the technology's use; Acceptance Readiness Level (ARL), which measures societal and user acceptance; and Organizational Readiness Level (ORL) assesses how prepared a technology is for real-world deployment by considering all relevant factors.

Each readiness level is indicated under three categories, based on literature evidence by various authors: High, Moderate, Low, or Info Not enough information (Info N.E.). We use Info N.E. because, for certain applications, the information provided in the studies is either insufficient, too vague, or, in some cases, entirely absent to determine their readiness. A High readiness level reflects strong evidence and conditions supporting successful adoption, Moderate indicates partial fulfillment or mixed conditions requiring improvement, and Low signals insufficient readiness or major gaps hindering deployment.

Floating breakwaters

As per the Table 1, floating breakwaters are floating structures designed to dissipate wave energy and reduce sediment transport, providing protection for coastal areas and ports (Fitriadhy et al. 2017; Sutko, 1975). Floating breakwaters evolved from early

Table 1 BRLa of floating breakwaters

Dimension	Readiness level	Evidence and source
TRL	High	Floating breakwaters have been widely studied in model experiments (Rytkonen and Broas 1992; Sutko, 1975), real-life applications such as Port Hercule in Monaco (Angrisano 2003), and actual ship reuse as breakwaters. Advanced investigations employing CFD and physical models demonstrate high technological maturity (Christensen et al. 2018; Fitriadhy et al. 2017; Qin et al. 2019).
MRL	Moderate	Floating breakwaters are commercially employed (for example, the Port Hercule enlargement, (Angrisano 2003), marina projects (Wheeler 1989). Techno-feasibility analysis (Borg et al. 2024) indicates that, despite technical viability, complete commercial profitability frequently requires government help for major offshore applications, indicating a relatively strong but not entirely developed market.
RRL	Info N.E.	None of the studies presented discuss legal restrictions, permitting processes, or regulatory obstacles particular to floating breakwaters.
ARL	Moderate	Generally recognized in practice for marina and port improvements (Angrisano 2003; Wheeler 1989), with an additional positive view of environmental and tourism benefits (Rahman et al. 2018). Only limited societal pushback is reported.
ORL	Moderate	Floating breakwaters are already used in marina and harbor operations (Angrisano 2003; Wheeler 1989), and designs consider operational issues like mooring challenges (Sutko 1973). Nevertheless, big offshore multi-use systems (Borg et al. 2024; Sutko 1973) require new operational models, implying that some alterations are still required.

* Info N.E. – Not enough information

studies in the 1970s, which addressed the offshore petroleum industry's demand for wave protection.

Sutko (1975) established critical performance characteristics, demonstrating that wave reduction diminishes with increasing wave period and that square cross-sections perform better (Sutko, 1975). Vasco Costa (1988) underlined the importance of aligning breakwaters parallel to wave crests and fastening them with cables for effective deep-water applications (Vasco Costa 1988). By focusing on marina development, Wheeler (1989) emphasized the increasing usage of floating breakwaters for greater berthing. Rytkonen and Broas (1992) undertook model studies to evaluate wave transmission coefficients and motion responses, enhancing understanding of floating breakwaters under different conditions.

Researchers in the 2000s began incorporating floating breakwaters into large-scale projects, broadening their applicability. Shigemitsu et al. (2001) drastically lowered wave loads by equipping Mega-Float structures with wave energy-absorbing devices, allowing installations to operate in harsher sea conditions. Angrisano (2003) improved Port Hercule's capacity to receive large ships by building a floating breakwater. Lázaro et al. (2013) investigated the use of decommissioned ships as floating breakwaters, highlighting their potential for shoreline protection. Fitriadhy et al. (2017) demonstrated the efficiency of cylindrical floating breakwaters for mitigating coastal erosion by simulating their impact on sediment movement.

Further investigation indicates that the Monaco Port Authority led the development of a large-scale semi-floating maritime structure, measuring 352 m in length and weighing approximately 160,000 tones, constructed at the foot of the Rock of Monaco. This floating configuration enabled the preservation of local marine fauna and flora while providing effective wave protection (Monaco Port Authority, 2022).

Recent research has focused on increasing floating breakwater efficiency and multifunctionality. By evaluating several damping systems, a study discovered that wing plates and porous materials considerably minimize wave transmission (Christensen et al. 2018). Zhang et al. (2022) used the Moving Particle Semi-implicit (MPS) and Finite Element Method (FEM) coupling to simulate hydro-elastic reactions of floating breakwaters in harsh situations. A study presented an innovative floating breakwater that combines energy storage and multi-use marine parks, thereby accommodating solar farms, aquaculture, and vessel berthing (Borg et al. 2024). Although these developments improve floating breakwater applications, researchers continue to address issues such as cost-effectiveness, mooring stability, and performance under high-energy wave conditions.

Floating terminals

Researchers in 2020 focused on floating modular platforms to improve port capacity while avoiding space-constrained onshore terminals (Table 2). A study conducted as part of the Horizon 2020 project Space@Sea envisioned a floating transport and logistics center to increase hinterland connectivity by merging river-sea and sea-going inland vessels. Floating container terminals have evolved as a response to land scarcity and rising cargo demand, utilizing very large floating structures (VLFSs) to increase port capacity.

The use of gill cells was proposed to reduce differential deflection in severely loaded floating terminals, allowing water to flow freely within compartments to improve structural stability while lowering bending strains (Wang and Wu 2006). A scaled floating terminal model was built in South Korea, demonstrating the viability of massive floating port infrastructure, verifying modular connection approaches and mooring systems to ensure stability in both operating and severe environments (Ahn et al. 2013). Tsunami

Table 2 BRLa of floating terminals

Dimension	Readiness level	Evidence and source
TRL	High	Floating terminals are technically advanced and have been successfully used for dry bulk transshipment (Lindemalm 1982) and passenger ferries (Cichanski et al. 2004). Modular floating terminals for container operations are being developed with customized transport systems (Assbrock et al. 2020), yet big modular terminal systems such as Space@Sea are still not commercially operational.
MRL	Moderate	Floating terminals exist for specific applications (dry bulk and ferry transport) (Cichanski et al. 2004; Lindemalm 1982), but floating modular container terminals (such as the Space@Sea project) are still in development and require more economic validation for wider market adoption (Assbrock et al. 2020).
RRL	Info N.E.	State environmental protection rules influenced the Bremerton floating ferry terminal project (Cichanski et al. 2004), necessitating project design changes and permit administration. Regulations exist; yet they can result in considerable process delays and uncertainty, indicating low readiness.
ARL	Moderate	Floating terminals for ferries and dry bulk commodities have received popular support, with no significant public opposition observed (Cichanski et al. 2004; Lindemalm 1982). Modular floating terminals are also seen as potential solutions to port congestion (Assbrock et al. 2020), with isolated case studies indicating generally good, if not widespread, adoption.
ORL	Info N.E.	Successful ferry port operations (Cichanski et al. 2004) indicate organizational readiness for small- to medium-sized applications. Nevertheless, big modular floating terminals (Assbrock et al. 2020) will require major operational restructuring (e.g., new transport logistics models), implying that organizational integration is not yet complete.

* Info N.E. - Not enough information

resistance was investigated by creating a simulation model that predicts pontoon-type floating body motions during extreme wave events (Masuda et al. 2017).

Subsequent studies identifying real world applications revealed that in Bremerton, USA, the Passenger Only Ferry Terminal (POF Terminal) represents a floating component of the larger Bremerton Transportation Center. The POF Terminal is a state-of-the-art floating transportation facility designed to provide seamless connections for ferry passengers arriving at and departing from the Bremerton Transportation Center (Cichanski et al. 2004). Similar to the Space@Sea project, the SeaTech Floating Terminal (STFT) is a scalable, modular, and sustainable concept designed to expand cargo and container handling capacity without the need for land reclamation. The concept has received Approval in Principle (AiP) from DNV in August 2025, confirming its technical feasibility, safety, and capability to operate under demanding environmental conditions (MEYER Floating Solutions, 2024).

Recent research has focused on enhancing floating terminal designs to improve hydrodynamic performance and operational economy. Advanced mooring methods and modular designs increase stability and adaptability in a variety of marine conditions. Researchers investigated wave-induced vibrations and external forces impacting floating terminals to improve resilience to adverse weather conditions. Studies on energy absorption and dynamic response helped to improve design strategies. The growing integration of floating terminals with offshore logistics hubs emphasizes their importance in mitigating port congestion and transshipment issues. While floating terminals provide flexibility, improving loading and unloading procedures remains a top research priority.

Current trends in floating terminal design prioritize automation, sustainable energy integration, and cost-effectiveness. Modular building techniques save money and increase scalability, and hybrid energy solutions improve operational sustainability. Floating terminal uses have been investigated for offshore container handling and disaster relief operations. Despite breakthroughs, obstacles such as costly initial investment, long-term viability, and regulatory limits remain. Future research must focus on changes required in port governance structures to ensure that floating terminals including container, bulk, tanker, and dry bulk become a viable alternative to conventional port infrastructure.

Floating piers

Floating piers are modular or single-structure floating berths designed for specific vessel operations, optimizing mooring and operational efficiency (Cichanski et al. 2004; Starr and Wainwright 1996). Floating piers have evolved from early designs targeted at assisting naval operations to current structures that maximize berthing efficiency and area utilization. During the 1980s, research focused on Navy pier designs, with studies looking into floating expeditionary piers, tension leg piers, and modular utility galleries for ship-to-shore services (Table 3).

Chow and Haynes (1983) proposed a double deck floating pier, emphasizing benefits such as increased loading capacity and flexibility. Another study developed advanced pier designs, with an emphasis on the possibilities of floating structures in naval applications. By the 2000s, research shifted to the impact of environmental pressures on floating piers, with Huang and Chen (2003) evaluated berthing energy in shallow water

Table 3 BRLa of floating piers

Dimension	Readiness level	Evidence and source
TRL	High	Multiple advanced studies on floating piers have been conducted, including complex berthing analyses under shallow conditions (Huang and Chen 2003), hydrodynamic modeling (Tajali and Shafieefar 2011), berthing impact formulations (Mostofi and Bargi 2012), tsunami response (Masuda et al. 2017), ship collision impacts, and soil-structure interactions during berthing (Chegenizadeh et al. 2015). This indicates rapid technological advancement, yet large-scale real-world implementation for all scenarios (for example, tsunami-resistant piers) may still be emerging.
MRL	Moderate	Floating piers are widely explored in academic and simulation settings. While some real-world instances exist (Masuda et al. 2013), there is little concrete evidence of significant market adoption when compared to traditional piers. Market interest exists, although it is relatively niche and project specific.
RRL	Info N.E	The studies presented did not contain any direct discussions of permitting processes, regulatory systems, or legal aspects.
ARL	Info N.E	There is no evidence of significant social reaction. In contrast, floating piers outperform fixed piers in terms of resilience (e.g., against tsunamis) (Masuda et al. 2013), indicating a positive perception within marine and coastal engineering communities.
ORL	Info N.E	Organizational integration issues include novel berthing design methodologies (Mostofi and Bargi 2012) and complicated dynamic responses that affect mooring and maintenance (Chegenizadeh et al. 2014; Tajali and Shafieefar 2011). Thus, floating piers necessitate operational changes that go beyond typical pier management.

* Info N.E. - Not enough information

conditions and LaNier et al. (2005) created a hybrid modular floating pier for the United States Navy with a 100-year service life.

Researchers in the 2010s refined floating pier designs by improving stability and hydrodynamic performance. Tajali and Shafieefar (2011) analyzed multi-body floating piers, examining how pontoon configurations affect motion responses in waves. Masuda et al. (2017) introduced the Floating Tsunami Protection Wharf (FTPW) to mitigate vessel drifting during tsunamis, demonstrating its disaster prevention capabilities. Following Masuda et al. (2017), it is observed that at Shiogama Harbor in Japan a floating dock, known as the High-speed Berth, is in operation and is used as a VIP lounge facility. By integrating advanced numerical simulations, Chegenizadeh et al. (2015) assessed ship collision impacts on floating piers, revealing differences in energy absorption mechanisms compared to fixed piers.

The rise of Very Large Floating Structures (VLFS) expanded floating pier applications, with Wu et al. (2017) discussed large-scale floating infrastructure for offshore logistics, floating airports, and disaster resilience. Recent research focuses on optimizing floating pier construction and mooring efficiency. Jung et al. (2020) compared steel and concrete floating piers for car ferry berthing in Incheon, South Korea, demonstrating that modular concrete construction enhances durability and space utilization while reducing the need for mooring dolphins. By assembling concrete modules on seawater instead of traditional floating docks, the researchers improved construction efficiency and material quality. While floating piers continue to evolve, challenges such as cost-effectiveness, long-term durability, and resilience to extreme weather remain areas for further research.

Floating berths

Floating berths are modular or single-structure floating platforms specifically designed for vessel berth, providing stable mooring under various environmental conditions (Johnson et al. 2016; LaNier et al. 2005).

Floating berths have evolved from serving passenger and freight traffic to accommodating huge vessels and disaster resilience. The floating berth built at Parkeston Quay in 1984 improved traffic flow by combining a Roll-On/Roll-Off (RO-RO) system with deeper dredging. Starr and Wainwright (1996) developed a floating berth designed expressly for submarines, illustrating the capabilities of twin-hulled post-tensioned concrete structures. Le and Ding (2013) conducted berthing tests on a floating mooring system and found that floating berths absorb more energy than rigid systems (Table 4). Murata et al. (2015) investigated mooring forces during tsunamis and found that floating berths reduce vessel drifting and mooring line failures when compared to quay walls, demonstrating their usefulness in disaster-prone areas.

Berthing infrastructure expanded to accommodate larger vessels and more difficult environmental circumstances. Johnson et al. (2016) created floating cruise ship berths in Alaska to address major tidal changes and geotechnical problems. The project incorporated concrete pontoons, mooring dolphins, and steel transfer bridges to provide stability under harsh situations. Dai et al. (2019) created a floating hydrocarbon storage facility in Singapore using modular floating berths connected by inter-modular connectors. Their findings emphasized the importance of structural flexibility in enduring hydro-elastic stresses while preserving operating efficiency. These improvements showed how floating berths can evolve into scalable, versatile solutions for a variety of maritime applications.

Further investigation shows that there is a floating RoRo (Roll on, Roll off) berth at London Medway. The facility was officially unveiled at the Port of Sheerness during a ceremony marking the completion of a new in river vessel berth and floating pontoon.

Table 4 BRLa of floating berths

Dimension	Readiness level	Evidence and source
TRL	High	Starr and Wainwright (1996) report a fully complete and functioning concrete floating berth for submarines with dual hulls weighing 85,000 tonnes. Simulation studies are also used to assess the advanced tsunami resilience performance of floating docks (Murata et al. 2015). Nevertheless, broader use cases beyond specialized military/submarine or disaster resilience scenarios are still being researched and developed.
MRL	Info N.E	Although real uses exist (for example, undersea berths), there is no evidence of significant commercial implementation for conventional ports and shipping. Floating berths appear to be more niche-specific (specialist military or disaster-resilient ports) than prevalent in commercial markets.
RRL	Info N.E	No direct mention of permitting, safety regulations, or legal challenges for floating berths are made in the two papers provided.
ARL	Info N.E	Floating berths are regarded favorably in military contexts and for tsunami-resistant port planning (Murata et al. 2015). However, larger public or business sector perceptions are not addressed, implying positive but limited society acceptability.
ORL	Info N.E	Specialized engineering and post-tensioning construction methods are required (Starr and Wainwright 1996), and special anchoring strategies must be considered depending on vessel sizes (Murata et al. 2015). Integration with standard port operations is possible but requires significant technical adaptation.

* Info N.E. - Not enough information

This development increases the port's capacity for RoRo cargo handling and supports the introduction of key freight services at the terminal (Peel Ports Group, 2025).

Recent research has focused on optimizing floating berths to increase efficiency and robustness. Researchers aimed to improve structural integrity in high-energy wave situations by fine-tuning intermodular connectivity designs. Floating berth installations continue to grow, incorporating hybrid materials and automation to improve stability and save maintenance costs. Despite their benefits, obstacles such as high building costs, susceptibility to severe weather, and regulatory constraints necessitate additional exploration. Future research must focus on long-term durability and economic feasibility to guarantee that floating docks remain viable options for increasing maritime infrastructure.

Floating mega-structures/very large floating structures (VLFS)

Floating mega-structures or very large floating structures (VLFS) refer to extremely large, modular floating platforms used for ports, airports, or military bases, which require advanced hydro-elastic analysis (Lamas-Pardo et al. 2015; Wang et al. 2006).

VLFSs developed in response to space limits and offshore development requirements, starting with structural research on double hulls and floating infrastructure (Table 5). Dimache et al. (2005) used finite element analysis to improve VLFS structural performance and efficiency. Riggs et al. (2008) created computer models for VLFS hydro-elastic response, which improved wave interaction predictions. Lamas-Pardo et al. (2015) discussed initiatives such as Mega-Float and the Mobile Offshore Base (MOB), emphasizing their potential for coastal and offshore applications. Gu et al. (2015) investigated ship accidents and wave loads on VLFSs, creating time-domain mathematical methods for predicting connector loads. Wu et al. (2017) investigated hydro-elasticity in complicated

Table 5 BRLa of mega- structures and VLFS

Dimension	Readiness level	Evidence and source
TRL	Moderate	Extensive research on structural designs (Wang et al. 2006), hydro-elastic modeling (Riggs et al. 2008; Wu et al. 2017), connector load behavior (Gu et al. 2015), tsunami and typhoon effects (Li et al. 2022; Murata et al. 2015), and practical project examples (Mega-Float, floating oil bases) (Wu et al. 2017) demonstrate significant technological progress. However, most works are simulations and pilot projects; actual large-scale commercial operational systems (for example, full floating airports) are still uncommon.
MRL	Moderate	There are only a few major VLFS applications (for example, Mega-Float in Tokyo Bay and floating oil storage), which are mostly experimental or for a specific purpose (Wu et al. 2017). Many applications (floating cities, airports) are still at the conceptual or pilot stage, with no plans for widespread commercialization.
RRL	Info N.E	None of the studies address specific permitting, maritime zoning restrictions, or legal frameworks for constructing and operating VLFSs.
ARL	Info N.E	VLFSs are becoming increasingly popular for ocean space utilization (Wu et al. 2017), environmental sensitivity (Gaftar and Drimer 2022), and resilience benefits (Murata et al. 2015). However, public acceptance of big floating cities or airports has not yet been completely realized or tested.
ORL	Info N.E	VLFS operations necessitate extensive modification, including specialized mooring designs (Gaftar and Drimer 2022), understanding hydro-elastic reactions near islands and reefs (Wu et al. 2017), and complicated connector load control (Gu et al. 2015). Integration with normal port, city, or infrastructure operations is currently complicated and not usual.

* Info N.E. - Not enough information

wave environments, identifying essential design parameters for VLFS deployment in shallow and wide seas.

More recent research broadens the scope of VLFS by addressing environmental and structural issues. Qin et al. (2019) investigated VLFS resistance to harsh ocean conditions by examining freak wave interactions with twin-plate breakwaters. Lim (2020) recommended VLFSs as a sustainable alternative to land reclamation in Singapore, claiming that floating businesses avoid environmental damage while also providing long-term urban expansion alternatives.

Li et al. (2022) presented a flexible module rigid connection (FMRC) model for simulating VLFS behavior under typhoon-driven waves. By evaluating hydrodynamic response characteristics, they improved VLFS resilience under adverse weather situations, revealing energy transfer pathways between structural components and environmental pressures.

Current trends favor incorporating VLFSs into urban planning, offshore logistics, and renewable energy projects. Researchers optimize VLFS designs to improve stability, flexibility, and cost-efficiency while addressing constraints including structural deformations and high maintenance costs. Modular connections and adaptable mooring methods provide robustness against extreme wave conditions. While VLFSs provide options for floating airports, seaports, and industrial hubs, there are still problems to decreasing energy losses, maximizing material utilization, and ensuring long-term economic feasibility. Future research must develop models and structural adaptation procedures to optimize the promise of VLFSs as a scalable infrastructure option.

Floating tourism structures

Floating tourism structures are floating platforms designed for tourism activities, integrating berthing and recreational functions in unique forms (Eto et al. 2008).

Floating tourist structures emerged because of space constraints in prime coastal locations and the necessity for long-term marine-based tourism solutions (Table 6). Chung et al. (2005) described an offshore floating marina system in Korea that was meant to function independently of fixed breakwaters. They handled tide, weather, and land reclamation issues by including a self-contained floating platform. Their modular architecture enabled progressive development without major infrastructural changes, enabling responsiveness to demand swings. Rahman et al. (2018) investigated the feasibility of floating vessel breakwater systems for coastal protection and tourism development. By refurbishing vessels, they suggested a hybrid system that provided economic, environmental, and operational benefits while also offering new business opportunities in local communities.

Recent research improves floating tourist platforms to incorporate structural resilience and multi-functional capabilities. Another study proposed a heart-shaped, very large floating tourism platform for the South China Sea that combined cruise ship docking and entertainment facilities. They used a three-dimensional hydro-elastic model to investigate complex vibration modes, structural loads, and water resonance effects. Their findings highlighted the importance of treating vertical and torsional vibrations to increase platform stability. Advanced simulation approaches enabled researchers to predict extreme load circumstances and detect structural flaws, resulting in improved

Table 6 BRLa of floating tourism structures

Dimension	Readiness level	Evidence and source
TRL	High	Offshore floating marina systems have been technically constructed to account stability, motion, mooring, and modularity (Chung et al. 2005). Advanced hydro-elastic modeling of a heart-shaped tourism platform ("Ocean Diamond") demonstrates extensive structural analysis. However, "Ocean Diamond" looks to be in the design/simulation phase rather than fully operational.
MRL	Moderate	Floating marinas (Chung et al. 2005) and floating vessel breakwater designs for tourism (Rahman et al. 2018) indicate growing interest. While modular extension ideas are being studied, and local acceptance appears to be promising, there is currently no broad commercial deployment of floating tourism megastructures.
RRL	Info N.E	None of the papers explicitly discuss regulatory approval, licensing, or marine zoning laws affecting deployment of floating tourism structures.
ARL	Moderate	Rahman et al. (2018) indicate an innovative concept of a floating vessel breakwater system is offered to improve the sustainability of coastal areas and the tourism industry by combining commercial and social benefits. No societal opposition is mentioned for floating marinas or platforms.
ORL	Moderate	Operational models for floating marinas (Chung et al. 2005) and modular expansion strategies exist, but managing complex wave loads, hydro-elastic behavior, and internal water resonance in large platforms introduces significant operational complexity that necessitates specialized maintenance and monitoring.

* Info N.E. - Not enough information

design optimization. Floating tourism buildings are increasingly using advanced hydro-dynamic modeling to improve safety and operational efficiency.

Current trends prioritize environmentally friendly materials, energy-efficient operations, and multi-purpose tourism infrastructure. Researchers investigate self-sustaining platforms that incorporate renewable energy sources like solar and wind power. Modular floating tourism hubs with customizable design support a wide range of activities, including ecotourism, luxury resorts, and recreational facilities. Optimizing structural performance under adverse weather conditions and guaranteeing cost-effective maintenance remain difficult challenges. Future research should focus on improving material durability, increasing hydrodynamic resilience, and refining design approaches to create floating tourism structures that are both sustainable and commercially feasible.

Floating shipyards

Floating shipyards (see Table 7) are fully floating facilities designed for ship repairs and maintenance, offering flexibility and reduced capital costs, particularly advantageous for remote locations (Ohl et al. 2020).

Floating shipyards developed in response to space constraints and the demand for adaptable, cost-effective ship maintenance and construction facilities. Ahn et al. (2013) demonstrated the viability of big floating structures by creating a modular floating facility in South Korea that enhanced shipbuilding productivity by shortening equipment transfer times. Burlacu and Domnisoru (2019) investigated the dynamic behavior of small floating docks during relocation to ensure safe transportation under varying wave conditions. In 2019, they broadened their research to assess the structural strength of big floating docks, with a focus on docking operations in river and coastal environments. These studies demonstrated floating shipyards as viable alternatives to typical

Table 7 BRLa of floating shipyards

Dimension	Readiness level	Evidence and source
TRL	Moderate	There are several real-world implementations and field tests. A large concrete floating port prototype was tested and installed for industrial use in Samsung Heavy Industries (Ahn et al. 2013); small and large floating docks are actively used and studied under dynamic and structural loadings (Burlacu and Domnisoru 2019); and floating shipyard concepts are actively designed and partially deployed (Ang et al. 2020; Ohl et al. 2020). However, full floating shipyards are not yet common across all shipyard types.
MRL	Moderate	The concept of totally floating shipyards is gaining popularity, particularly in land-scarce and deep-water areas such as Singapore and Angola. Nevertheless, these developments remain limited and exploratory for major shipyard replacement, and are not yet widely adopted globally.
RRL	Info N.E	Occupational hazard and safety rules are being thoroughly explored for floating docks and shipyards (Bayhun and Demirel 2024), showing a limited regulatory engagement. However, a fully developed regulatory framework designed exclusively for big floating shipyard operations has not yet been constructed.
ARL	Moderate	Due to land shortages and environmental sustainability goals, floating buildings are becoming more popular in industrial applications (Ang et al. 2020; Lim 2020). Floating docks are already widely recognized, while full floating shipyards are still in the early stages of adoption for a broader industrial shift.
ORL	Info N.E	Existing floating docks are integrated into standard shipbuilding and repair operations (Ahn et al. 2013; Burlacu and Domnisoru 2019), but full modular floating shipyard operations require significant organizational changes (Ohl et al. 2020), particularly concerning floating infrastructure management, safety, and modular scalability.

* Info N.E. - Not enough information

land-based facilities by providing flexibility for ship maintenance and equipment storage while lowering land acquisition expenses.

Recent research has refined floating shipyard models to improve safety, operational efficiency, and resilience. Ohl et al. (2020) suggested a totally floating shipyard for deep-water locations, which would have lower capital building costs than land-based facilities. Their design increased flexibility and cost-effectiveness by combining modular floating docks with power generation units. Ang et al. (2020) investigated multi-purpose floating structures in Singapore, citing shipyards as one of several potential uses for massive floating platforms. Lim (2020) emphasized the environmental benefits of transferring shipyards to floating platforms, which reduced the requirement for land reclamation while limiting ecological damage. These improvements established floating shipyards as a sustainable and adaptable option for ship maintenance and repair.

Automation, safety, and sustainability are the current priorities in floating shipyard operations. Bayhun and Demirel (2024) created a risk assessment model for floating dock operations that includes workplace hazards such as restricted crane movement and limited emergency access. Researchers are investigating new mooring techniques and hydrodynamic modeling to improve stability under shifting sea conditions. Floating shipyards use renewable energy and modular construction to maximize cost efficiency. Despite these advantages, issues such as regulatory approval, long-term structural durability, and exposure to extreme weather remain. Future research should concentrate on automating shipyard procedures, enhancing structural resilience, and assuring economic viability for large-scale floating shipyard developments.

Floating renewable energy platforms

Floating renewable energy platforms are floating platforms that integrate renewable energy systems, such as solar and marine parks, thereby creating multi-use marine spaces (Borg et al. 2024). Renewable energy integration on floating structures emerged as a long-term solution for offshore energy generation.

Shigemitsu et al. (2001) introduced the “Eco-Float” concept, which combined solar, wind, and wave energy harvesting technologies on a single floating platform. This study showed that wave energy absorption can lower structural loads while also generating electricity, making floating platforms self-sufficient. Lim (2020) expanded on this concept by arguing for floating structures as alternatives to land reclamation, highlighting their potential to house energy-intensive companies in a more environmentally responsible manner Table 8.

Recent research examines the techno-economic viability of floating renewable platforms. Borg et al. (2024) investigated offshore solar photovoltaics and an integrated floating breakwater system that stores energy while establishing a protected marine park. The study concluded that multi-use revenue models, such as aquaculture and vessel berthing, are insufficient to maintain profitability in the absence of government backing. Rijnsdorp et al. (2022) created a numerical model to anticipate wave-induced responses in floating structures, which is essential for developing robust floating renewable energy platforms. These developments demonstrated that, while floating renewables are promising, their economic sustainability remains dependent on subsidies and outside finance.

Current issues include structural resilience, energy storage, and financial sustainability. Floating renewable platforms must resist extreme environmental conditions while being efficient. Mooring techniques must be refined, wave energy conversion efficiency improved, and cost-effective integration of different energy sources developed. To increase investment attractiveness, future research should focus on energy management

Table 8 BRLa of floating energy platforms

Dimension	Readiness level	Evidence and source
TRL	Moderate	Various concepts are technically well-researched: self-sufficient floating mega-floats (Shigemitsu et al. 2001), floating marine airports with energy conversion mechanisms under typhoon waves (Li et al. 2022), floating marine parks integrating energy storage (Borg et al. 2024), and even frozen ice-based modular floating structures (Vadus et al., 1998). However, many remain at prototype, pilot, or simulation stage without full-scale operational commercialization.
MRL	Info N.E	Borg et al. (2024) argue that floating renewable energy platforms require extensive government support to be economically feasible. Market acceptance is growing but still unstable, relying primarily on subsidies and multi-purpose commercial models to justify investment.
RRL	Info N.E	None of the articles specifically address the governmental clearances, environmental permits, or licensing requirements for floating renewable platforms.
ARL	Info N.E	Offshore renewable projects are becoming more widely accepted in concept (Borg et al. 2024; Sato and Nagatomi 2023), notably for combining energy production with ocean conservation initiatives. However, adoption is mostly at the institutional/academic level; widespread popular acceptability has yet to be fully investigated.
ORL	Info N.E	Floating energy platforms necessitate novel multi-sector management approaches that include energy generation, marine transportation, aquaculture, and research (Borg et al. 2024; Sato and Nagatomi 2023). This complicated integration necessitates significant organizational adaptability.

* Info N.E. - Not enough information

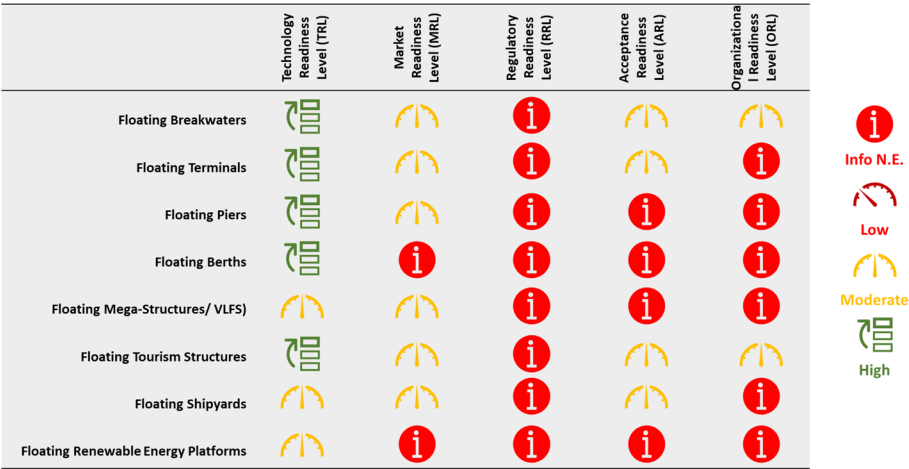


Fig. 7 Summary of BRLa

automation and creative finance approaches. Floating renewable platforms have the potential to revolutionize offshore energy generation, but technical and economic constraints must be overcome.

In Fig. 7, many individual components: floating breakwaters, terminals, piers, berths, mega-structures, tourism platforms, shipyards, and renewable energy platforms, have achieved moderate to high technological maturity and show growing, albeit limited, market interest and social acceptance. However, regulatory frameworks and organizational readiness remain underdeveloped or only partially addressed across almost all categories, indicating that while technological capabilities are frequently sufficient for integration, full real-world deployment is still heavily reliant on overcoming legal, operational, and market obstacles. It can be concluded that none of the floating port applications have yet reached the level of fully large-scale operational seaports.

Potential applications for future developments of floating ports

Building on the preceding analysis, which demonstrated that while many floating port components have reached moderate to high technological maturity, their integration into fully operational and established ports is still hampered by market, regulatory, societal, user organizational gaps. Therefore, it is necessary to investigate future opportunities where these technological advancements may converge. The demonstration of technological preparedness across floating structures, together with the obvious identification of persistent impediments, supports the need to envisage and specify strategic future directions. As a result, the following section proposes how floating ports could evolve from fragmented applications to comprehensive, sustainable maritime hubs, highlighting specific opportunities for research, governance innovation, and technological integration to address current limitations and fully realize the potential of floating port systems.

Floating ports instead of dry ports

Dry ports, which are inland extensions of maritime terminals, are vital for logistics and intermodal shipping (Pratelli et al. 2021). However, its effectiveness is constrained by land scarcity, traffic congestion, and environmental issues. Floating ports offer an alternative by acting as offshore hubs for empty container yards, customs clearance,

warehousing, and multimodal transport, hence removing the need for major onshore or land infrastructure. Research on floating terminals (see Sect. [Floating Terminals](#)) and modular platforms such as Space@Sea (Assbrock et al. 2020) indicated that floating logistics centers are technically viable and might successfully replace traditional dry ports. These floating dry ports might be situated in congested harbors or at strategic off-shore locations, reducing bottlenecks and promoting easier cargo flow.

Floating transshipment hubs

With expanding global trade volumes, transshipment hubs have emerged as critical components of maritime logistics. A floating transshipment center might be strategically located in deep-sea areas, enabling efficient cargo transfer between huge boats without the need for regular ports. Research on floating terminals (Cichanski et al. 2004; Lindemalm 1982) and Very Large Floating Structures (VLFSs) (Watanabe et al. 2006; Wu et al. 2017) has confirmed the technical viability of flexible and scalable floating systems capable of handling containerized, bulk, and liquid freight. Improvements in hydrodynamic stability (Christensen et al. 2018; Qin et al. 2019) boost the possibility of floating transshipment hubs that can withstand unfavorable marine conditions. Further, concepts such as STFT illustrates how floating terminals can offer a viable future pathway for transshipment terminals by enabling capacity expansion, operational flexibility, and resilience without reliance on land-based port expansion (MEYER Floating Solutions, 2024).

Sustainable energy storage and handling

Floating ports may implement renewable energy solutions to enhance green shipping and port sustainability. Platforms built with floating solar farms, wind turbines, and wave energy converters could produce and store electricity for on-site or offshore distribution. Floating renewable energy platforms that incorporate energy storage into breakwaters (Borg et al. 2024). Section [Floating shipyards](#) demonstrates the concept's technological maturity. Furthermore, hydrogen generation and storage on floating platforms, based on modular megastructure designs (Li et al. 2022), could enable alternative fuel bunkering for ships migrating to cleaner energy sources, in line with future decarbonization aspirations (IMO, 2023).

Floating service stations for offshore wind farms

Floating service stations for offshore wind farms represent a promising solution to address the logistical and operational challenges of maintaining these large-scale energy installations. By integrating renewable energy systems, these floating platforms can become self-sufficient hubs, potentially combining solar, wind, and wave energy harvesting technologies as demonstrated by the “Eco-Float” concept (Shigemitsu et al. 2001). This multi-use approach, akin to the concept of multi-use marine spaces (Borg et al. 2024), could allow for the housing of energy-intensive operations directly offshore, offering an environmentally responsible alternative to land-based infrastructure (Lim 2020). While the techno-economic viability of such platforms requires careful consideration and may benefit from government backing and diverse revenue models (Borg et al. 2024), advancements in numerical modeling for wave-induced responses (Rijnsdorp et al. 2022) are crucial for developing the robust and resilient structures necessary

to withstand extreme offshore conditions. Overcoming challenges related to structural resilience, energy storage, and financial sustainability through refined mooring techniques, improved wave energy conversion, and innovative financing will be key to realizing the full potential of floating service stations in revolutionizing offshore wind farm operations.

Floating service stations for vessels and seafarers

Floating ports might potentially serve as offshore service stations for vessels, including fuel, replenishment, repair, and personnel changeout facilities. The concepts proposed for floating shipyards (Burlacu and Domnisoru 2019; Ohl et al. 2020) and modular floating docks (Starr and Wainwright 1996) help offshore replenishment hubs achieve technological readiness. Furthermore, floating service centers could provide leisure amenities to improve seafarers' well-being during long voyages. Incorporating floating breakwaters (Fitriadhy et al. 2017) would ensure that these service stations can operate reliably even in rough seas.

Floating husbandry services

Floating husbandry services may assist vessels that require maintenance, fueling, or crew changes without having to dock at typical ports. The operational flexibility of floating shipyards (Ohl et al. 2020) and multi-use VLFS platforms (Wu et al. 2017) demonstrate the viability of establishing movable floating hubs for husbandry services. Such technologies could particularly benefit long-distance maritime routes and offshore sectors such as oil, gas, container, and bulk operations, while also reducing congestion at major ports.

The concept of fully operational floating ports thus extends beyond individual buildings to include massive offshore hubs capable of replacing or supplementing traditional port infrastructure. Research into hydrodynamics (Riggs et al. 2008; Wu et al. 2017), structural robustness (Gu et al. 2015), and renewable energy integration (Borg et al. 2024) is enhancing the viability of such floating solution. However, implementing floating ports as sustainable maritime infrastructures requires concentrated efforts in cost-effectiveness, legal frameworks, and environmental impact assessments.

Findings

Current applications and functions of floating ports

To address the question of what types of floating port applications currently exist and what functions they serve across different contexts, the literature reveals a wide range of floating port related concepts and implementations. Concepts for floating ports have been applied in a variety of settings: floating breakwaters, terminals, piers, berths, very large floating structures (VLFS), tourism platforms, shipyards, and renewable energy platforms, exhibiting moderate to high degrees of technological maturity. These applications have proven particularly useful in disaster-prone areas for resilient infrastructure, offshore energy logistics, and marina extensions. But rather than being a part of a unified, extensive port infrastructure system, most of the implementations continue to be specialized, fragmented, and frequently project-specific.

Floating ports have not yet developed into fully functional substitutes for traditional seaports, even after being proposed decades ago. These days, they frequently play auxiliary functions that support operations such as crew transfers, offshore supply (like

Brazil's PSV ports), or tourism. According to the literature, the scalability of floating ports is limited by the lack of connectivity among their many components, such as terminals, piers, and breakwaters.

Balanced readiness assessment

To examine how ready existing floating port applications are for wider adoption, and to identify patterns of evolution and potential synergies across application types, the literature was analyzed across multiple readiness dimensions, including technical maturity, regulatory alignment, and market feasibility. Although floating port technology is still developing, some crucial aspects of readiness are still lacking. There are notable gaps in organizational, market, societal, and regulatory readiness, as described in Sect. [Balanced readiness level assessment of floating ports applications](#). These gaps were identified through the literature based BRLa and were subsequently validated through expert consultation, which confirmed that non-technical dimensions consistently lag technological capability. There aren't many instances of integrated legal systems made to manage jurisdictional overlap, responsibility, and safety enforcement for floating platforms, therefore governance frameworks and acceptance frequently fall behind.

Most of the floating port projects do not comply with national permitting procedures or international marine rules, indicating a notably low level of regulatory preparedness. Experts collectively confirmed that while regulations often exist for individual components, system-level regulation for integrated floating infrastructure remains unclear or fragmented, with approval pathways varying strongly by location. Barriers to market acceptance for floating ports can include high initial expenditures, unpredictable profits, and low investor trust. Consistent with the literature, expert input indicated that technical readiness alone does not directly translate into viable business models, particularly for integrated or multi-use floating port concepts. Because port authorities and operators frequently lack the institutional capacity to manage the intricate societal, logistics and stakeholder dynamics of floating infrastructure, organizational preparation is also lacking.

Projects involving floating shipyards and renewable energy demonstrate how public-private partnerships (PPPs) are a viable way to address funding issues. However, further research is needed to determine how they adapt to port-specific circumstances. Nevertheless, expert validation indicates that such arrangements remain highly context dependent and are not yet embedded as standard governance models within port systems. Another area of weakness is stakeholder engagement is inclusive governance models that consider the opinions of local communities, environmental organizations, labor unions, and the private sector will be necessary for successful implementation.

Expert consultation further reinforced several cross-cutting insights that align with the literature. First, technological readiness across floating port functions is generally moderate to high; core subsystems for terminals, energy production, storage, and offshore hubs are largely based on adapted and recombined technologies rather than entirely new inventions. Integration and scale, rather than technical feasibility, increase complexity. Second, market readiness remains low to moderate, as demand exists in principle but commercial models for integrated floating ports are not yet stable. Third, regulatory readiness is consistently weak, with fragmented governance structures and the absence of standardized permitting pathways for system-level floating infrastructure. Fourth,

societal acceptance remains fragile and highly location specific, shaped by safety perceptions, environmental concerns, and familiarity with floating solutions. Finally, organizational readiness emerges as one of the weakest dimensions, with unclear ownership, coordination challenges, and high first-mover risk across actors.

In summary, these findings demonstrate that the BRLa results derived from literature are consistent with expert experience across diverse floating port initiatives. The expert input does not replace the literature analysis but serves to validate and contextualize it, while also underscoring the importance of location specific conditions, such as environmental exposure and regulatory context, in shaping readiness outcomes.

Future potential of floating port developments

It is becoming increasingly acknowledged that floating ports have the potential to transform maritime logistics infrastructure, particularly in response to challenges such as land scarcity, urban congestion, and evolving environmental conditions. However, strategic research that fills in existing gaps and foresees new needs must direct future applications.

Modular terminals for emerging areas with shallow coasts or limited land availability, climate-adaptive port nodes, and floating hubs for transshipment are promising avenues. These future directions call for strong governance frameworks that can oversee businesses across several jurisdictions and enforce environmental regulations. To support long-term deployment, resilience planning, sustainability certifications, and flexible legal and insurance frameworks will be essential.

Transnational coordination methods that facilitate cross-border collaboration for regulatory supervision, environmental compliance, and dispute resolution should also be the subject of research. To fully realize the promise of floating ports, governance solutions that put stakeholder legitimacy, operational efficiency, societal acceptance and ecological responsibility first must be developed.

Conclusion

This review demonstrates that while individual components of floating ports, such as floating breakwaters, terminals, piers, berths, very large floating structures, tourism platforms, shipyards, and renewable energy platforms, have reached moderate to high levels of technological maturity, these advances have not yet translated into fully operational floating ports equivalent to traditional seaports. The BRLa analysis shows that although technological readiness is relatively advanced for several applications, market readiness remains limited, and regulatory, organizational, and acceptance dimensions are frequently insufficiently addressed in the literature. In several cases, information related to these readiness dimensions is not explicitly evaluated in existing studies, indicating that research on floating port applications has largely focused on engineering feasibility rather than institutional, regulatory, or organizational deployment conditions. The findings reveal that floating port technologies are being applied successfully in specific, often niche contexts, such as marina expansions, offshore energy hubs, or disaster-resilient infrastructure. However, these applications tend to be fragmented and project-specific rather than part of an integrated, scalable port system. Many floating port elements still lack clear legal frameworks and standardized permitting processes, while broader market adoption is slowed by high capital costs and uncertain commercial

viability. Organizational readiness is similarly underdeveloped, with existing port management structures often unprepared for the operational complexities introduced by floating platforms. For floating ports to evolve into sustainable and transformative maritime hubs, research must prioritize bridging these systemic gaps. Future work should focus on developing adaptive governance models that can manage floating ports operating across different jurisdictions. Regulatory alignment at international and national levels will be crucial to enable deployment and ensure compliance. Financing strategies, including public-private partnerships, are needed to support investment while balancing public accountability. Equally important is the integration of ecological adaptation strategies, ensuring that floating ports enhance environmental resilience while minimizing ecological impacts. Finally, inclusive stakeholder engagement is essential to secure societal acceptance and integrate diverse interests. In summary, the transition from experimental floating structures to viable floating port systems requires coordinated progress across technical, regulatory, economic, and governance domains.

Abbreviations

ARL	Acceptance readiness level
BRLa	Balanced readiness level assessment
FCSTT	Floating container storage and transshipment terminal
FLSF	Floating logistics supporting facility
IMO	International maritime organization
MRL	Market readiness level
Info N.E	Not enough information
NWO	Nederlandse Organisatie Voor Wetenschappelijk Onderzoek (Dutch Research Council)
ORC	Onderzoek langs Routes door Consortia (Research along Routes by Consortia)
ORL	Organizational readiness level
PPP	Public-Private partnership
PSV	Platform supply vessel
RRL	Regulatory readiness level
TRL	Technology readiness level
VLFS	Very large floating structure
WoS	Web of science

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Author contributions

All authors contributed substantially to the work. Buddhi A. Weerasinghe is the primary author and developed the paper as part of his PhD research. Wouter Spekkink, Ron van Duin, and Jurian Edelenbos, as his supervisors, contributed equally to the conceptualization, design, and evaluation phases of the study. All authors reviewed and approved the final manuscript and are accountable for its content.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. The data supporting the findings of this study, including the list of relevant articles identified through a systematic bigram-based keyword search across Scopus and Web of Science, are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

Not applicable.

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