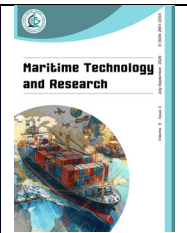




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Review Article

Nearshore floating solar photovoltaic systems: A review

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Article information	Abstract
Received: November 17, 2025 Revision: April 14, 2026 Accepted: April 25, 2026	The critical necessity of a global energy transition to a low-carbon energy mix underlines the importance of developing innovative renewable energy options that simultaneously meet energy and environmental concerns. Nearshore floating solar photovoltaic systems (N-FPVs) have been identified as a state-of-the-art renewable energy option that can increase solar photovoltaic energy while simultaneously improving coastal resilience challenges. The N-FPV approach uses photovoltaic panels on floating structures in sheltered marine environments, eliminating land use conflicts and using water-based cooling to increase efficiency while simultaneously improving responses to coastal resilience challenges due to climate change. In accordance with the ROSES approach to systematic evidence synthesis and reporting, this study uses a broad array of literature sources using the Scopus, Web of Science, and Dimensions databases. Thematic analysis of the literature on N-FPVs identifies three main themes: floating solar systems, coastal resilience and the low-carbon energy transition, and mooring systems and platform design. Compared to land-based solar photovoltaic systems, N-FPVs have higher upfront costs, with a competitive levelized cost of electricity (LCOE) between 271 and 703 USD/MWh (250 to 650 EUR/MWh) based on latitude and exposure, and potential hybridization with other marine energy systems. In addition, despite the lack of information on long-term ecological effects and hydrodynamic interactions, this study provides evidence that N-FPVs are not only a technological innovation but simultaneously a socio-environmental strategy that is integral to the global energy transition to a low-carbon energy mix.
Keywords Clean energy; Coastal energy; Mooring systems; Nearshore floating; Solar photovoltaic systems; Systematic review	

1. Introduction

The global transition towards low-carbon-based energy systems has sparked interest in developing innovative forms of renewable energy technologies that can address land-use limitations and facilitate large-scale deployment (Ilojanyia et al., 2024). Nearshore floating solar photovoltaic systems (N-FPVs) is an emerging form of marine-based renewable energy infrastructure, for which it is essential to integrate different forms of environmental and technical parameters for ensuring structural integrity and performance of these structures (Jifaturrohman et al., 2024). Among these, wave dynamics play a critical role, where hydrodynamic forces significantly impact the stability and movement of these structures (Jifaturrohman et al., 2024). The wind velocities in nearshore zones are important to energy production and loads on structures and, hence, require design assessment (Katare et al., 2024). Moreover, tidal and current activities affect mooring tension and energy production consistency (Zheng et al., 2024). Despite the multidisciplinary nature of this area, and the increased

number of pilot projects in Singapore and South Korea, there is limited literature on nearshore systems, with most authors favoring inland and deep sea applications (Naiborhu et al., 2025). Therefore, there is a major information gap on nearshore design optimization, ocean interactions, and techno-economic viability. Although installation costs are 10 to 25 % higher than on land, they are significantly lower compared to offshore options due to lower mooring and submarine cable needs (Martinez & Iglesias, 2024). Moreover, durability under marine conditions, ecological effects on nearshore ecosystems, and a lack of supporting regulations are other challenges to N-FPV deployment (Jifaturohman et al., 2024; Zheng et al., 2024; Zhang et al., 2022). Therefore, there is a need to assess the current status of N-FPV systems based on the literature.

Several review articles have examined aspects of floating photovoltaic technology in recent years, yet none has comprehensively addressed nearshore-specific systems. Cazzaniga (2020) classified FPV platform structures into pontoon, membrane, and modular types and outlined design principles for buoyancy and material selection, though limited to inland calm-water applications without considering marine hydrodynamic loads. Vo et al. (2021) did not differentiate nearshore from fully offshore deployments. Chowdhury et al. (2023) focused exclusively on cooling mechanisms without examining structural, mooring, or environmental dimensions. More recent reviews have broadened the thematic scope: Benjamins et al. (2024) synthesized environmental impact knowledge, though predominantly from freshwater studies with limited marine empirical evidence; they retained an inland focus without addressing wave-driven structural challenges. Liu et al. (2024) examined offshore floating PV systems exposed to open-sea conditions, yet did not address the distinct hydrodynamic, bathymetric, and economic characteristics of sheltered nearshore environments. Selj et al. (2025), in the IEA PVPS framework, reviewed FPV energy yield and reliability broadly, acknowledging the scarcity of nearshore-specific field data and design standards. **Table 1** summarizes the scope and limitations of these existing reviews relative to the present study. Collectively, no existing review has integrated technical, environmental, and economic dimensions specifically for nearshore coastal deployments, where moderate wave exposure, shallow-water mooring, and coastal ecosystem interactions define a distinct challenge domain. **Figure 1** maps the positioning of existing FPV reviews, revealing a clear knowledge gap in the nearshore-comprehensive quadrant that the present review aims to address.



Figure 1 The dashed box highlights the identified knowledge gap in comprehensive nearshore-focused reviews.

Table 1 Comparison of existing floating solar photovoltaic review articles and the present study.

Review	Year	Scope	Key Themes Covered	Nearshore Focus	Key Gap / Limitation
Cazzaniga (2020)	2020	FPV structures and design concepts	Platform design; buoyancy; material selection	Not addressed	Focused on inland/calm-water; no marine-specific loads (wave, current, salinity)
Vo et al. (2021)	2021	Solar FPV in offshore industry	Offshore FPV feasibility; deployment overview	Partially (no differentiation)	Did not distinguish nearshore from offshore; preliminary feasibility level only
Chowdhury et al. (2023)	2023	Cooling performance of FPV systems	Thermal management; CFD modeling; efficiency gain	Not addressed	Focused on cooling mechanism; no mooring, structural, or environmental analysis
Benjamins et al. (2024)	2024	Environmental impacts of FPV	Ecological effects; light regime; water quality	Partially	Predominantly freshwater studies; limited marine empirical data; no techno-economic or structural analysis
Ramanan et al. (2024)	2024	Recent advancements in FPV technology	Energy yield; cooling; equipment lifespan; co-benefits	Not addressed	Inland FPV focus; no hydrodynamic, mooring, or marine-specific design analysis
Garrod et al. (2024)	2024	FPV systems and energy storage	System integration; energy storage; cooling benefits	Not addressed	Broad scope dilutes nearshore insights; storage analysis for inland contexts
Liu et al. (2024)	2024	Offshore floating PV systems	Platform types; mooring; open-sea deployment	Not differentiated	Open-sea focus; did not address shallow-water or sheltered coastal conditions
Selj et al. (2025)	2025	FPV energy yield, reliability, maintenance (IEA PVPS)	Performance; degradation; operation and maintenance (O&M); design codes	Partially	General FPV scope; limited nearshore-specific field data and design guidelines
This review (2025)	2025	Nearshore floating solar PV systems	Platform design; mooring; energy performance; hydrodynamics; environmental; techno-economic; grid integration; regulatory; deployment drivers	Primary focus	First systematic review dedicated to nearshore FPV, integrating all technical, environmental, and economic dimensions specific to sheltered coastal deployment

Note: “Nearshore focus” indicates whether the review specifically addressed sheltered coastal/nearshore marine environments, as distinct from inland freshwater or open-sea offshore contexts.

This review addresses the identified gap by presenting the first systematic synthesis dedicated exclusively to nearshore floating solar photovoltaic systems. Unlike prior reviews, this study specifically targets the nearshore domain- defined as sheltered to semi-exposed coastal waters within a few kilometers from shorelines- where moderate wave loading, tidal variability, saltwater exposure, and grid proximity create distinct engineering and environmental challenges not addressed by inland or open-sea FPV reviews. Following the ROSES guidelines, this review integrates findings from 33 peer-reviewed studies published between 2019 and 2025, synthesizing knowledge across six interconnected dimensions: (1) platform design and array configuration, (2) mooring and anchoring systems, (3) energy performance and efficiency, (4) environmental impacts, (5) techno-economic assessment, and (6) deployment drivers and regulatory considerations. By providing this integrated nearshore-specific synthesis, the present work offers a consolidated knowledge base for researchers, engineers, policymakers, and coastal planners.

With these research gaps in mind, this review addresses four research questions: (1) What are the major technical, environmental, and economic factors in the deployment of N-FPV systems? (2) What are the comparative advantages and disadvantages of N-FPV installations in terms of energy production and economic viability? (3) How do site-specific oceanographic conditions affect the performance and structural integrity of N-FPVs? (4) What are the major innovations and remaining challenges in mooring design, platform configuration, and grid integration?

2. Methodology

A systematic literature review (SLR) approach was used, which comprised five steps: review protocol development, research question formulation, systematic search, quality assessment, and data analysis.

2.1 Review protocol

The ROSES (Reporting Standards for Systematic Evidence Syntheses) framework (Haddaway et al., 2018) was adopted as a basis for this systematic literature review. Its structured templates are particularly suited to multidisciplinary N-FPV research spanning marine engineering, environmental science, and energy policy (Kraus et al., 2020).

2.2 Formulation of research question

The research questions were formulated using the PICO framework — Population/Problem, Interest, and Context — the qualitative counterpart of PICO, in which the lowercase ‘o’ denotes Context rather than Outcome (Lockwood et al., 2015). In this context, the research questions were formulated using the PICO framework (Frandsen et al., 2020), targeting nearshore coastal deployment and performance of N-FPV systems within a low-carbon energy transition context (Hosseini et al., 2024).

2.3 Systematic searching techniques

2.3.1 Identification

A systematic approach to literature identification was used to search using primary keywords on floating solar, photovoltaic systems, nearshore, and coastal energy, with alternative terms drawn from various sources, including Boolean search terms, used with field code constraints and applied to four different databases: Scopus, Web of Science, IEEE Xplore, and Google Scholar. **Table 2** presents the search logic used in each of the databases. This search approach resulted in 334 unique articles on N-FPV deployment, feasibility, environmental effects, and systems.

2.3.2 Screening process

The screening process, as per Mohamed Shaffril et al. (2019) and Samsuddin et al. (2020), is a significant step in the systematic literature review process, which filters out irrelevant and low-

quality literature based on predetermined criteria. Inclusion criteria required articles to be: (i) written in English and published in peer-reviewed journals; (ii) published between 2015 and 2025; and (iii) addressing nearshore or coastal FPV across domains of marine engineering, environmental science, or techno-economic evaluation. As a result, 63 articles were excluded from this review process, while 96 articles remained as a result of the two-step screening process, considering their relevance and suitability for the review process.

Table 2 Search strings.

Database	Search String
Scopus	TITLE-ABS-KEY(("floating solar*" OR "floating photovoltaic*" OR "FPV system*" OR "nearshore solar*") AND ("coastal energy " OR "low-carbon transition" OR "renewable energy" OR "marine energy") AND ("mooring system*" OR "platform design*" OR "wave dynamics" OR "tidal current*" OR "offshore solar"))
Web of Science	TS=(("floating solar*" OR "floating photovoltaic*" OR "FPV system*" OR "nearshore solar*") AND ("coastal energy " OR "low-carbon transition" OR "renewable energy" OR "marine energy") AND ("mooring system*" OR "platform design*" OR "wave dynamics" OR "tidal current*" OR "offshore solar"))
IEEE Xplore	((("floating solar*" OR "floating photovoltaic*" OR "FPV system*" OR "nearshore solar*") AND ("coastal energy " OR "low-carbon transition" OR "renewable energy" OR "marine energy") AND ("mooring system*" OR "platform design*" OR "wave dynamics" OR "tidal current*" OR "offshore solar"))
Google Scholar	("floating solar" OR "floating photovoltaic" OR "FPV system" OR "nearshore solar") AND ("coastal energy" OR "low-carbon transition" OR "renewable energy" OR "marine energy") AND ("mooring system" OR "platform design" OR "wave dynamics" OR "tidal current" OR "offshore solar")

2.3.3 Eligibility

The process involved assessing all remaining articles manually, based on their title and abstract, to identify those addressing the major themes and topics in relation to this review. Full-text assessment of the 96 screened articles against the eligibility criteria resulted in the exclusion of 63 publications. The remaining 33 articles were found to be most relevant and, thus, included in this review, providing detailed information concerning the structural design, suitability, and dynamics of the N-FPVs, as well as their role in enhancing coastal energy resilience and sustainability. **Figure 2** presents a flow diagram showing the process followed in this review, in accordance with the PRISMA flow diagram, concerning the identification, screening, and eligibility process.

2.4 Thematic classification of reviewed studies

Following eligibility assessment, the 33 included articles were thematically categorized using an inductive coding framework, from which 10 categories emerged: Platform Design and Configuration (PD), Mooring and Anchoring Systems (MO), Energy Performance and Efficiency (EP), Hydrodynamic Analysis (HY), Environmental Impacts (EN), Techno-Economic Assessment (TE), Grid Integration (GI), Regulatory and Policy (RE), Case Study and Field Validation (CS), and Deployment Drivers (DD). Articles addressing multiple themes were assigned to all relevant categories. **Table 3** shows the complete thematic mapping across all 33 studies; a detailed synthesis of each study's contributions is provided in the Appendix as Supplementary **Table S1**.

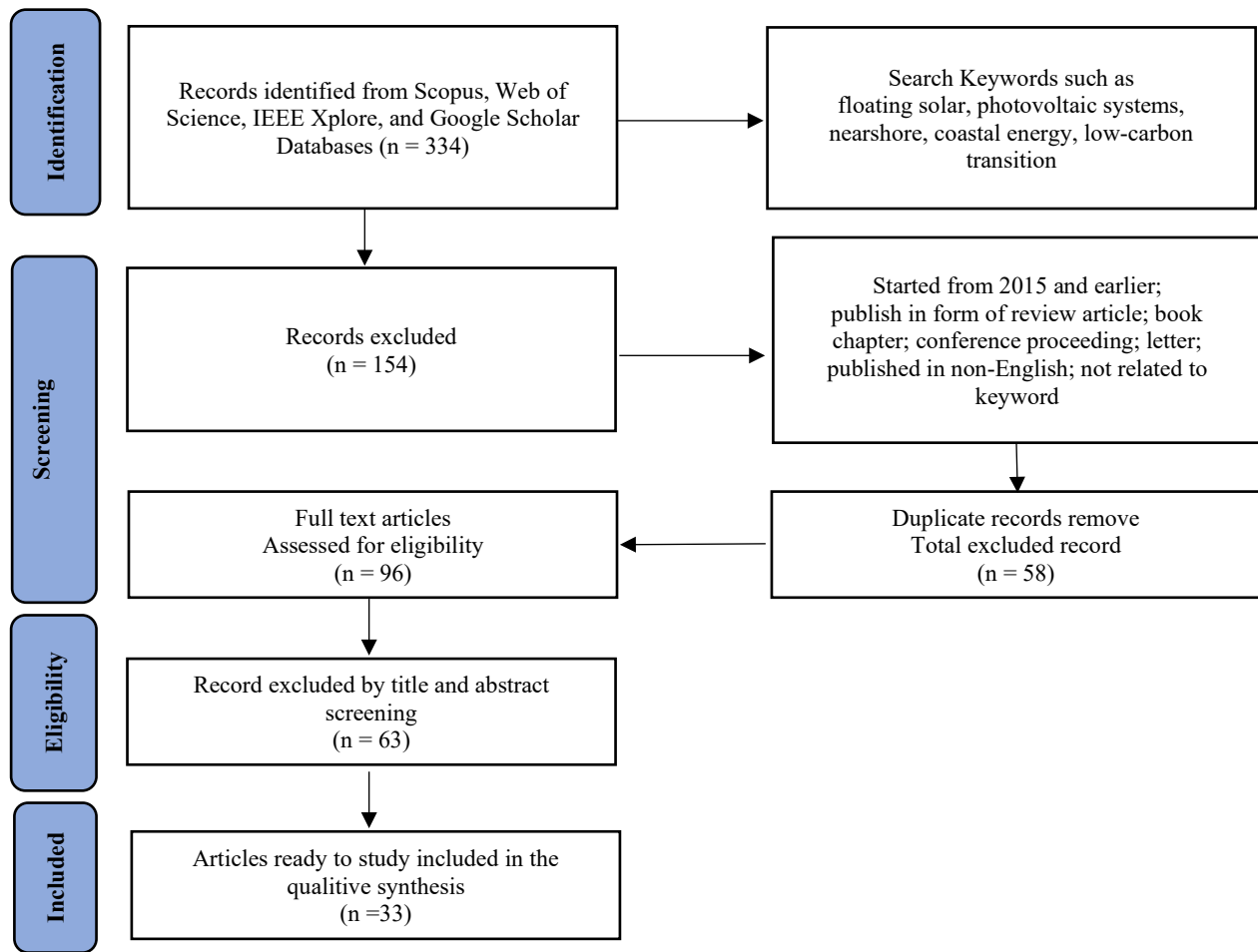


Figure 2 PRISMA flow diagram.

Table 3 Thematic mapping of reviewed articles on nearshore floating solar photovoltaic systems.

Author(s) & Year	PD	MO	EP	HY	EN	TE	GI	RE	CS	DD
Bai et al. (2024)					✓	✓				✓
Benjamins et al. (2024)					✓			✓		
Cazzaniga (2020)	✓									
Chowdhury et al. (2023)			✓							
Ramanan et al. (2024)			✓			✓				✓
Joshi et al. (2023)						✓		✓	✓	✓
Garrod et al. (2024)	✓		✓							
Ilgen et al. (2023)			✓		✓					
Ji et al. (2025)		✓		✓						
Jiang et al. (2023)	✓	✓		✓			✓			
Jifaturrohman et al. (2024)	✓			✓						
Jokhu et al. (2025)								✓		✓
Lee and Sim (2024)	✓			✓						

Table 3 (continued) Thematic mapping of reviewed articles on nearshore floating solar photovoltaic systems.

Author(s) & Year	PD	MO	EP	HY	EN	TE	GI	RE	CS	DD
Li et al. (2024)	✓	✓		✓						
Liu et al. (2024)	✓	✓		✓						
Ma et al. (2024)	✓	✓		✓						
Magkouris et al. (2023)			✓	✓					✓	
Martinez and Iglesias (2024)						✓			✓	
Mavraki et al. (2023)					✓				✓	
Naiborhu et al. (2025)	✓			✓						
Ray et al. (2024)					✓					
Selj et al. (2025)	✓		✓			✓				
Song et al. (2022)	✓			✓						
Suja and Chandrasekaran (2025)		✓		✓						
Van Der Zanden et al. (2024)	✓			✓					✓	
Vo et al. (2021)	✓					✓				✓
Wu et al. (2024)					✓			✓		✓
Xiong et al. (2025)	✓			✓						
Xu et al. (2024)	✓			✓						
Zhang et al. (2024)	✓	✓	✓	✓					✓	
Zhang et al. (2022)	✓			✓						
Zhang et al. (2025)	✓			✓						
Zheng et al. (2024)			✓	✓						
Total	18	7	8	18	6	6	1	4	6	6

Note: PD = Platform Design & Configuration; MO = Mooring & Anchoring; EP = Energy Performance & Efficiency; HY = Hydrodynamic Analysis; EN = Environmental Impacts; TE = Techno-Economic Assessment; GI = Grid Integration; RE = Regulatory & Policy; CS = Case Study / Field Validation; DD = Deployment Drivers. ✓ indicates the study addresses the corresponding theme.

3. Technical and operational aspects

3.1 System configuration and design

Nearshore floating photovoltaic (N-FPV) systems represent advanced engineering practices that bring together various fields to ensure optimal performance in hostile environments. The nearshore floating PV system is distinct from the inland floating system because of the high environmental loading, such as high wave energy, strong wind forces, and saltwater corrosion (Li et al., 2024; Zhang et al., 2024).

3.1.1 Nearshore vs offshore deployment

Nearshore FPV systems, placed at a distance of a few kilometers from the shore, benefit from decreased wave heights and hydrodynamic forces when compared to offshore installation (Song et al., 2022). These FPVs take advantage of breakwaters, bays, and estuaries to avoid harsh oceanic conditions and harness maximum solar power. Materials for these structures need to have good

resistance against corrosion, strong mooring, and dynamic anchoring capabilities for tidal and saline conditions and seasonal storms (Liu et al., 2024). Nearshore installation is economically viable for remote communities and, specifically, 200 kW FPVs can power 30-50 island homes and reduce diesel consumption (Vo et al., 2021). **Figure 3** illustrates the distinction between nearshore and offshore FPVs regarding oceanic conditions and design demands.

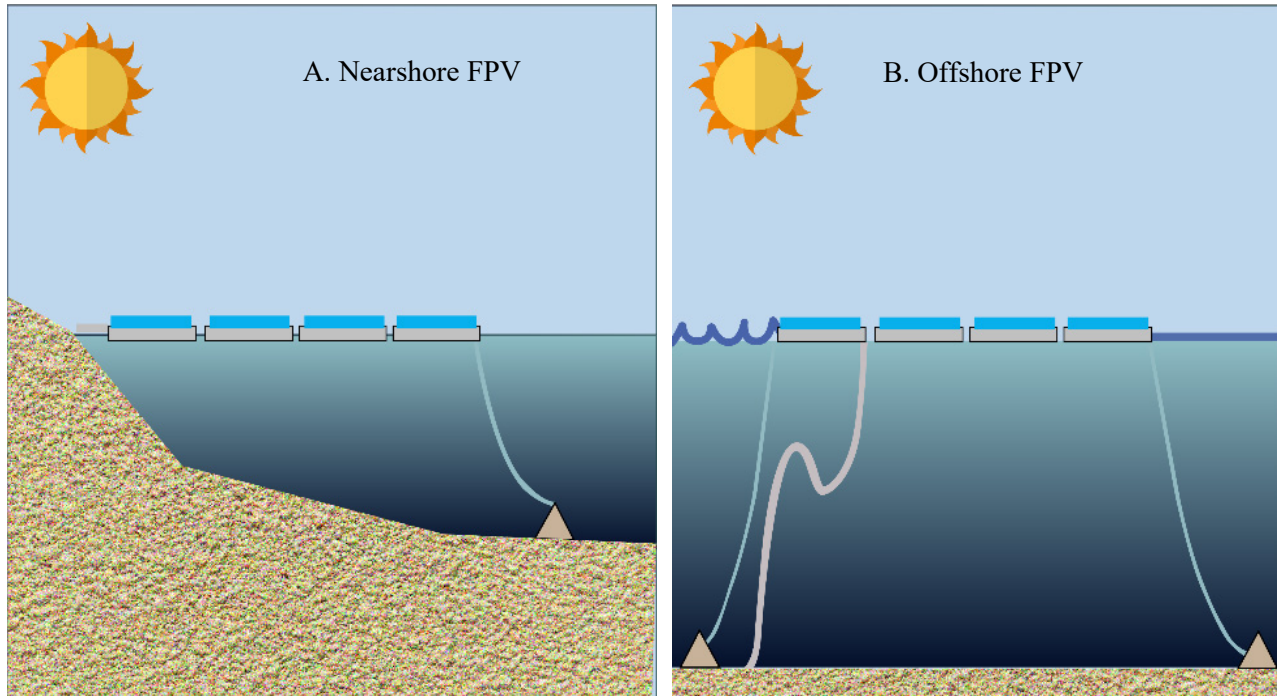


Figure 3 Types of floating photovoltaic (FPV) installations, (A) nearshore FPV and (B) offshore FPV.

3.1.2 Floating platform technologies

Currently, there are two major structural paradigms for N-FPV platforms. For pontoon-type platforms, there are distinct floating structures, usually made of high-density polyethylene (HDPE), arranged in modules and carrying photovoltaic panels with rigid or semi-rigid frames (Zhang et al., 2024). HDPE is known for its excellent resistance to UV degradation, saltwater corrosion, and biofouling, and its structural integrity over a wide range of temperatures (Li et al., 2024). Additionally, its modular design allows for compliant motions, where it is able to adapt to and match wave profiles rather than oppose them. Full-scale testing of these structures at the 5 MW Woodlands floating solar plant in Singapore showed its effectiveness in accommodating dynamic marine conditions (Zhang et al., 2024). For membrane-based FPV platforms, there is a flexible membrane carrying photovoltaic modules with minimal substructure requirements. Recent hydrodynamic investigations of these structures showed promising seakeeping characteristics under combined wave and current actions (Xiong et al., 2025).

3.1.3 Array configuration optimization

The geometric arrangement of floating modules plays a central role in determining hydrodynamic behavior and structural loading in N-FPV arrays. Numerical analyses by Zhang et al. (2025) comparing rectangular, hexagonal, and triangular configurations show that array geometry affects motion response more strongly than individual float shape. Triangular layouts demonstrated the best performance, with peak heave and pitch motions reduced by about 15 % compared with rectangular arrays, due to more uniform dissipation of wave energy and lower localized stress

concentrations (Zhang et al., 2025). Although having the advantage of easier fabrication and assembly, the rectangular array showed greater susceptibility towards resonance as the wave periods approached the natural frequencies, resulting in increased motion and, consequently, high cyclic loading on the mooring systems (Xu et al., 2024). Hexagonal arrangements provided intermediate hydrodynamic behavior, offering lower motion responses than rectangular layouts while maintaining efficient surface coverage through dense modular packing (Zhang et al., 2025). For nearshore sites characterized by multidirectional wave fields, the superior stability and consistent motion response of triangular arrays provide clear operational advantages (Zhang et al., 2025).

3.1.4 Float geometry and material considerations

The geometric form of floating elements represents an essential design factor that significantly influences the hydrodynamic performance of nearshore floating photovoltaic systems. Comparative studies have consistently demonstrated that spherical floats, particularly in triangular configurations, provide enhanced stability in float movement with uniform load distribution owing to isotropic interaction with waves and reduced hydrodynamic resistance (Zhang et al., 2025). Conversely, box-type floats provide benefits in terms of simplicity in fabrication, high packing density, and structural frame integration. However, they have been associated with higher hydrodynamic resistance and enhanced effects of wave diffraction, particularly in energetic sea states (Jiang et al., 2023; Liu et al., 2024). Cylindrical floats have been reported to provide a moderate balance in hydrodynamic performance and structural feasibility. **Table 4** provides a comparative summary of the performance characteristics of different float geometries in terms of hydrodynamics and economics.

Table 4 Summary of key float geometry types and their functional characteristics.

Geometry Type	Key Characteristics	Hydrodynamic Behavior	Suitable Conditions	Representative References
Spherical Float	Lightweight, isotropic load distribution; simple structure	High stability against multi-directional waves; low drag	Mild to moderate waves; shallow-to-mid-depth nearshore	(Zhang et al., 2025)
Box-Type Float	Large surface area; higher buoyancy; easier module mounting	Higher drag; moderate stability; sensitive to wave direction	Sheltered nearshore sites; low-medium wave climates	(Lee & Sim, 2024)
Pontoon-Type Float	Modular; suitable for linear array structures; strong longitudinal stiffness	Good response in aligned waves; moderate heave and pitch	Semi-exposed nearshore; longwave-dominant coasts	(Sadeghi et al., 2019)
Hexagonal / Honeycomb Float	Interlocking structure; high structural integrity; minimizes gaps	Improved wave dissipation; excellent stability under multi-direction seas	Exposed sites; moderate-high wave energy	(Van Der Zanden et al., 2024)
Hybrid Floats (HDPE + Composite Reinforcements)	Enhanced durability; optimized strength-to-weight ratio	Better fatigue resistance; reduced deformation under cyclic loads	Long-term offshore-nearshore deployments	(Jiang et al., 2023; Mavraki et al., 2023)

The materials used for floating elements must provide long-term durability, environmental resistance, recyclability, and economic viability. High-density polyethylene (HDPE) currently

dominates N-FPV applications owing to its balance of mechanical properties, saltwater durability, and cost-effectiveness (Li et al., 2024). The structural performance of HDPE can be enhanced through reinforcement with corrosion-resistant fibres, forming composite materials suitable for harsh offshore conditions (Jiang et al., 2023). Alternative materials proposed for N-FPV deployment include FRP composites and marine-grade aluminum alloys, although their use in floating-element applications remains limited compared to HDPE-based systems.

3.1.5 Cross-study synthesis: System configuration

Cross-study synthesis reveals both consensus and divergence on N-FPV system configuration. HDPE pontoon-type platforms represent the most mature and widely deployed option for nearshore applications (Zhang et al., 2024; Li et al., 2024; Jiang et al., 2023). Array geometry has stronger influence on hydrodynamic performance than float shape, with triangular layouts achieving 15 % lower peak motions than rectangular (Zhang et al., 2025; Xu et al., 2024). However, there is a significant difference of opinion regarding economic feasibility and hydrodynamic performance. Although spherical floats achieve better hydrodynamic stability in triangular arrays, box-type floats are more economical for rectangular arrays in sheltered sites (Jiang et al., 2023; Liu et al., 2024). Although membrane-type platforms have been considered favorable for reducing construction costs and installation complexity, membrane-type platforms remain under-evaluated, with only one numerical study available (Xiong et al., 2025), and no field-validated comparison against pontoon designs. Long-term performance data exceeding five years are absent for all platform types. Additionally, there is a lack of information regarding long-term performance and degradation rates of any of these platforms for marine applications, as none of these works report any long-term field performance (i.e., more than five years of operation).

3.2 Mooring and anchoring systems

Mooring systems anchor floating N-FPV platforms to the seabed while accommodating environmental forces from waves, winds, currents, and tides (Li et al., 2024). Nearshore constraints-shallow depths, large tidal ranges, and extreme wave loading-require specialized design optimization for structural adequacy, station-keeping, and cost-effectiveness. Design conditions include operational seas ($H_s = 0.5 - 2.0$ m, $T_p = 5 - 10$ s) and survival scenarios with 50 - 100-year return periods (H_s up to 6.5 - 8.0 m; gusts 70 - 85 m/s). Mooring stiffness and array spacing are tuned to maintain response amplitude operators below ~ 1.5 m/m (heave) and 3° /m (pitch), minimizing motion-induced power losses and peak line tensions under combined wave-wind-current loading (Ji et al., 2025; Zhang et al., 2025).

3.2.1 Mooring typologies

Nearshore floating photovoltaic (FPV) mooring systems can be classified into three major categories, namely, catenary, taut-leg, and hybrid. Catenary-based systems use chains of considerable weight and curved profiles for design simplicity but require large footprints (Jiang et al., 2023). Taut-leg-based systems use pre-tensioning synthetic fibers for near-vertical geometries and smaller footprints but have poor resistance to extreme loads (Liu et al., 2024). Hybrid-based systems combine catenary and taut-leg structures with clump weights and buoyancy modules for synergetic effects. Comparative analyses for 8 m depth showed a 38 % reduction in maximum tensions compared to traditional catenary-based systems (**Figure 4**). Multi-point spread mooring with evenly spaced lines provides directional restraint for floating structures. Finite element analyses showed 20 - 25 % reduction in maximum tensions for six-point spread mooring over three-point spread mooring (Ma et al., 2024; Zhang et al., 2025). Parametric optimization of spread angles of $35 - 45^\circ$ is considered suitable for typical N-FPV structures, balancing restraint and loads (Li et al., 2024; Liu et al., 2024).

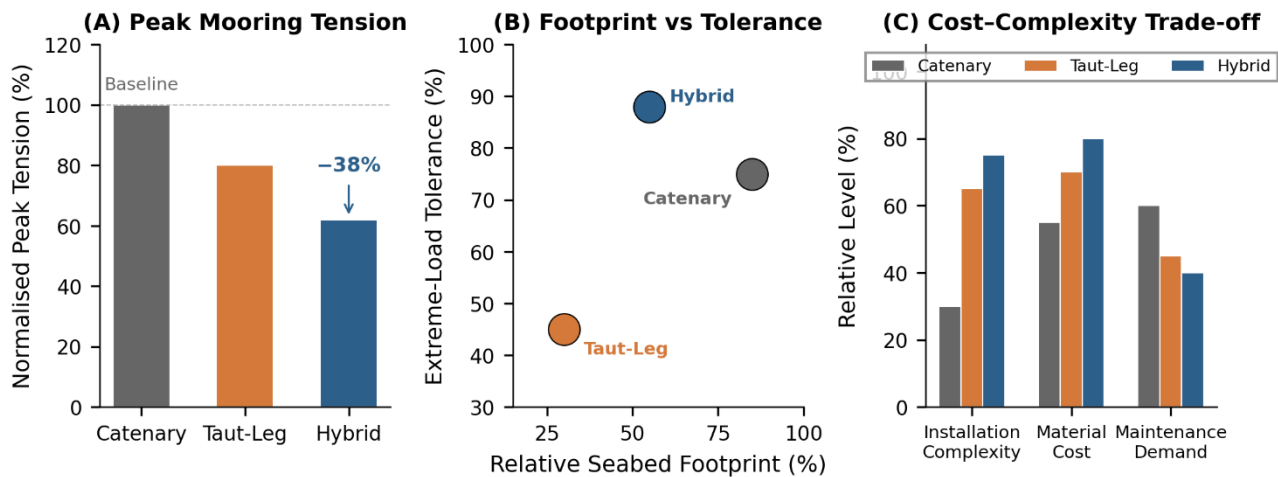


Figure 4 Comparative performance analysis of nearshore FPV mooring configurations synthesized from reviewed literature. (A) Normalized peak mooring tension: hybrid configurations achieve 38 % reduction versus catenary baseline (Jiang et al., 2023). (B) Trade-off between seabed footprint and extreme-load tolerance across mooring types (Liu et al., 2024). (C) Relative installation complexity, material cost, and maintenance demand for each configuration (Jiang et al., 2023; Ma et al., 2024).

The spatial configuration and geometric positioning of mooring attachment points are critical in determining the motion responses and loads in nearshore floating photovoltaic (N-FPV) systems. Current practices in N-FPV systems usually involve multi-point spread mooring systems, in which three or more mooring lines are arranged to achieve an omnidirectional mooring restraint (Zhang et al., 2025). Although three-point symmetric mooring with a 120-degree angle spacing is the minimum requirement, four and six-point mooring configurations can be advantageous in terms of redundancy and load-carrying capacity. Numerical simulations revealed that the use of a six-point mooring system can achieve a 20 - 25 % reduction in peak line tensions compared to three-point mooring systems due to more uniform load distribution under extreme offset conditions (Ma et al., 2024). In terms of spread angle, the horizontal spread angle refers to the angle between mooring lines and the horizontal plane. It is evident that the horizontal spread angle significantly affects the balance between vertical and horizontal loads in nearshore floating photovoltaic (N-FPV) systems. In optimization studies, the horizontal spread angle was determined to fall in the range of 35 to 45 degrees to achieve optimal balance in station keeping and vertical load-carrying capacity (Li et al., 2024). **Figure 5** showing the quantitative relationship between the number of mooring attachment points and the reduction in peak line tension (Panel A) and optimization analysis of the horizontal spread angle (Panel B).

3.2.2 Connection systems and load transfer mechanisms

N-FPV platforms employ two connection paradigms: rigid and flexible. Rigid connections, where photovoltaic modules are connected and assembled together through bolting and welding, play an important role in sharing loads among different modules and reducing stress concentration. However, different loads acting on different modules of the photovoltaic array result in large amounts of bending and shear forces at the connections, making fatigue damage a major concern for these structures. This necessitates increased detailing and inspection (Ma et al., 2024). In contrast, flexible connections allow neighboring modules to move independently. Experimental investigations have shown that flexible connections can reduce peak loads at connections by 40 - 60 % relative to rigid connections, thereby reducing fatigue damage and broadening the natural frequency range to lower resonance risk.

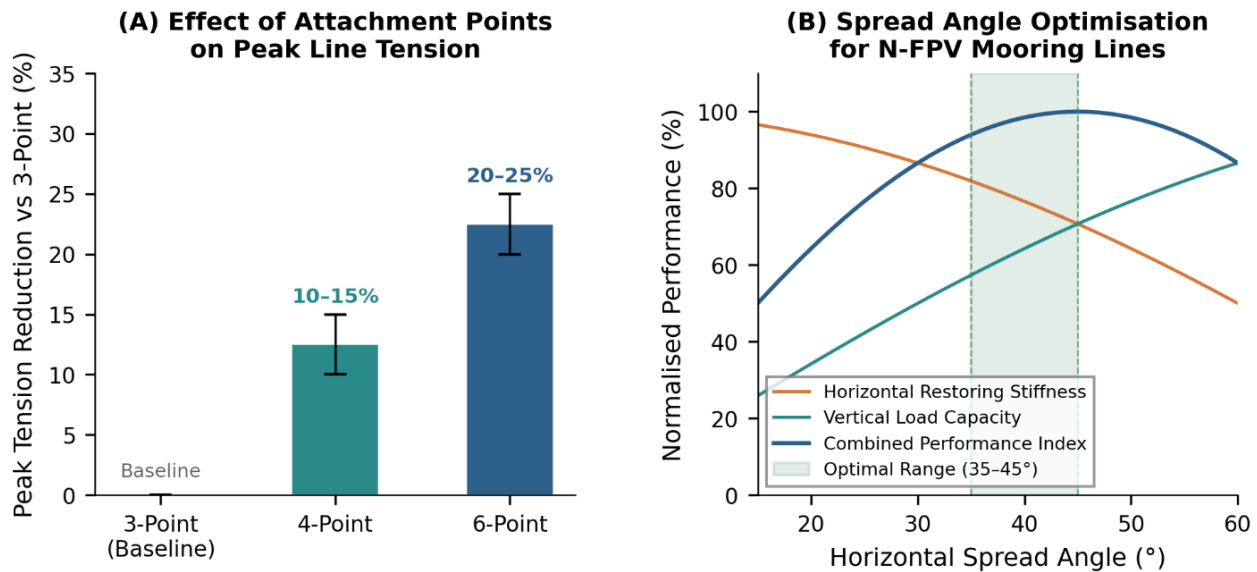


Figure 5 Multi-point mooring performance: tension reduction and spread angle optimization. (A) Peak line tension reduction relative to three-point baseline: four-point systems achieve 10 - 15 % reduction and six-point systems achieve 20 - 25 % reduction (Ma et al., 2024; Zhang et al., 2025). Error bars indicate reported ranges. (B) Normalized mooring performance as a function of horizontal spread angle, showing the optimal 35 - 45° range where combined horizontal restoring stiffness and vertical load capacity are maximized (Li et al., 2024; Liu et al., 2024).

3.2.3 Anchor technologies and seabed interface

Selection of the anchor system used in nearshore floating photovoltaic systems should consider the soil conditions, including soil types, soil strength, soil slope, and mobility/scour potential, especially with the spectrum of soil conditions varying from very soft clays to hard rock (Jiang et al., 2023). Good geotechnical characterization is still essential. Four principal anchor types are applicable to N-FPV deployments, each suited to distinct seabed conditions and load profiles. **Table 5** summarizes their performance characteristics, applicable seabed conditions, key advantages and limitations, and representative references.

3.2.4 Cross-study synthesis: Mooring and anchoring

Studies consistently support hybrid mooring configurations (catenary + taut-leg), which achieve a 38 % reduction in peak tension relative to catenary-only systems (Jiang et al., 2023; Liu et al., 2024). Six-point spread mooring reduces peak line tensions by 20 - 25 % versus three-point systems (Ma et al., 2024; Zhang et al., 2025). Flexible connections reduce peak connection loads by 40 - 60 % compared to rigid connections, albeit at the expense of more robust module designs (Lee & Sim, 2024; Ma et al., 2024). Key divergences include: (i) numerically recommended spread angles of 35 - 45° remain unvalidated by field measurements (Li et al., 2024; Liu et al., 2024); and (ii) no published study captures fatigue performance across multiple storm seasons at full scale. In addition, there is a lack of study on the effects of biofouling on mooring performance, Biofouling effects on mooring line tension distribution also remain unquantified (Mavraki et al., 2023).

3.3 Energy performance and efficiency

The energy performance of N-FPV systems is considered a key factor in evaluating the economic viability of N-FPV systems in terms of their competitive advantage over land-based PV

systems (Chowdhury et al., 2023). The energy performance of N-FPV systems depends on several physical mechanisms. A clear understanding of the energy performance of N-FPV systems helps in optimizing the design of N-FPV systems for different environmental conditions.

3.3.1 Water cooling effects on module efficiency

Water cooling is the most significant technical benefit of floating photovoltaic systems because crystalline silicon cells exhibit strong temperature sensitivity, with efficiency losses of -0.40 % to -0.65 %/°C (Chowdhury et al., 2023; Ilgen et al., 2023). Ground-mounted systems frequently reach operating temperatures 20 - 30 °C above ambient, resulting in 8 - 15 % performance reductions, especially in tropical climates. In contrast, water surfaces enhance convective and evaporative cooling and moderate ambient temperature fluctuations due to their high thermal capacity. Field comparisons consistently show that floating systems operate 2 - 4 °C cooler on the module front surface, and 5 - 11 °C cooler at the rear, yielding 5 - 15 % efficiency improvements depending on design and climate (Chowdhury et al., 2023; Zhang et al., 2024). As illustrated in **Figure 6**, typical floating systems exhibit an average temperature reduction of 9.6 °C in tropical/subtropical settings, equivalent to roughly 4.3 % efficiency gain based on -0.45 %/°C coefficients (Chowdhury et al., 2023; Selj et al., 2025). More advanced systems using active water-circulation cooling have demonstrated efficiency enhancements up to 15.45 %, representing the upper bound of thermally driven performance improvements. These cooling benefits are most pronounced during high-temperature periods, aligning well with peak electricity demand profiles.

Table 5 Anchor type selection matrix for nearshore floating photovoltaic systems.

Anchor Type	Applicable Seabed Conditions	Key Advantages	Key Limitations	Representative References
Drag / Embedment Anchors (Fluke, Plow)	Soft to medium clays and sands	Cost-effective; high holding capacity after embedment; suitable for horizontal load–dominant mooring	Reduced performance in dense/rocky seabeds; requires adequate horizontal chain length	Li et al. (2024); Jiang et al. (2023)
Suction Caisson Anchors	Wide soil range (soft clay → dense sand)	High capacity; supports vertical & horizontal loading; low environmental disturbance; fully retrievable	Requires specialized installation equipment and controlled pressure systems	Jiang et al. (2023)
Gravity Anchors (Concrete/Steel Blocks)	Hard/rocky seabeds; penetration-resistant substrates	Simple installation; suitable when embedment infeasible	Large weight for high loads; potential scour issues in sandy or mobile seabeds	Li et al. (2024)
Pile Anchors (Driven/Drilled)	Dense sands; rock; steep slopes	High stiffness and long-term reliability; effective in harsh wave climates	High installation cost; requires heavy equipment and seabed penetration capability	Naiborhu et al. (2025)

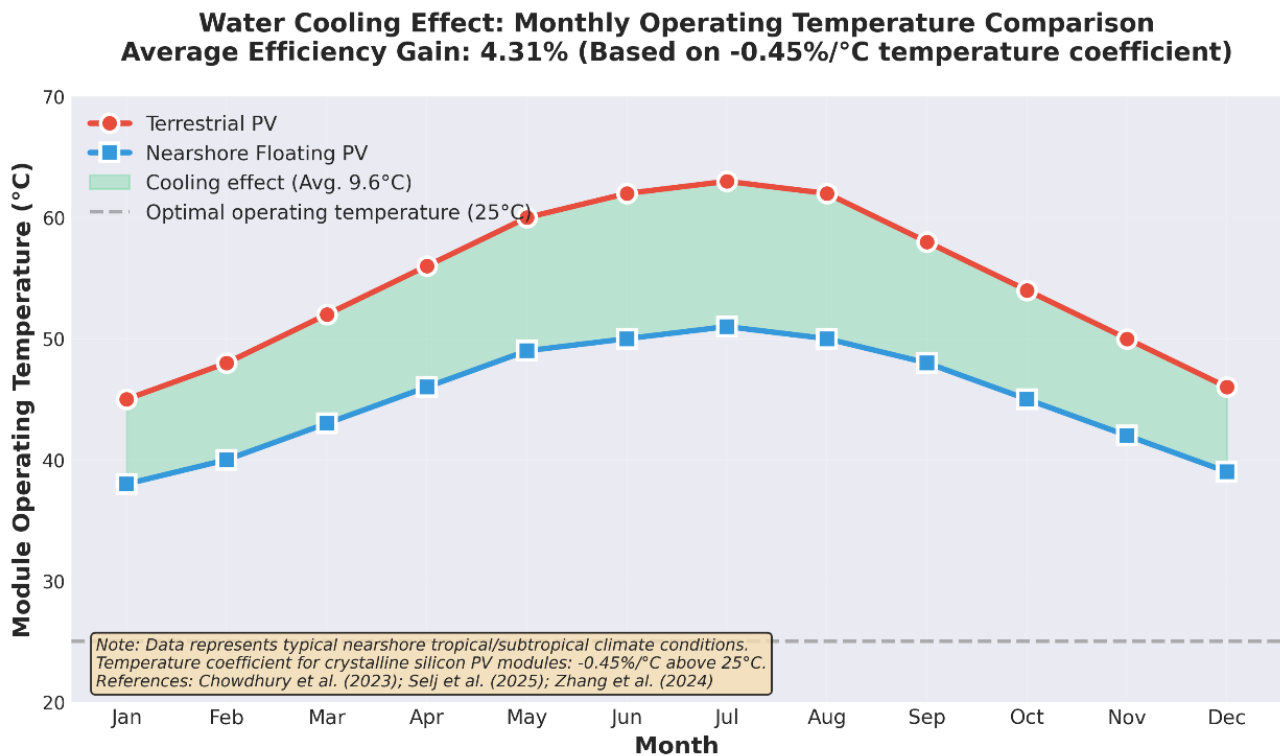


Figure 6 Water cooling effect- monthly operating temperature comparison ($^{\circ}\text{C}$).

3.3.2 Albedo effects and bifacial module performance

Water surface albedo (the fraction of incident solar radiation reflected by a surface) typically ranges from 0.05 to 0.15, varying with sun elevation, wave state, and water clarity. Bifacial N-FPV modules capture reflected irradiance on their rear surface, achieving rear-side efficiencies of 70 - 95 % relative to the front surface; combined with diffuse sky irradiance, this contributes 5 - 15 % additional yield over monofacial configurations, subject to module height, tilt, and local albedo conditions. As shown in **Figure 7**, these three geometric parameters- module height, inter-row spacing, and tilt angle- require joint optimization via computational ray-tracing models to maximize rear-side irradiance capture while controlling shading losses (Chowdhury et al., 2023).

3.3.3 Operational performance and capacity factor

N-FPV systems achieve capacity factors of 15 - 25 %, matching or exceeding ground-mounted PV at equivalent latitudes. Reduced soiling and natural rainfall cleaning offset losses from salt-spray crystallization, yielding a net 2 - 6 % capacity factor advantage (Ilgen et al., 2023; Zhang et al., 2024). Higher coastal wind speeds augment cooling efficiency but introduce salt aerosol and mechanical stress risks. **Table 6** represents the capacity factors of photovoltaic modules across different regions of the world, showing the strong performance of N-FPV systems under different climatic conditions.

3.3.4 Motion-induced performance losses

Dynamic movements, such as those induced by waves, can create deviations in panel tilt and azimuth, thus affecting irradiance capture since floating solar platforms are not perfectly aligned with optimal conditions (Magkouris et al., 2023). According to theoretical studies, deviations in pitch movements of $\pm 5^{\circ}$, which are commonly experienced in moderate sea conditions, can result in an average irradiance loss of 2 - 3 %. Higher deviations of $\pm 10^{\circ}$ can lead to greater loss of 8 - 10 %. Field studies on floating solar platforms placed in nearshore waters have also supported these studies,

showing losses of 3 - 7 % during storm conditions with wave heights greater than 2 m, while losses are less than 2 % during regular conditions with waves less than 1 m in height (Zhang et al., 2024). Thus, these movements can create secondary losses, especially in relation to other factors like temperature and optical effects. Hydrodynamic stability, including proper stiffness and damping properties of the mooring system, is required to ensure minimal losses, especially in platforms placed in regions with high wave conditions (Li et al., 2024; Ji et al., 2025).

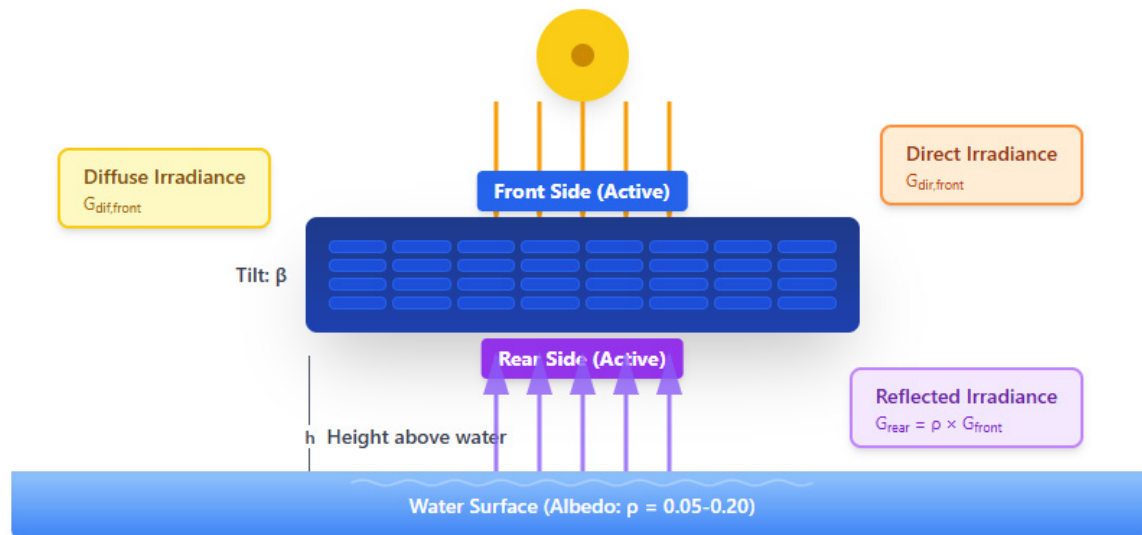


Figure 7 Bifacial module configuration diagram for nearshore FPV systems illustrating three key geometric design parameters: module height above water surface (m), inter-row spacing (m), and panel tilt angle (°). These parameters jointly govern rear-side irradiance capture from water-surface albedo reflection (typical albedo: 0.05 - 0.15) and diffuse sky irradiance. Rear-side efficiencies of 70 - 95 % of front-side performance contribute 5 - 15 % additional annual energy yield over monofacial configurations, depending on site-specific albedo conditions and array geometry.

Table 6 Capacity factor comparison by region: nearshore FPV vs terrestrial PV systems.

Region / Climate	Nearshore FPV Capacity Factor (%)	Terrestrial PV Capacity Factor (%)	Key Drivers of FPV Advantage	Representative References
Tropical (SE Asia)	18 - 25	15 - 20	Lower soiling, enhanced cooling, higher wind speeds	Zhang et al. (2024); Ilgen et al. (2023)
Subtropical (East Asia)	17 - 23	14 - 19	Reduced dust load, periodic natural cleaning	Ilgen et al. (2023)
Mediterranean	16 - 22	14 - 18	Cooling benefit during summer peak temperatures	Chowdhury et al. (2023)
Temperate (Europe)	15 - 20	13 - 17	Better cooling + moderate albedo gains	Zhang et al. (2024)
Arid / Semi-Arid	17 - 21	12 - 16	Major soiling reduction vs. desert dust conditions	Chowdhury et al. (2023)

3.3.5 Cross-study synthesis: Energy performance

Water cooling provides the most consistently documented performance advantage, with 5 - 15 % efficiency gains and 5 - 11 °C rear-surface temperature reduction (Chowdhury et al., 2023; Zhang et al., 2024; Selj et al., 2025). The capacity factor also shows a 2 - 6 % advantage for floating PV compared to terrestrial PV (Ilgen et al., 2023; Zhang et al., 2024). The thermal advantage is somewhat reduced due to motion-induced performance losses, which reach 3 - 7 % during storms, although these are reduced to below 2 % under typical conditions (Magkouris et al., 2023; Zhang et al., 2024). The albedo contribution remains the most contested gain: although rear-side efficiencies of 70 - 95 % are reported, the net yield increase of 5 - 15 % varies widely with module design and no standardized test methodology exists (Chowdhury et al., 2023). Most notably, the performance data from the literature are mostly simulated using CFD tools or short-term measurements in controlled environments, while long-term performance monitoring data from operational floating PV installations are not available. The combined effects of biofouling, salt-spray-induced soiling, and degradation on long-term performance have not been quantified in any study, which is a significant gap in the field. As shown in **Figure 8**, a quantitative performance summary is presented from the literature; (A) Efficiency gains: water cooling (5 - 15 %), albedo (5 - 15 %), and capacity factor advantage (2 - 6 %); (B) Performance factors: motion-induced performance losses (3 - 7 % and <2 %), and temperature reduction (5 - 11 °C); (C) Mooring optimization: tension reduction using hybrid mooring (30 - 38 %), six-point mooring compared to three-point mooring (20 - 25 %), and hinged compared to rigid mooring (40 - 60 %).

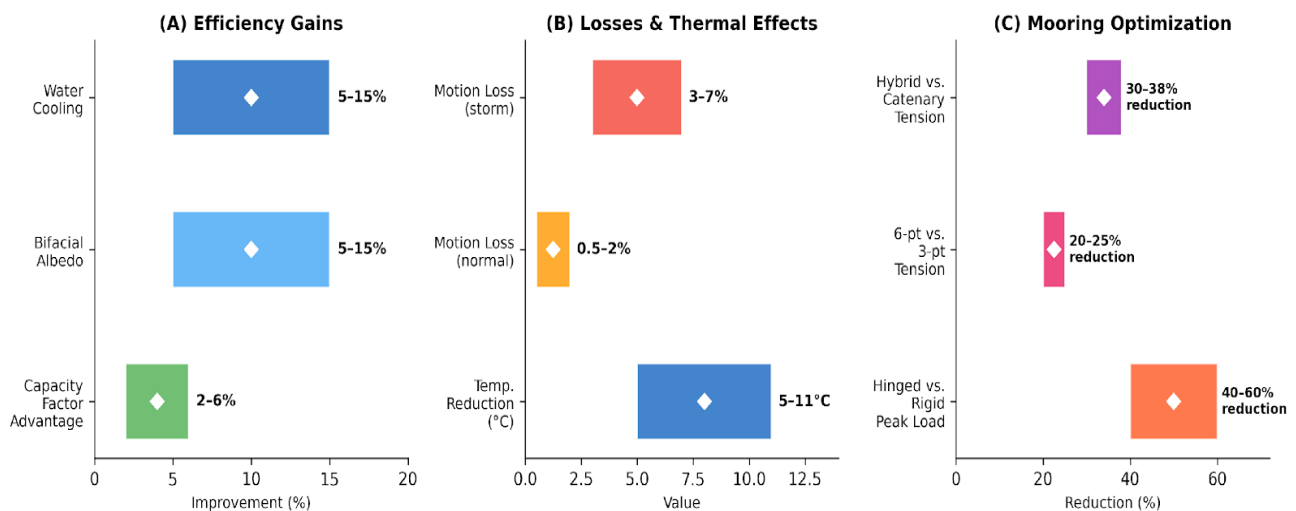


Figure 8 Quantitative energy performance and structural summary synthesized from reviewed literature. (A) Energy performance gains relative to land-based PV: water cooling efficiency improvement (5 - 15 %), bifacial rear-side albedo gain (5 - 15 %), and capacity factor advantage (2 - 6 %) (units: % improvement relative to land-based PV). (B) Performance limiting factors: wave-induced power losses during storm conditions (3 - 7 %) and normal operation (<2 %), and rear-surface module temperature reduction (5 - 11 °C). (C) Structural optimization outcomes: mooring tension reductions from hybrid versus catenary configurations (30 - 38 %), six-point versus three-point mooring arrangements (20 - 25 %), and hinged versus rigid inter-module connections (40 - 60 %) (units: % reduction in peak tension). Horizontal bars indicate reported ranges; diamond markers indicate range midpoints.

3.4 Grid integration

The integration of electrical power from N-FPV systems into the utility grid distribution network involves consideration of various technical aspects, as identified in Jiang et al. (2023). Unlike other ground-mounted solar power systems, where integration with the grid is often done through simple trenching of cables over a very short distance to reach existing grid infrastructure, there is a need for specialized underwater cables, remote power conditioning units, sometimes mounted on the floating platforms themselves, and maritime electrical safety standards, which address safety concerns related to the electrical and aquatic environment (Jiang et al., 2023; Ringwood, 2022).

3.4.1 Underwater cable systems and power transmission

The integration of N-FPV power plants into the grid requires specific infrastructure that is different from traditional land-based solar power plants. Such infrastructure includes submarine cables, maritime power conditioning equipment, and compliance with maritime electrical safety standards (Jiang et al., 2023). Submarine cables are designed for carrying electrical power from floating platforms to shore-based integration points and require multi-layer construction for ensuring electrical integrity under saline and dynamic loading conditions due to the movement of floating platforms. Submarine cables need to avoid regions of strong currents and dense maritime traffic and usually involve dynamic cables, fixed cables on the seabed, and shore-based cables (**Figure 9**). Dynamic submarine cables require fatigue resistance to ensure long lifetimes of millions of cycles. Another design consideration is related to the placement of inverters on platforms and shores, where it is essential to balance electrical losses and harsh maritime conditions. For large-scale integration, HVDC is often employed for transmitting power over long distances of up to several kilometers, and its configuration is dependent on economic considerations (Jiang et al., 2023; Zhang et al., 2024). Grid integration of large-scale solar power plants becomes more complicated with increasing penetration of solar power, and it may require additional infrastructure, storage, and cooperation between developers and utilities (Zhang et al., 2024).

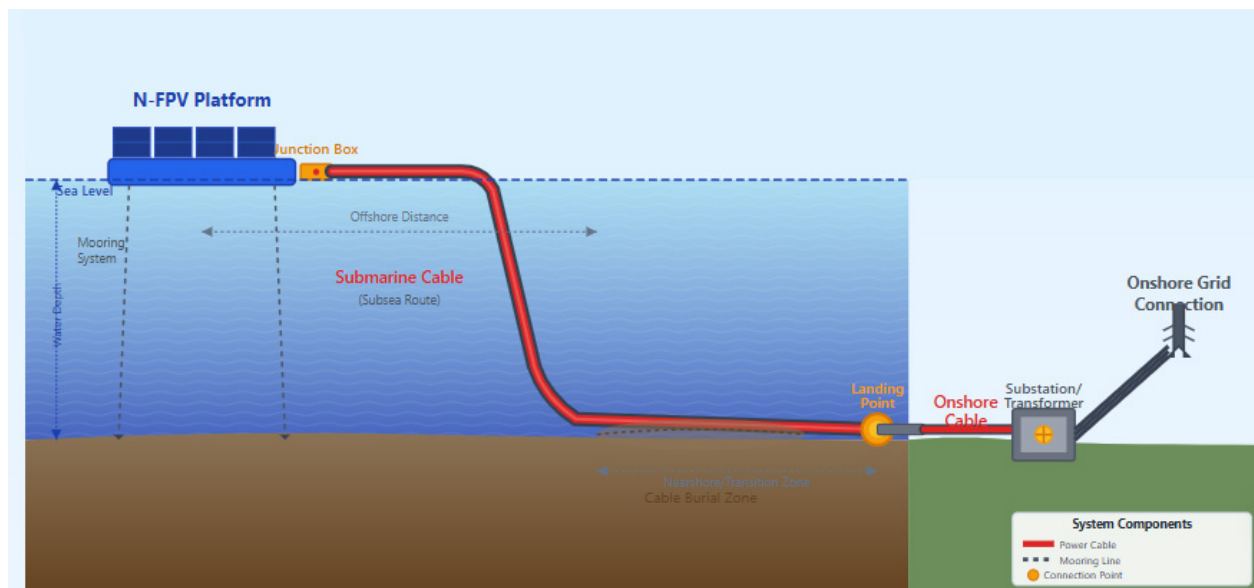


Figure 9 Submarine cable routing schematic for nearshore FPV grid connection, illustrating the three-zone transition: (1) dynamic floating cable section connecting the FPV platform to a fixed seabed cable (water depth: 5 - 30 m), (2) fixed seabed cable routed to the shoreline along a path avoiding high-current zones and marine traffic lanes, and (3) onshore cable termination and grid interconnection point. Dynamic sections employ fatigue-resistant designs rated for millions of load cycles over a 20 - 25 year service life. Inverter placement options (onboard platform or onshore) affect transmission losses and maintenance accessibility.

3.4.2 Cross-study synthesis: Grid integration

The theme of grid integration is the least explored among all the articles reviewed in this chapter, with only a single article by Jiang et al. (2023) providing in-depth technical information on submarine cable systems, power conditioning, and grid synchronization techniques for nearshore floating photovoltaic (FPV) systems. This is due to the fact that nearshore FPV systems are still in their early stages of development, with most research work being carried out on the design and development of platforms and mooring systems rather than electrical systems. Although Zhang et al. (2024) discuss voltage regulation and grid compatibility issues in general terms, there is no study that provides in-depth information on the power quality of operational nearshore FPV systems, including the level of harmonic distortion, voltage fluctuation, and fault ride-through performance. In addition, there is no study that compares the performance of different inverter configurations on board and onshore in terms of real-life marine environment conditions, as this aspect plays a very important role in determining the overall cost of ownership of nearshore FPV systems. Furthermore, there is no study that assesses the implications of integrating nearshore FPV systems on the distribution grid level, considering the fact that grid proximity is one of the most important advantages of nearshore FPV systems compared to their offshore counterparts (Bai et al., 2024; Joshi et al., 2023).

3.5 Technical challenges and innovations

The deployment of nearshore floating photovoltaic (N-FPV) systems on a large scale involves addressing a variety of technical challenges related to materials, structural design, maritime operations, and environment management. Some of these challenges are similar to those of inland floating photovoltaic, but they are more pronounced in the nearshore marine environment. Current research and development activities are improving technologies for greater reliability, cost reduction, and environment friendliness (Selj et al., 2025).

3.5.1 Material durability and corrosion management

The long-term durability of the materials in the marine environment is still a major challenge for N-FPV systems. The saltwater environment accelerates the degradation rate of materials due to electrochemical corrosion in metallic components, such as aluminum frames and steel mooring hardware, and due to exposure to UV radiation in polymeric components, such as HDPE floats and XLPE cable insulation, which is more severe than in the freshwater environment (Jiang et al., 2023). The mitigation strategies for metallic components include using corrosion-resistant alloys, coatings, cathodic protection, and regular inspections, while polymeric components can make use of modern-day additives and formulation enhancements, which provide improved resistance to both UV radiation and saltwater exposure (Li et al., 2024). The submarine cables and connectors also face exposure to moisture, resulting in dielectric breakdown, fatigue due to cyclic bending, and exposure to abrasive action from the seabed, which require multi-layer cables and fatigue-resistant materials (Jiang et al., 2023; Ma et al., 2024). The sealants and adhesives are also prone to hydrolytic degradation in the saltwater environment, requiring special formulations and regular inspections (Li et al., 2024). These mitigation strategies have already been proven in the field of material science, but their efficacy in the real environment has not been proven for nearshore FPV systems, as discussed in the cross-study synthesis (Section 3.5.5).

3.5.2 Biofouling accumulation and mitigation

Biofouling of submerged components of N-FPV, which can be caused by bacteria, algae, mollusks, and crustaceans, can lead to an increase in hydrodynamic drag, mass, reduced freeboard, and wave overwash. Fouling of electrical connectors can compromise the seals. Rapid colonization was observed during the Dutch North Sea pilot project, where over 40 species, including barnacles and mussels, were identified. Biofouling can have positive effects, such as those of artificial reefs,

but operational effects require management. Copper-based coatings are effective but have been found to have potential risks of metal leaching. Non-toxic coatings include foul release silicone coatings, biomimetic coatings, and UV-resistant coatings. Active management, including the use of remotely operated vehicle (ROV)-assisted and diver-assisted cleaning, ensures effective management but increases operational costs (Mavraki et al., 2023).

3.5.3 Monitoring systems and predictive maintenance

The installation of these N-FPV systems at an offshore location poses difficulties for inspection and repair, leading to the need for developing more advanced inspection methodologies. Current methodologies rely on distributed sensors for monitoring various parameters, including mooring tensions, motions of the platforms, strain on structures, and environmental conditions. These measurements can be employed for developing predictive capabilities and reducing overall lifecycle costs of these structures. Digital twin-based platforms combine numerical simulations and actual sensor measurements for facilitating predictive capabilities and scenario-based forecasts of system performance. Machine learning algorithms can identify minor precursors of failures before they actually happen. Wireless sensor networks, powered by compact photovoltaic and/or thermoelectric-based harvesting devices, are promising for reducing overall lifecycle costs. However, there is a need for careful engineering of these devices for ensuring water resistance and communication capabilities (Ma et al., 2024).

3.5.4 Standardization and design code development

The emerging nature of N-FPV technology in terms of standardization of design approaches, performance parameters, passive control techniques, and safety standards creates uncertainty and contributes to investment risks in N-FPV technology development. In this context, passive control techniques in the design of offshore structures, such as the use of tuned mass dampers (TMD) in compliant structures, have shown promising potential applicability to N-FPV technology. TMD can effectively control wave-induced pitch and surge motions at resonant frequencies and can be used in conjunction with mooring stiffness adjustment with minimal design complexity (Suja & Chandrasekaran, 2025). In comparison to other mature offshore renewable energy technologies, such as wind energy, which has clear international design standards and codes, N-FPV technology development lacks unified design standards and approaches, leading to inconsistent engineering approaches and difficulties in obtaining funding and approval (Selj et al., 2025).

In this context, several international and classification-body standards are currently used- in full or by analogy- to guide N-FPV design, certification, and operation. No international standard dedicated exclusively to FPV has yet been published; designers therefore apply a combination of terrestrial PV module standards, marine-environment test standards, and FPV-specific recommended practices, most notably DNV-RP-0584, which explicitly addresses near-shore deployments. The principal references are summarized below (Wu et al., 2024; Jiang et al., 2023; Selj et al., 2025).

IEC standards (module, safety, and commissioning):

- **IEC 61215-1/-2-** Terrestrial PV module design qualification and type approval (baseline applied to FPV modules)
- **IEC 61730-1/-2-** PV module safety qualification (construction and testing)
- **IEC 61701-** Salt mist corrosion testing of PV modules (critical for nearshore exposure)
- **IEC 60068-2-52-** Salt mist cyclic environmental testing for components
- **IEC 62109-1/-2-** Safety of power converters for PV systems
- **IEC 62446-1-** Grid-connected PV: commissioning and periodic inspection
- An IEC Technical Specification for FPV is currently under development by IEC TC 82 WG

3.

DNV standards and classification-society references:

- **DNV-RP-0584 (2021)**- Design, development and operation of floating solar photovoltaic systems (primary FPV recommended practice; applicable to sheltered near-shore sites)
- **DNV-RP-C205**- Environmental conditions and environmental loads (wind, wave, current)
- **DNV-OS-C101**- Design of offshore steel structures, general
- **DNV-OS-E301**- Position mooring
- **Bureau Veritas NR 673**- Certification of floating offshore PV installations
- **Lloyd's Register ShipRight (FPV)**- FPV-specific certification procedures
- **Singapore TR 100:2022**- Floating photovoltaic power plants- Design guidelines and recommendations (widely cited national reference)

3.5.5 Cross-study synthesis: Technical challenges

The literature under review identifies material durability, biofouling, and standardization as the key technical challenges for nearshore floating photovoltaic (N-FPV) deployment, though evidence for each of these is limited. Though Jiang et al. (2023) and Li et al. (2024) present detailed accounts of degradation mechanisms and mitigative measures for metallic and polymeric materials, these are based on material science principles and accelerated testing rather than actual field evidence of deployed nearshore floating photovoltaic devices. Similarly, evidence for biofouling is based on a single study carried out in the Dutch North Sea (Mavraki et al., 2023), and its general applicability to other climatic and water conditions is limited. However, all these studies agree that the absence of unified design guidelines is a fundamental impediment for large-scale deployment and funding (Selj et al., 2025; Wu et al., 2024; Jiang et al., 2023), though design guidelines for nearshore floating photovoltaic devices are yet to be developed and released by IEC and classification society authorities. Notably, there is a lack of research on digital twin applications and machine learning-based predictive maintenance techniques validated for nearshore floating photovoltaic devices, though these have been identified as promising technologies (Ma et al., 2024). Overall, Section 3 of this chapter reveals that there is a preponderance of numerical simulation and laboratory testing of nearshore floating photovoltaic devices, and there is a need for actual field evidence of these devices for design validation.

4. Drivers, impacts, and case studies

4.1 Deployment drivers

Nearshore floating photovoltaic (N-FPV) roll-out is driven by the convergence of technical, environmental, and economic factors, the relative importance of which varies depending on the geographical area (Wu et al., 2024). **Figure 10** summarizes the relative influence of each driver category.

4.1.1 Technical drivers

Land scarcity in densely populated coastal areas is a major technical driver, as the competition for land usage limits the possibility for conventional solar growth (Bai et al., 2024). The geographical proximity of N-FPV systems to coastal load centers allows for the generation of electricity closer to demand centers, thus minimizing transmission losses (Bai et al., 2024). This is especially true for island nations and coastal city-states. Water surface dual-use compatibility with aquaculture and hydropower provides additional co-benefits (Joshi et al., 2023; Lopez et al., 2024).

4.1.2 Environmental drivers

Several nations have incorporated specific floating PV capacity targets into their renewable energy strategies, driven by GHG reduction obligations (Bai et al., 2024; Joshi et al., 2023). Water

conservation is another factor, considering the 30 - 50 % reduction in evaporation due to the application of floating PV, whereby covering 10 % of China's water bodies measuring more than 1 km² can conserve 5 billion cubic meters of water annually (Bai et al., 2024). Moderate coverage can also help in reducing the occurrence of algal blooms, but their ecological significance is observed at coverage greater than 10 - 15 % of the water body's surface area (Benjamins et al., 2024). Coverage effects on light penetration, dissolved oxygen, and water temperature are discussed in Section 4.2 (Ilgen et al., 2023). **Figure 11** quantifies these ecological impacts across coverage levels, biofouling dynamics, and overall risk–benefit balance. Navigation, fisheries, and aesthetic impacts require stakeholder engagement and equitable co-ownership models to achieve social acceptability (Benjamins et al., 2024; Wu et al., 2024).

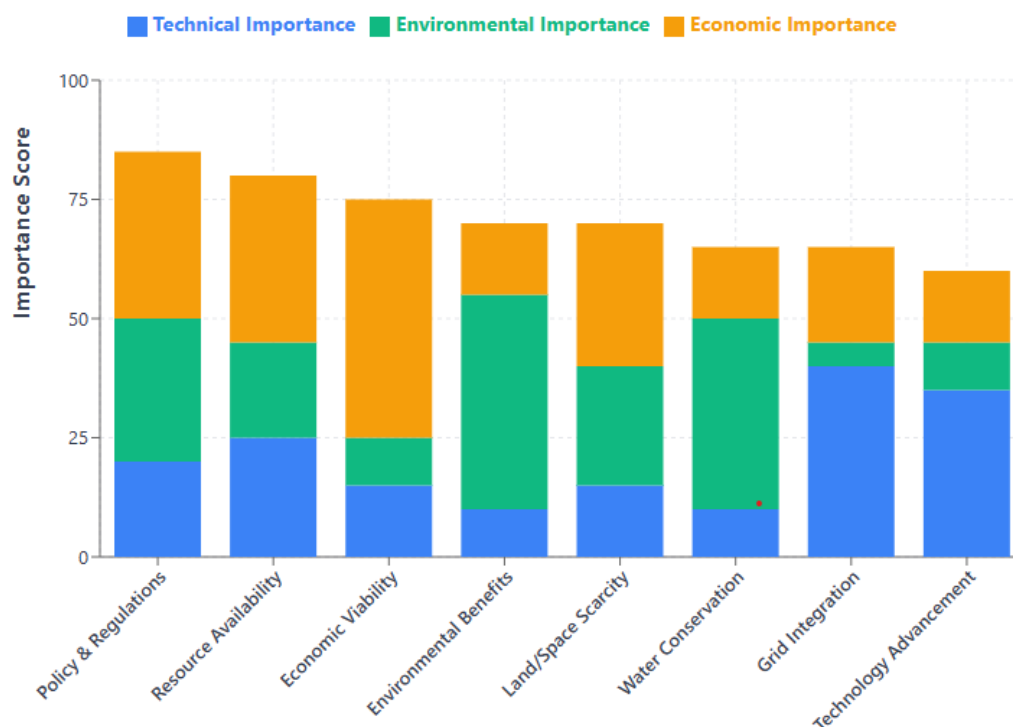


Figure 10 Relative importance ranking of N-FPV deployment drivers across technical, environmental, and economic categories, synthesized from the 33 reviewed studies. Importance is expressed on a qualitative five-point scale (1 = minor influence to 5 = critical influence) based on citation frequency and emphasis in the reviewed literature. Policy support, solar resource availability, and economic viability (LCOE reduction) consistently ranked as the three most influential drivers across all geographic contexts. Land scarcity and grid proximity were most influential in Southeast Asian and island settings, while environmental co-benefits ranked higher in European studies with stringent sustainability requirements.

4.1.3 Economic drivers

The reduction in levelized cost of electricity (LCOE) is the primary economic driver. The techno-economic studies have shown that the LCOE varies from 250 EUR/MWh (approximately 271 USD/MWh) in favorable locations in Southern Europe, 400 - 440 EUR/MWh (approximately 433 - 476 USD/MWh) in intermediate locations such as the North Sea and Baltic Sea, and 650 EUR/MWh (approximately 703 USD/MWh) in Northern Europe (Martínez & Iglesias, 2024). The financial

incentives provided by governments, such as feed-in tariffs, production tax credits, and renewable energy certificates, are also major factors in bridging the economic gap. For example, Germany has introduced special auction models, and Southeast Asian countries have signed favorable power purchase contracts (Joshi et al., 2023). It is also observed from sensitivity analysis that a 20 % reduction in CAPEX due to technology maturation can result in a 15 - 18 % reduction in LCOE (Martínez & Iglesias, 2024). The avoided land costs are economic incentives, especially in urban coastal areas (Martínez & Iglesias, 2024; Bai et al., 2024).

To enable cross-study comparison, LCOE values reported in the reviewed literature were harmonized to a common basis of 2024 USD/MWh. Original values were converted from the reporting currency to USD using the annual average official exchange rate of the publication year (primary source: 1 EUR = 1.082 USD for 2024), with no additional CPI adjustment applied because all studies reporting LCOE for N-FPV were published between 2022 and 2025. **Table 7** reports the original currency, reporting year, and exchange-rate factor applied to each study, providing full transparency of the conversion process and enabling readers to re-harmonize against alternative base years or indices.

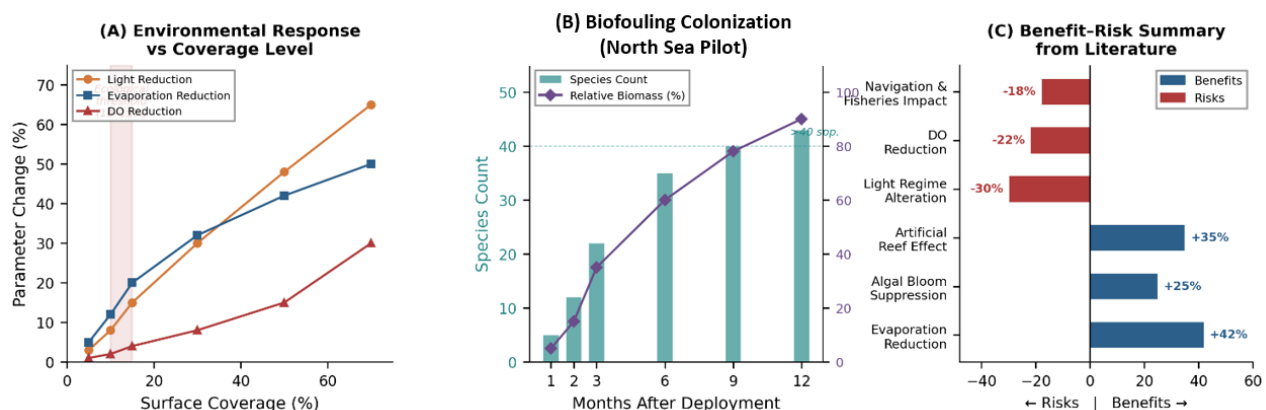


Figure 11 Synthesized environmental impact analysis of nearshore FPV systems. (A) Environmental parameter response as a function of surface coverage level: light reduction, evaporation reduction (30 - 50 % at high coverage; Bai et al., 2024), and dissolved oxygen (DO) reduction, with ecological significance threshold at 10 - 15 % coverage (Benjamins et al., 2024; Ray et al., 2024). (B) Biofouling colonization timeline at the Dutch North Sea pilot site, documenting >40 species within 12 months (Mavraki et al., 2023). (C) Environmental benefit-risk summary synthesized from reviewed literature, showing relative magnitude of documented positive and negative impacts.

As shown in **Figure 12**, N-FPV LCOE (250 - 650 EUR/MWh; 271 - 703 USD/MWh) remains substantially above terrestrial PV (37 - 46 EUR/MWh) and offshore wind benchmarks. Net present value (NPV) studies indicate economic viability only in some jurisdictions in Southern Europe, including Spain, Turkey, and Italy. Additional revenue streams, including the value of water savings, capacity value based on peak demand correlations, and carbon credits above 50 EUR/ton CO₂ (or 54 USD/ton CO₂), are found to have positive effects on the economic viability of floating solar but are still insufficient to offset the cost of energy differentials (Bai et al., 2024; Martínez & Iglesias, 2024). All EUR-USD conversions are based on the 2024 annual average exchange rates, 1 EUR = 1.082

USD. **Figure 12** shows comparative ranges of LCOE values and capital cost structures for nearshore floating solar, offshore floating wind, terrestrial solar, and other renewable technologies.

Table 7 Harmonized levelized cost of electricity (LCOE) values across the reviewed N-FPV and comparator studies. All harmonized values are expressed in 2024 USD/MWh.

Source	Region / System	Original LCOE	Original Currency	Reporting Year	Exchange Rate to USD	Harmonized (2024 USD/MWh)
Martínez and Iglesias (2024)	Southern Europe (Atlantic)- N-FPV	250	EUR/MWh	2024	1 EUR = 1.082 USD	271
Martínez and Iglesias (2024)	North Sea & Baltic- N-FPV	400 - 440	EUR/MWh	2024	1 EUR = 1.082 USD	433 - 476
Martínez and Iglesias (2024)	Northern Europe- N-FPV	650	EUR/MWh	2024	1 EUR = 1.082 USD	703
Martínez and Iglesias (2024)	EU benchmark- Terrestrial PV	37 - 46	EUR/MWh	2024	1 EUR = 1.082 USD	40 - 50
Benchmark: Martínez and Iglesias (2024)	Fixed-bottom offshore wind	46 - 92	EUR/MWh	2024	1 EUR = 1.082 USD	50 - 100
Benchmark: Martínez and Iglesias (2024)	Floating offshore wind	69 - 138	EUR/MWh	2024	1 EUR = 1.082 USD	75 - 150
Synthesized case-study range	Nearshore pilots (Section 4.3)	360 - 650	EUR/MWh	2021 - 2024	1 EUR = 1.082 USD	390 - 703

Note: Where a study reported LCOE in a currency other than USD, and at a year other than 2024, conversion used the annual average official exchange rate of the reporting year. Because the reporting window is short (2021 - 2024), and N-FPV cost data are themselves forward-looking projections, CPI adjustment was not applied; published values are treated as constant to their reporting year.

4.1.4 Cross-study synthesis: Deployment drivers

Studies converge on three primary N-FPV deployment drivers: land scarcity, policy incentives and renewable targets, and declining technology costs (Bai et al., 2024; Joshi et al., 2023; Wu et al., 2024). LCOE dominates economic assessment: N-FPV at 250 - 650 EUR/MWh (271 - 703 USD/MWh) remains well above terrestrial PV at 40 - 50 EUR/MWh (43 - 54 USD/MWh) (Martínez & Iglesias, 2024). Co-benefits such as water conservation, algal bloom reduction, and coastal employment are acknowledged across multiple studies (Ramanan et al., 2024; Benjamins et al., 2024; Bai et al., 2024), yet none have quantified these through a formal cost–benefit framework. Social license and community engagement remain under-examined despite evidence of their significance as deployment barriers (Jokhu et al., 2025; Benjamins et al., 2024). Developing a standard methodology for calculating levelized cost of energy for nearshore floating photovoltaic technology would greatly benefit future research works.

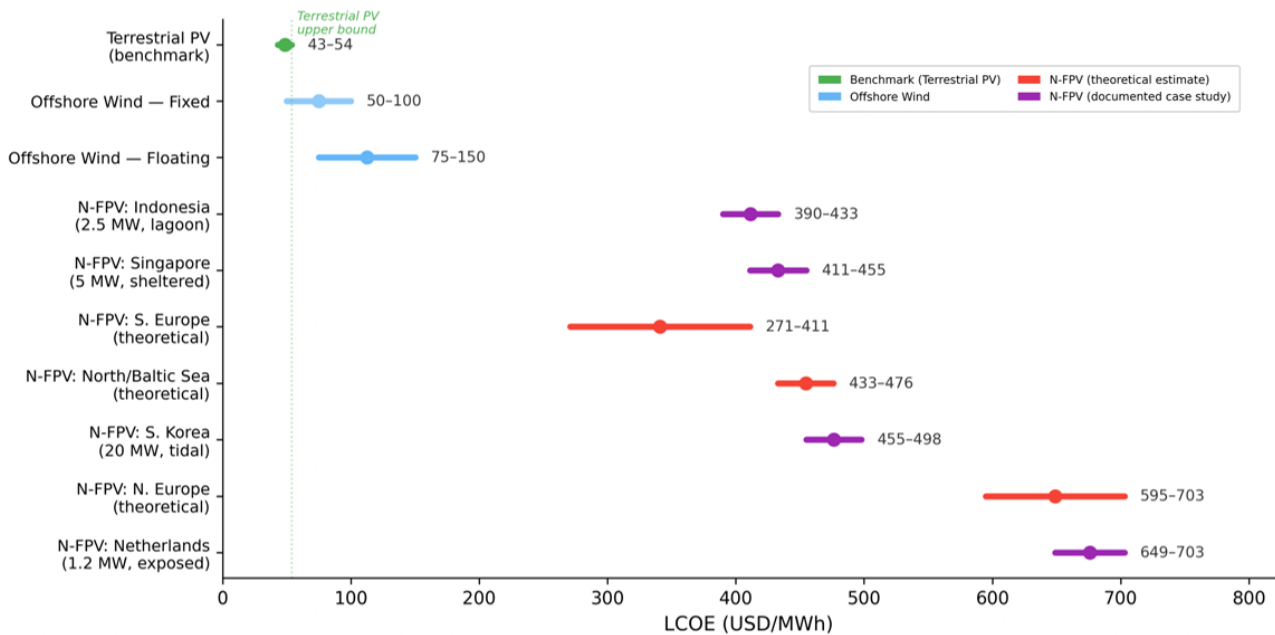


Figure 12 Harmonized levelized cost of electricity (LCOE) comparison across nearshore FPV deployments and benchmark renewable technologies (units: EUR/MWh; USD/MWh equivalent in parentheses using 2024 annual average exchange rate of 1 EUR = 1.082 USD). Left panel: LCOE ranges for nearshore FPV by region (250 - 650 EUR/MWh; 271 - 703 USD/MWh) versus terrestrial PV (37 - 46 EUR/MWh; 40 - 50 USD/MWh), fixed-bottom offshore wind (46 - 92 EUR/MWh; 50 - 100 USD/MWh), and floating offshore wind (69 - 138 EUR/MWh; 75 - 150 USD/MWh). Right panel: N-FPV capital cost breakdown by component category (%). All values derived from Martinez & Iglesias (2024), Bai et al. (2024), and Ramanan et al. (2024).

4.2 Benefits and limitations

The comprehensive evaluation of N-FPV technology involves the identification of its favorable attributes and limiting factors. The importance of each of its favorable and limiting factors depends on its application scenario. The following subsections will assess its direct and indirect benefits and limitations based on the discussed evidence in Section 4.2.1 and Section 4.2.2, respectively.

4.2.1 Direct benefits and indirect benefits

The enhanced energy yield due to the cooling effect of water cooling is the first major direct benefit, which has been found to be around 0.6 - 4.4 % more energy generation, and 0.1 - 4.45 % more efficiency, when compared with the energy generation on land (Ramanan et al., 2024). The benefits of these floating solar farms would be more pronounced during the peak summer season. The reduction of evaporation from the surfaces would also have co-benefits for areas where water scarcity is a major problem (Bai et al., 2024). The indirect benefits include the possibilities of controlling the growth of harmful algae due to the provision of shade for the water bodies, which would be more pronounced for eutrophic water bodies, though excessive coverage would also have the side effect of reduced dissolved oxygen levels (Benjamins et al., 2024). The employment generation for the coastal areas would also be an indirect benefit, which would be more pronounced for areas where the traditional marine industry has declined (Joshi et al., 2023).

4.2.2 Direct limitations and indirect limitations

Elevated capital costs represent the key limitation for nearshore floating photovoltaic deployment. Current analyses report premiums of 10 - 25 % due to floating structures, marine-grade

electrical equipment, robust mooring systems, and installation complexity (Martinez & Iglesias, 2024). LCOE remains well above grid parity (271 - 703 USD/MWh versus 43 - 54 USD/MWh for terrestrial PV), with floating structures and mooring representing 38 - 51 % of total capital cost. Technological limitations regarding long-term reliability under harsh marine conditions represent key operation risks for floating photovoltaic deployment, with limited field deployment and operation generating uncertainty regarding lifespan and degradation rates. Saltwater corrosion, biofouling, and wave-induced fatigue require conservative design allowances (Selj et al., 2025), and wave motions cause 3 - 7 % power losses under normal conditions (Magkouris et al., 2023). Regulatory uncertainty is compounded by overlapping maritime, environmental, water, and electricity jurisdictions, creating permitting complexity in most coastal markets (Wu et al., 2024). The public acceptance barriers and stakeholder resistance from commercial fisheries, recreation, and environmental groups are also major barriers to the timely deployment of this technology, owing to concerns about navigational safety, visual impacts, and access equity (Benjamins et al., 2024). Inadequate insurance products- neither conventional marine nor terrestrial renewable policies fully cover N-FPV risk profiles- add further cost premiums (Joshi et al., 2023).

4.2.3 Cross-study synthesis: Benefits and limitations

The N-FPV benefit-limitation profile is characterized by well-documented short-term technical benefits alongside unresolved long-term viability uncertainties. The most clearly documented benefit is increased thermal efficiencies of 5 - 15 %, as consistently documented by independent studies using different approaches and methods (Chowdhury et al., 2023; Ramanan et al., 2024; Ilgen et al., 2023). Land-use avoidance and reduction in evaporation losses of 30 - 50 % are also consistently documented as benefits of N-FPV systems (Bai et al., 2024). The principal limitations of N-FPV systems are consistently identified as higher capital costs (a 10 - 25 % premium) and regulatory and reliability concerns; however, these are variably quantified in existing literature (Martinez & Iglesias, 2024; Selj et al., 2025; Joshi et al., 2023). The most striking observation is that most of the benefits are based on short-term measurements and assessments, while most of the limitations are long-term phenomena that are not yet well understood, and for which long-term data are not yet available. No comprehensive lifecycle assessment simultaneously addressing energy savings, maintenance costs, environmental consequences, and end-of-life treatment has yet been published for N-FPV systems.

4.3 Case studies

Operational experience from pioneering N-FPV installations informs design methodology, policy, and regulatory development. The 5 MW Singapore Woodlands installation is the most comprehensively documented case, demonstrating acceptable hydrodynamic response, a 10 % cooling-related energy gain, and LCOE aligned with financial models- though still above grid parity and requiring long-term PPA support (Zhang et al., 2024). The technical performance validation provides useful evidence to support the design prediction with regard to the hydrodynamics, with the observed motion response to the operational wave loading within the acceptable range, and the energy output exceeding the predicted values, thus providing useful evidence to support the anticipated efficiency improvement concerning the water cooling effects (Zhang et al., 2024). The economic assessment of the installation provides useful evidence that the installation achieved the desired levelized cost, thus meeting the financial modeling prediction, though remaining higher than the grid parity, and therefore necessitating the long-term power purchase agreement support (Zhang et al., 2024).

The 2.1 GW Saemangeum project (South Korea) is the world's largest planned N-FPV deployment; its phased approach (200 MW validation first) and bird-migration impact concerns illustrate the need for rigorous ecological site screening prior to large-scale commitment (Joshi et al., 2023). The Dutch North Sea pilot confirmed survivability in offshore-exposed conditions; biofouling

monitoring documented rapid species colonization with no catastrophic environmental effects (Mavraki et al., 2023). Indonesia's 192 MW Cirata floating photovoltaic installation is Southeast Asia's largest installation, deployed successfully through public-private partnerships and commissioned in 2023. **Table 8** represents a comparative analysis of various nearshore floating photovoltaic installation case studies implemented across different countries of Southeast Asia, namely, Thailand, Indonesia, Malaysia, etc., between 2021 and 2025.

Table 8 Summary of representative N-FPV case studies (2021 - 2025).

Country / Location	Installed Capacity (MW)	Water Depth (m)	Significant Wave Height, Hs (m)	Levelized Cost of Electricity (LCOE) (USD/MWh)	Cooling Gain (%)	Key Outcomes / Findings
Singapore – Woodlands Reservoir (2021)	5.0	5 - 8	0.3 - 0.5	411 - 455	8 - 12	First large-scale nearshore floating photovoltaic (N-FPV) pilot in tropical conditions. Demonstrated reliable operation under high irradiance with moderate wave motion; achieved 10 % energy yield gain from cooling effect and reduced evaporation by ~30 %.
South Korea – Saemangeum Tidal Zone (2022)	20.0	6 - 10	0.6 - 1.0	455 - 498	6 - 9	Utilized high-density polyethylene (HDPE) pontoon-type platforms with reinforced mooring. Proved structural stability under tidal range of 3 m; achieved positive grid integration results. Identified corrosion mitigation as major maintenance issue.
Netherlands – North Sea Pilot (2023)	1.2	12 - 15	1.5 - 2.5	649 - 703	4 - 6	Offshore-exposed nearshore prototype integrated with wind turbines. Validated survivability under 50-year storm load simulations. Economic feasibility limited by high mooring and cabling costs.
Indonesia – Bali Coastal Lagoon (2024)	2.5	4 - 6	0.4 - 0.7	390 - 433	9 - 14	Community-scale hybrid FPV-aquaculture system. High solar yield with 12 % efficiency gain due to cooling; enhanced fish productivity through moderated water temperature and algae control. Demonstrated socio-economic co-benefits.

4.3.1 Cross-study synthesis: Case studies

The extant case studies collectively suggest that nearshore FPV technology is technologically viable over a range of different geographical and environmental settings, from tropical Singapore to

temperate Dutch waters. The Singapore Woodlands project, for instance, at 5MW capacity, represents the most comprehensive case study to date, and suggests that design predictions for hydrodynamic performance and energy output can be validated, with the 10 % cooling-related energy gains reported representing the 5 - 15 % range reported within the extant literature (Zhang et al., 2024). However, a number of important limitations associated with the case study evidence base can be highlighted when cross-comparing the extant literature. First, all projects reported upon to date have been at demonstration or early operational stage, with no project yet reported with performance data exceeding three years. Second, the reported LCOE values for each case study range from 360 - 650 EUR/MWh, with the assumptions upon which each of these values is based reported inconsistently. Third, while the Dutch North Sea pilot reported upon within the extant literature reported upon environmental monitoring data (Mavraki et al., 2023), the majority of case studies report limited ecological data. Fourth, all case studies reported upon to date have been located within Asia and Northern Europe, with no reported nearshore FPV deployments within Africa, the Americas, or the Pacific Islands, despite these regions frequently being reported as having high deployment potential.

4.4 Research gaps and future directions

The cross-study synthesis presented throughout Sections 3 and 4 reveals a consistent pattern: while the fundamental technical feasibility of nearshore FPV systems has been established through numerical modeling, laboratory experimentation, and a limited number of demonstration projects, critical evidence gaps persist across multiple dimensions. The 20 specific gaps identified across preceding synthesis sections are consolidated below into four priority areas, each contrasting current knowledge with remaining unknowns.

4.4.1 Technical design and performance gaps

The most significant technical knowledge gap relates to the absence of long-term field performance data, with no peer-reviewed study reporting operational monitoring greater than five years in duration on any nearshore floating PV platform type (Section 3.1.5). No head-to-head field comparison of pontoon-type and membrane-type platforms exists, with the sole membrane study (Xiong et al., 2025) relying solely on numerical simulation. In the area of mooring engineering, while numerical optimization methods universally indicate that hybrid-type moorings with 35 - 45° spread angle are optimal (Section 3.2.4), no field validation of these design parameters has been conducted to date. Furthermore, the interaction between the accumulation rate of biofouling material on the mooring system over time and the redistribution of tensions has not been investigated, with high rates of biofouling colonization documented in nearshore environments (Mavraki et al., 2023).

The cumulative impacts of biofouling, salt spray soiling, and degradation have not been quantified in any of the reviewed works (Section 3.3.5). There is also no standardized test methodology for quantifying the gains from albedo due to reflection from the water surface. Grid integration and digital-twin predictive maintenance remain the least researched themes, with no field-measured power quality data and no study assessing distribution-level hosting capacity (Sections 3.4.2, 3.5.5). The rapid progress in the formulation of unified design standards by IEC and classification societies is also essential in limiting technical and financial risks. Priority actions include: multi-year instrumented monitoring at existing sites to calibrate design codes; controlled pontoon-versus-membrane field trials; and grid integration studies linking floating PV output characteristics to distribution hosting capacity.

4.4.2 Environmental interaction gaps

Environmental understanding of nearshore FPV deployment remains limited by geographic and time factors. For example, the available ecological monitoring information is only from a single

location, the Dutch North Sea pilot (Mavraki et al., 2023), with no study reporting environmental monitoring information over a period greater than three years (Section 4.3.1). These findings cannot be generalized across tropical, subtropical, or Southern Hemisphere conditions. All the case studies are from Asia and Northern Europe, with no nearshore FPV deployment information available from Africa, the Americas, and the Pacific Islands (Section 4.3.1), which are regularly identified as having considerable deployment potential. Cumulative ecological effects of multiple co-located installations, and impacts on migratory species, remain uninvestigated. Priority actions include: multi-site, multi-year ecological monitoring with standardized metrics (light, DO, primary productivity, benthos); pilot deployments in under-represented regions; and cumulative impact assessments for co-located installations in shared coastal ecosystems.

4.4.3 Economic and financial assessment gaps

The economic evaluation of nearshore floating photovoltaic (N-FPV) systems is hindered by the non-existence of a standardized levelized cost of energy (LCOE) approach. Inconsistent discount rates (5 - 10 %), lifetimes (20 - 25 years), currency units, and degradation models across studies preclude direct comparison (Section 4.1.4). In addition to standardizing the LCOE approach, no study has carried out a comprehensive cost-benefit analysis to incorporate the environmental externalities of water conservation value, suppression of algae blooms, and coastal employment generation with the direct energy generation costs. Moreover, no study has carried out a comprehensive life cycle analysis that incorporates energy generation, maintenance, environmental, and end-of-life effects of nearshore FPV systems simultaneously (Section 4.2.3). In addition, specialized insurance schemes that can handle new risks in marine renewable energy are underdeveloped, with traditional marine insurance policies not being able to capture the risk profile of floating photovoltaic systems (Section 4.2.3). Priority actions include: a nearshore-specific LCOE standard incorporating marine material and mooring costs; social cost-benefit analyses monetizing environmental co-benefits; cradle-to-grave lifecycle assessments validated against operational data; and joint development of N-FPV-appropriate insurance risk models with the insurance sector.

4.4.4 Regulatory and social acceptance gaps

No jurisdiction has established a purpose-built permitting framework for nearshore FPV; existing deployments navigate overlapping maritime, energy, and environmental regulations designed for other uses, generating procedural uncertainty and elevated development costs (Section 3.5.5). Furthermore, there is a need for multi-use maritime spatial planning guidelines for the integration of floating solar deployments with other nearshore activities, such as fishing, shipping, conservation, and recreation. Although Jokhu et al. (2025) highlight community engagement and social license as essential for nearshore floating photovoltaic deployment success, these topics have been subject to limited systematic investigation within the nearshore floating photovoltaic research domain, despite evidence of stakeholder opposition as a major deployment impediment (Benjamins et al., 2024).

4.4.5 Overarching methodological observation

This review reveals a pervasive reliance on simulation over field measurement of the 33 reviewed studies, most employ CFD, FEA, or analytical methods, while only four report primary operational field data (Zhang et al., 2024; Mavraki et al., 2023; Ilgen et al., 2023; Naiborhu et al., 2025). Simulation and laboratory work remain essential, but as the technology transitions to commercial scale, closing the simulation-to-reality gap is the overarching research priority.

5. Conclusions

This systematic review aggregates 33 peer-reviewed papers and presents the inaugural comprehensive review of nearshore floating solar photovoltaic systems (N-FPVs). N-FPVs are based on modular floating structures made of corrosion-resistant materials and mooring systems optimized for deployment in shallow water areas of nearshore regions. The water-cooling effect increases module efficiencies by 5 - 15 %, and hybrid mooring systems reduce peak tensions by 38 % compared to traditional catenary moorings. Capacity factors are between 15 - 25 %, but wave-induced losses of 3 - 7 % occur in energetic sea states. Levelized cost of energy (LCOE) estimates are between 271 - 703 USD/MWh (250 - 650 EUR/MWh) and are higher than traditional ground-mounted solar photovoltaic systems at 43 - 54 USD/MWh. However, potential savings of 20 % in capital expenditure (CAPEX) via technology maturity could reduce LCOE by 15 - 18 %. The evidence base for N-FPVs on ecological aspects is twofold: suppression of precipitation and evaporation reduction by 30 - 50 %, and inhibition of algal growth as positive ecological impacts are counterbalanced by ecological shifts and changes in dissolved oxygen profiles as negative ecological impacts. The case studies of N-FPVs in Singapore, Korea, Indonesia, and the Dutch North Sea demonstrate technical feasibility but also underscore the absence of long-term monitoring results, economic assessments, and permitting schemes. N-FPVs are a strategic opportunity for renewable energy and coastal resilience. The evidence gaps identified must be filled by long-term monitoring results, economic assessments of LCOE, ecological impacts of N-FPVs, and hybrid solar/wind/wave integration to advance N-FPVs from the demonstration phase to the sustainable commercial deployment phase.

Taken together, the evidence reviewed in Sections 3 and 4 indicates that nearshore floating photovoltaic systems occupy a technically and regulatorily distinct space between inland freshwater FPV and fully offshore marine PV, and this intermediate position is itself the source of many of the open research questions. Five priority directions emerge.

First, long-term structural and electrical reliability remains under-characterized: most reviewed studies report performance over months to a few years, whereas N-FPV projects require 25-year bankability under combined corrosion, biofouling, and cyclic hydrodynamic loading. Second, extreme-event survivability- particularly under typhoon, storm-surge, and steep nearshore wave conditions- is currently estimated from offshore-wind analogues rather than from N-FPV-specific field or basin data. Third, ecological impact at the coastal interface is documented for isolated indicators (shading, temperature, fouling) but not yet synthesized into full life-cycle assessments that reflect biodiversity-rich nearshore zones. Fourth, techno-economic transparency is limited; LCOE estimates vary widely due to heterogeneous assumptions on installation cost, O&M, and degradation, and standardized reporting conventions for N-FPV are still lacking. Fifth, standardization and permitting frameworks specific to N-FPV are nascent; while IEC TS 63163 and DNV-RP-0584 provide foundational guidance, nearshore projects continue to fall into a regulatory gap between inland-water and offshore regimes. Coordinated progress across these five fronts- reliability, survivability, ecology, economics, and governance- will be critical for N-FPV to move from pilot-scale demonstration to mainstream deployment in coastal energy systems.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI in scientific writing

During the preparation of this manuscript, the authors used AI tools (ChatGPT and Claude) for language refinement, grammar checking, and figure formatting assistance. No AI tools were used for data analysis, interpretation, or formulation of research conclusions. All outputs were critically reviewed and edited by the authors, who take full responsibility for the content and integrity of the work. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRediT Author Contribution Statement

Kornpaphop Ruttanawijit: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization, Project administration. **Yodchai Tiaple:** Conceptualization, Writing – Review & Editing, Methodology, Supervision, Funding acquisition, Project administration.

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Appendix

Table S1 Synthesis of reviewed literature on nearshore floating solar photovoltaic systems (N = 33).

No.	Author(s) & Year	Theme(s)	Methodology	Key Findings	Limitations
1	Bai et al. (2024)	TE, DD, EN	GIS-based techno-economic assessment; spatial analysis	Assessed FPV potential across China's water bodies (>1 km ²); 10 % coverage could conserve ~5 billion m ³ water annually; evaporation reduction of 30 - 50 %; identified high-potential deployment zones based on solar irradiance and water availability.	Focused on inland reservoirs; limited applicability to marine/nearshore conditions; did not model wave or mooring effects.
2	Benjamins et al. (2024)	EN, RE	Systematic literature review of environmental impacts	Shading effects ecologically significant when coverage exceeds 10 - 15 %; dissolved oxygen reductions documented under 70 % coverage; identified cascading food-web effects from altered light regimes; highlighted navigation safety and fisheries displacement concerns.	Predominantly based on freshwater studies; limited empirical data for marine/nearshore environments; long-term cumulative impact data lacking.
3	Cazzaniga (2020)	PD	Review of floating PV structural concepts	Classified FPV structures into pontoon, membrane, and modular types; outlined design principles for buoyancy, load distribution, and material selection; established foundational taxonomy for FPV platform engineering.	Focused on inland/calm-water applications; did not address marine-specific loads (waves, currents, salinity); no quantitative performance comparison across platform types.
4	Chowdhury et al. (2023)	EP	State-of-the-art review with CFD modeling analysis	Quantified temperature sensitivity of crystalline Si cells at -0.40 to -0.65 %/°C; floating systems operate 5 - 11 °C cooler at rear surface; efficiency gains of 5 - 15 % depending on design and climate; average 9.6 °C reduction in tropical settings equivalent to ~4.3 % efficiency gain.	Most CFD models not validated against marine field data; limited consideration of wave-induced cooling disruptions; albedo assumptions vary significantly across studies.
5	Ramanan et al. (2024)	EP, TE, DD	Comprehensive review of FPV advancements	Floating systems generate 0.6 - 4.4 % more energy with 0.1 - 4.45 % efficiency improvements vs. land-based PV; documented cooling benefits and extended equipment lifespan from moderated temperatures; identified water conservation as a significant co-benefit.	Primarily inland FPV focus; limited nearshore/marine-specific analysis; techno-economic data not harmonized across reviewed studies.
6	Joshi et al. (2023)	TE, DD, RE, CS	Technical potential assessment; policy and market analysis (NREL report)	Assessed FPV deployment potential for Southeast Asia; documented Saemangeum (S. Korea) and Cirata (Indonesia) case studies; identified policy incentives (feed-in tariffs, PPAs) as critical enablers; highlighted insurance product gaps as financing barriers.	Regional focus on SE Asia; LCOE estimates based on limited operational data; regulatory analysis may not generalize to other regions.
7	Garrod et al. (2024)	EP, PD	Comprehensive review of FPV systems and energy storage	Assessed FPV system integration with energy storage; documented that nearshore FPVs benefit from high solar irradiance and water cooling; land-use conflicts avoided through water-surface deployment.	Broad scope dilutes nearshore-specific insights; energy storage analysis primarily for inland contexts; limited quantitative marine performance data.

Table S1 (continued) Synthesis of reviewed literature on nearshore floating solar photovoltaic systems (N = 33).

No.	Author(s) & Year	Theme(s)	Methodology	Key Findings	Limitations
8	Ilgen et al. (2023)	EN, EP	Field measurement and numerical modeling of lake temperature impacts	Quantified FPV impact on water temperature and stratification; temperature sensitivity coefficient confirmed at -0.40 to -0.65 $^{\circ}\text{C}$; 2 - 6 % higher capacity factors for floating vs. collocated ground-mounted arrays; documented seasonal mixing pattern alterations.	Study conducted on freshwater lakes, not marine environments; limited to temperate climate conditions; short monitoring duration.
9	Ji et al. (2025)	HY, MO	Experimental (wave tank) and numerical simulation	Validated hydrodynamic responses of novel offshore FPV structure; established mooring stiffness criteria to maintain RAO below ~ 1.5 m/m (heave) and 3° /m (pitch); confirmed design methodology for combined wave-wind-current loading.	Tested under idealized wave conditions; scale effects not fully quantified; limited to specific platform geometry.
10	Jiang et al. (2023)	PD, MO, GI, HY	Design development and model testing of soft-connected lattice FPV	Developed lattice-structured FPV with soft connections for harsh offshore conditions; documented anchor types (drag, suction caisson, gravity, pile) with selection criteria; outlined submarine cable requirements and grid integration considerations; provided material durability assessment for marine environments.	Prototype-scale testing only; long-term marine durability not validated; cost analysis limited to component-level estimates.
11	Jifaturrohman et al. (2024)	HY, PD	Numerical simulation of single array-hull wave interaction	Correlated hull configurations with wave spectrum response; hydrodynamic forces significantly affect stability, motion, and durability of floating platforms; identified optimal hull-wave alignment for reduced motion response.	Single-body analysis; did not model multi-module array interactions; limited wave spectrum range tested.
12	Jokhu et al. (2025)	DD, RE	Qualitative case study; community empowerment framework analysis	Demonstrated that early stakeholder participation and shared-benefit schemes improve social license; community-centered models with livelihood co-benefits reduce permitting friction; principles directly adaptable to N-FPV siting.	Not specific to FPV technology; findings from ecotourism/maritime context; limited quantitative metrics for transferability.
13	Lee & Sim (2024)	HY, PD	Experimental study (wave tank) on multi-linked floating structures	Hinged connections reduce peak connection loads by 40 - 60 % vs. rigid configurations; improved fatigue life and lower maintenance demands; added compliance broadens natural frequency range and decreases resonance likelihood.	Tested only two connection conditions; not FPV-specific (general floating structure); scale effects not fully addressed.
14	Li et al. (2024)	HY, MO, PD	Numerical hydrodynamic analysis; seabed topography and coastline modeling	Analyzed influence of seabed topography and coastlines on marine FPV hydrodynamics; HDPE identified as dominant material with strong environmental resistance; documented drag/suction/gravity anchor performance across soil types; mooring spread angle of $35 - 45^{\circ}$ optimal for N-FPV.	Numerical study without field validation; simplified bathymetry models; did not account for biofouling effects on hydrodynamic response.
15	Liu et al. (2024)	PD, MO, HY	Review of recent offshore floating PV systems	Classified offshore FPV technologies and mooring configurations; taut-leg systems reduce footprint but have lower extreme-load tolerance; identified optimal horizontal spread angle of $35 - 45^{\circ}$; documented hybrid solar-wind integration potential.	Broad offshore scope without nearshore differentiation; limited quantitative comparison of mooring types; did not provide standardized cost data.

Table S1 (continued) Synthesis of reviewed literature on nearshore floating solar photovoltaic systems (N = 33).

No.	Author(s) & Year	Theme(s)	Methodology	Key Findings	Limitations
16	Ma et al. (2024)	HY, MO, PD	Numerical hydrodynamic analysis of FPV with rigid connectors	Six-point mooring configurations reduce maximum line tensions by 20 - 25 % vs. three-point systems; rigid connections facilitate load sharing but increase fatigue damage risk at connection points; documented cable fatigue performance under platform motion coupling.	Analysis limited to rigid connection type only; did not compare with hinged/flexible systems; idealized environmental loading conditions.
17	Magkouris et al. (2023)	EP, HY, CS	Numerical simulation and site assessment for Greek sea region	Assessed floating solar feasibility in Greek nearshore sites; wave-induced motions cause 3 - 7 % performance reductions during storm conditions ($H_s > 2$ m); losses generally < 2 % under regular conditions ($H_s < 1$ m); documented site-specific capacity factors of 16 - 22 %.	Mediterranean-specific conditions; limited to numerical modeling without field validation; narrow range of platform designs evaluated.
18	Martinez & Iglesias (2024)	TE, CS	Spatial LCOE mapping using GIS and techno-economic modeling	Mapped LCOE across European Atlantic, North Sea, and Baltic Sea; LCOE ranges 250 - 650 EUR/MWh; Southern European locations most favorable; mooring and platforms account for 38 - 51 % of CAPEX; 20 % CAPEX reduction could lower LCOE by 15 - 18 %.	LCOE significantly above terrestrial PV (40 - 50 EUR/MWh); assumes specific discount rates and lifetimes; does not include externality values or subsidy effects.
19	Mavraki et al. (2023)	EN, CS	Field ecological monitoring of pilot FPV installation	Documented rapid biofouling colonization (> 40 species including barnacles and mussels) within months at Dutch North Sea pilot; artificial reef benefits identified; confirmed absence of catastrophic ecosystem disruptions; highlighted operational impacts requiring active management.	Single pilot site; short monitoring period; fouling community may differ across latitudes and water conditions.
20	Naiborhu et al. (2025)	HY, PD	Physical model testing (2D wave flume); scaling analysis	Developed scaling and modeling strategy for nearshore FPV physical models; validated 2D hydrodynamic response under controlled wave conditions; established scaling methodology for translating model results to prototype scale.	2D testing only (no 3D wave effects); limited wave condition range; scaling methodology requires further full-scale validation.
21	Ray et al. (2024)	EN	Field experiment measuring GHG dynamics in ponds	Documented immediate effects of FPV deployment on greenhouse gas dynamics; oxygen reductions observed under high coverage scenarios; quantified dissolved oxygen changes throughout water column under 70 % coverage conditions.	Pond-scale study, not marine; short-term deployment effects only; GHG dynamics may differ significantly in saline/tidal environments.
22	Selj et al. (2025)	EP, PD, TE	IEA PVPS review of energy yield, reliability, and maintenance	Active water-circulation cooling can enhance efficiency up to 15.45 %; documented degradation mechanisms (saltwater corrosion, biofouling, wave fatigue); highlighted limited field performance data creating uncertainty for lifespan expectations; identified need for unified design codes.	Review-level synthesis; limited original field data; primarily focused on general FPV rather than nearshore-specific conditions.

Table S1 (continued) Synthesis of reviewed literature on nearshore floating solar photovoltaic systems (N = 33).

No.	Author(s) & Year	Theme(s)	Methodology	Key Findings	Limitations
23	Song et al. (2022)	HY, PD	Numerical analysis of multi-connected floating solar panels with vertical cylinders	Characterized dynamic response of multi-connected FPV systems; nearshore FPV benefits from reduced wave heights compared to offshore; documented motion coupling between connected modules under wave forcing.	Specific to vertical cylinder geometry; limited wave condition range; did not assess energy performance implications of motion.
24	Suja & Chandrasekaran (2025)	HY, MO	Numerical simulation of TLP with tuned mass damper (TMD)	TMDs can reduce wave-induced pitch and surge near resonant frequencies; passive motion-control concepts from offshore platforms applicable to N-FPV; complements mooring-based stiffness adjustments with minimal design complexity.	TLP-specific, not directly tested on FPV platforms; single environmental loading scenario; TMD effectiveness under extreme conditions not assessed.
25	Van Der Zanden et al. (2024)	HY, PD, CS	Wave basin tests of multi-body FPV sheltered by floating breakwater	Validated wave basin testing methodology for multi-body FPV; floating breakwater shelter significantly reduces wave transmission to FPV array; hexagonal/honeycomb floats demonstrate excellent stability under multi-directional seas.	Laboratory-scale only; breakwater cost and feasibility not assessed; limited to specific breakwater-FPV spacing configurations.
26	Vo et al. (2021)	PD, TE, DD	Overview and feasibility assessment of solar FPV in offshore industry	200 kW nearshore systems can supply 30 - 50 island households, reducing diesel dependency; offshore FPV potential ranges 50 - 500 MW+; documented economic feasibility for remote coastal communities; identified hybrid solar-wind integration opportunities.	Preliminary feasibility level; limited to overview without detailed engineering analysis; cost projections based on early-stage estimates.
27	Wu et al. (2024)	EN, RE, DD	Review emphasizing marine environmental protection and policy	Identified policy and regulatory support as most influential adoption driver; documented multiple regulatory domain intersections (maritime, environmental, water, electricity); IEC developing technical specifications for FPV covering safety, mooring, and O&M guidelines.	Policy focus limits technical depth; regulatory landscape rapidly evolving; limited quantitative environmental impact data.
28	Xiong et al. (2025)	HY, PD	Numerical hydrodynamic analysis of membrane-structure FPV	Membrane-based FPV demonstrates favorable seakeeping characteristics and stability under combined wave and current loading; potential cost advantages through reduced material requirements; simplified installation vs. pontoon designs.	Long-term membrane durability under sustained marine exposure unknown; localized damage propagation risk not quantified; limited to specific membrane configuration.
29	Xu et al. (2024)	HY, PD	Numerical hydrodynamic study of FPV arrays with multiple floating bodies	Rectangular arrays susceptible to resonance when wave periods approach structural natural frequency; multi-body interactions amplify motions and cyclic mooring loads; array spacing significantly influences hydrodynamic coupling.	Numerical study without experimental validation; limited float geometry variations tested; did not evaluate energy performance effects.
30	Zhang et al. (2024)	PD, MO, EP, HY, CS	Design development, model testing, and field deployment (Singapore 5 MW)	Developed compliant modular FPV for coastal conditions using HDPE pontoons; Singapore 5 MW Woodlands project validated design predictions; measured motion responses within acceptable ranges; 10 % energy yield gain from cooling; compliant design reduces structural loads vs. rigid resistance to waves.	Single case study site (Singapore); tropical conditions may not generalize; limited long-term operational data reported.

Table S1 (continued) Synthesis of reviewed literature on nearshore floating solar photovoltaic systems (N = 33).

No.	Author(s) & Year	Theme(s)	Methodology	Key Findings	Limitations
31	Zhang et al. (2022)	HY, PD	Review and comparative study of hydrodynamic analysis methodologies	Compared methodologies for nearshore floating solar farm hydrodynamic analysis; established framework for selecting appropriate numerical approaches based on system scale and environmental conditions.	Review-level; no original experimental data; limited to methodology comparison without performance benchmarking.
32	Zhang et al. (2025)	HY, PD	Numerical simulation of array forms and float shapes under nearshore infragravity waves	Triangular arrays reduce peak heave/pitch by ~15 % vs. rectangular; spherical floats offer superior motion stability; array geometry affects response more than individual float shape; hexagonal arrays achieve 70 - 75 % surface coverage.	Focused on infragravity wave regime; limited to three array configurations; did not include mooring system effects.
33	Zheng et al. (2024)	HY, EP	Numerical simulation of multi-module FPV motion and energy harvesting	Characterized motion response and energy harvesting of multi-module FPV in seas; tidal and current dynamics influence mooring tension and energy consistency; documented potential for hybrid solar-tidal systems.	Numerical study without field validation; simplified multi-module coupling; energy harvesting estimates not experimentally verified.