

Review

Offshore Floating Photovoltaics in China: Structural Concepts, Hydrodynamic Challenges, and Future Perspectives

Xianlin Jia ¹, Su Guo ², Kangjie Wang ¹, Yong Zhao ³, Jinhui Du ⁴ and Wei Peng ^{4,*} 

¹ Power China Hua Dong Engineering Co., Ltd., Hangzhou 311122, China; jia_xl@hdec.com (X.J.); wang_kj2@hdec.com (K.W.)

² School of Renewable Energy, Hohai University, Nanjing 211000, China; guosu81@126.com

³ Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China; 22310183@tongji.edu.cn

⁴ College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 211000, China; 251303020012@hhu.edu.cn

* Correspondence: pengweihhu@hhu.edu.cn; Tel.: +86-025-8378-6648

Abstract

Offshore floating photovoltaics (OFPVs) offer a promising route for expanding solar energy development from land and inland waters to marine space, particularly in China's coastal regions where electricity demand, land-use constraints, offshore wind infrastructure, and photovoltaic manufacturing capacity are highly concentrated. This review examines the development status, structural concepts, hydrodynamic challenges, research methodologies, reliability issues, and future pathways of OFPV systems in China from the perspective of marine engineering. Demonstration projects, representative platform concepts, and recent studies on environmental loading, platform motion, multi-body interaction, connector and mooring responses, and hydroelastic behavior are systematically synthesized. The review shows that Chinese OFPV technology has progressed from conceptual exploration to prototype testing and sea-based validation, with flexible membrane, steel-frame, semi-submersible, tensioned floating-island, HDPE modular, and composite-material concepts under active investigation. However, mature and replicable engineering solutions remain limited. Key barriers include survivability under extreme sea states, fatigue reliability of large arrays, corrosion, biofouling, material degradation, insufficient long-term field data, and the lack of dedicated design standards. Future development should emphasize array-level hydrodynamic design, coupled connector–mooring optimization, life-cycle reliability assessment, full-scale monitoring, and integration with offshore wind, wave energy, floating breakwaters, aquaculture, and other marine energy systems.

Keywords: offshore floating photovoltaics; China; marine renewable energy; floating structures; hydrodynamic response; mooring systems; hybrid offshore energy systems



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1. Introduction

The global transition towards low-carbon energy systems has accelerated the deployment of renewable energy technologies. Among them, solar photovoltaic (PV) power has become one of the fastest-growing renewable energy sources because of its wide resource availability, modular configuration, short construction period, and continuously decreasing generation cost [1,2]. However, the rapid expansion of PV installations has also intensified constraints associated with land occupation, ecological protection, spatial competition, and the mismatch between large-scale generation sites and coastal load centers.

These constraints are particularly pronounced in economically developed coastal regions, where electricity demand is high but available land resources are limited. Extending PV systems from land to water bodies, and further to marine space, has therefore become an important pathway for the continued development of the PV industry.

Floating photovoltaic (FPV) systems provide an effective solution to land-use constraints. Compared with land-based PV, floating PV can reduce land occupation and may benefit from the cooling effect of water, which can lower the operating temperature of PV modules and improve power-generation efficiency. Considerable engineering experience has been accumulated in reservoirs, lakes, mining subsidence areas, and other inland water bodies [3]. Building on this experience, offshore floating photovoltaic systems (OFPVs) extend PV deployment to nearshore, offshore, and potentially deep-sea environments. Unlike inland floating PV, OFPV is not merely a spatial extension of existing floating PV technology. It represents a new type of marine renewable energy system in which PV modules, floating support structures, marine environmental loads, mooring systems, and offshore energy infrastructure are strongly coupled [4].

For China, OFPV has particular strategic and engineering significance. China's coastal regions are characterized by high electricity demand, limited land availability, abundant nearshore sea space, a mature PV manufacturing industry [5], and rapidly expanding offshore wind infrastructure [6]. These conditions provide a favorable basis for the development and demonstration of OFPV. In recent years, OFPV in China has progressed from conceptual exploration to prototype development, sea trials, and early-stage demonstration projects. Representative structural concepts include flexible membrane platforms, semi-submersible platforms, steel truss-supported platforms, tensioned floating-island systems, and novel composite-material platforms. Meanwhile, application scenarios have gradually expanded from sheltered nearshore waters to open-sea environments and offshore wind–PV co-location. These developments indicate that Chinese OFPV is currently undergoing a critical transition from technical feasibility verification to engineering validation.

Despite this progress, the large-scale deployment of OFPV remains challenging. Compared with land-based PV and inland floating PV, OFPV systems are exposed to more severe and uncertain marine environments, including waves, wind, currents, tidal variations, salt-spray corrosion, biofouling, overtopping, slamming, and extreme weather events [7]. These environmental actions may induce six-degree-of-freedom platform motions, multi-body hydrodynamic interactions within large arrays, amplified connector loads, mooring tension redistribution, hydroelastic deformation, fatigue damage, and array-level failure propagation. Therefore, the key technical challenge of OFPV is no longer limited to supporting PV modules on water, but lies in the integrated design of floating structures, hydrodynamic performance, connection systems, mooring safety, electrical reliability, and long-term operation and maintenance (O&M).

Existing reviews have examined floating PV and OFPV from perspectives such as system reliability, design requirements, environmental impacts, structural forms, power prediction, and hydroelastic theory [8–11]. These studies have provided useful insights into the development of floating PV technologies. However, most reviews focus either on floating PV in a broad sense or on global OFPV development, often covering electrical systems, environmental effects, economics, policy, and operation and maintenance within a general framework. In contrast, systematic reviews focusing on OFPV development in China remain limited, especially from the perspective of ocean engineering and hydrodynamics. Considering China's distinctive coastal conditions, including shallow-water sites, typhoon exposure, offshore wind development, and coastal industrial capacity, it is necessary to reassess the development pathway of Chinese OFPV with particular attention

to structural concepts, hydrodynamic response, array connections, mooring systems, hydroelastic effects, and engineering reliability.

This review examines OFPV development in China from the standpoint of marine structures and hydrodynamic performance. It begins by outlining the current status of demonstration projects and application scenarios, then evaluates representative platform concepts, including HDPE modular floats, metallic frame systems, flexible membranes, and semi-submersible or high-freeboard structures. The review subsequently discusses the hydrodynamic problems that control engineering feasibility, such as platform motion, multi-body array interaction, connector loading, mooring response, and hydroelastic behavior. It also compares the main research methods used in this field, ranging from analytical and potential-flow models to CFD, physical testing, field monitoring, and hybrid/data-driven approaches. The final part identifies the reliability, durability, survivability, standardization, and hybrid-energy challenges that must be addressed before OFPV in China can move from prototype verification to large-scale engineering application.

To improve the transparency and reproducibility of this review, a structured literature search was conducted using Web of Science, Scopus, ScienceDirect, Google Scholar, and CNKI. The search covered peer-reviewed journal articles, conference papers, technical reports, design guidelines, and publicly available information on representative offshore floating photovoltaic demonstration projects. The main search terms included “offshore floating photovoltaic”, “floating solar”, “marine floating photovoltaic”, “offshore FPV”, “floating photovoltaic platform”, “hydrodynamic response”, “multi-body interaction”, “mooring system”, “connector load”, “hydroelastic response”, “offshore wind-PV co-location”, “floating breakwater photovoltaic”, and their Chinese equivalents.

The reviewed studies were selected according to their relevance to offshore or marine floating photovoltaic systems, with particular emphasis on structural concepts, hydrodynamic performance, array interaction, connector and mooring response, model testing, field monitoring, reliability, and hybrid offshore renewable energy systems. Studies focusing only on conventional land-based PV systems or inland floating PV without clear relevance to marine environmental loading or offshore structural design were excluded, except where they provided useful background on floating PV technology or material performance. Because offshore floating photovoltaics remain an emerging field in China, official project reports, company releases, and publicly accessible engineering information were also used to summarize demonstration projects when peer-reviewed data were unavailable. The review is therefore intended as an engineering-oriented narrative synthesis rather than a bibliometric or meta-analytical study.

2. Development Status and Application Scenarios of Offshore Floating Photovoltaics in China

2.1. Strategic Background and Development Drivers

Against the background of China’s carbon peaking and carbon neutrality targets, as well as the continuous growth of electricity demand in coastal regions, offshore floating photovoltaic systems (OFPVs) provide a promising pathway for extending solar energy development into marine space. Compared with land-based PV, OFPV can reduce land occupation and may be integrated with offshore wind farms, marine ranching, island power supply, and other offshore energy applications. China’s coastal areas are characterized by concentrated electricity demand, abundant nearshore sea space, a mature PV manufacturing industry, and a rapidly developing offshore wind engineering base. These conditions provide favorable industrial and engineering foundations for OFPV demonstration and future deployment.

At present, OFPV in China remains largely at the stage of prototype development and field verification. Existing projects are generally small in scale and are primarily intended to validate structural safety, environmental adaptability, power-generation stability, and offshore operation and maintenance feasibility. Compared with inland floating PV, OFPV systems are exposed to more complex marine conditions, including waves, wind, currents, tidal variations, salt-spray corrosion, and biofouling. Consequently, the main engineering bottleneck has shifted from the basic arrangement of PV modules on floating supports to the integrated reliability of platform structures, hydrodynamic response, mooring systems, and long-term service performance.

2.2. Demonstration Projects and Engineering Progress

In recent years, several OFPV demonstration projects have been implemented in China, and the corresponding technical routes have become increasingly diverse (Table 1). These projects cover flexible membrane platforms, semi-submersible platforms, steel truss-supported platforms, tensioned floating-island systems, bamboo-based or composite-material platforms, and offshore wind–PV co-location concepts. Their main objectives have shifted from preliminary concept verification to sea-based testing of structural safety, hydrodynamic response, mooring behavior, environmental adaptability, and power-generation stability.

Table 1. Representative sea-trial and demonstration projects of offshore floating photovoltaics in China.

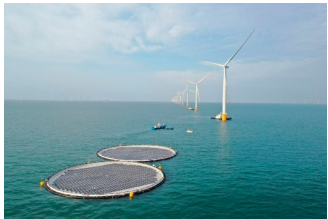
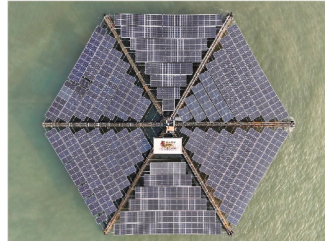
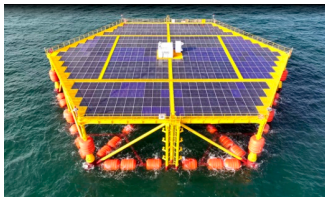
Project	Year	Location	Capacity	Structural Concept	Main Objective	Photograph
Shandong Peninsula South No. 3 offshore wind–PV co-location floating PV project [12]	2022	Haiyang, Shandong, China	500 kW	Flexible membrane	Verification of offshore wind–PV co-location	
CIMC Raffles offshore PV platform [13]	2023	Yantai, Shandong, China	400 kW	Semi-submersible	Sea trial of a semi-submersible OFPV concept	
Bamboo-based composite offshore floating PV platform “Jilin No. 1” [14]	2023	Yantai, Shandong, China	—	Bamboo-based truss platform	Exploration of low-carbon structural materials	
SPIC Shandong Institute offshore floating PV test platform [15]	2023	Rushan, Shandong, China	15 kW	Steel truss platform	Field measurement of motion and structural response	

Table 1. Cont.

Project	Year	Location	Capacity	Structural Concept	Main Objective	Photograph
Hexagonal tensioned floating-island FPV platform [16]	2023	Binhai New Area, Tianjin, China	2 MW	Tensioned floating island	Demonstration of a large-area lightweight platform	
Huaneng “Yellow Sea No. 1” wave-resistant floating PV platform [17]	2024	Southern waters of the Shandong Peninsula, China	—	Steel truss platform	Open-sea testing of a wave-resistant platform	
National Energy Group offshore floating PV wind–PV co-location project [18]	2024	Dongtai, Jiangsu, China	100 kW	Steel truss platform	Verification of offshore floating PV within a wind-farm scenario	

Overall, these demonstrations indicate that OFPV in China has entered an early engineering validation stage rather than remaining at the conceptual level. However, most projects are still limited in scale, monitoring duration, and environmental exposure. Long-term field data, full-scale reliability assessment, and replicable commercial solutions remain insufficient. Therefore, although Table 1 shows rapid progress and increasing technological diversity, further verification is still required before large-scale offshore deployment can be achieved.

2.3. Main Application Scenarios

The main application scenarios for OFPV in China are closely linked to sea-state severity, infrastructure availability, and the type of offshore demand. Nearshore and harbor waters remain the most suitable environments for early demonstrations because they usually offer milder waves, shorter installation distances, and more convenient access for maintenance. These sites are therefore valuable for prototype testing, structural verification, and the accumulation of field data before deployment in more energetic waters.

Offshore wind farms and their surrounding waters provide a more strategically important pathway. Wind–PV co-location can share sea space, offshore substations, export cables, transmission corridors, and operation and maintenance resources, thereby improving the utilization efficiency of marine space and reducing system-level development costs. Given China’s rapidly expanding offshore wind infrastructure, this scenario is among the most realistic routes for near-term OFPV commercialization.

Marine ranching, island and reef power supply, and offshore facility electrification form another group of practical applications. In these cases, floating PV can be coupled with aquaculture equipment, monitoring systems, energy storage, communication facilities, and distributed power systems to serve off-grid or weak-grid loads. Such applications may be particularly useful for remote islands, aquaculture bases, and offshore monitoring stations.

In the longer term, OFPV may become part of integrated deep-sea renewable energy systems that combine floating wind power, wave energy, offshore storage, and hydrogen production. This pathway is still largely conceptual, but it indicates how OFPV could evolve from a stand-alone generation technology into a component of multi-energy offshore infrastructure.

2.4. Current Development Characteristics

Although OFPV in China has made initial progress in terms of demonstration projects and structural concepts, a mature, reliable, and replicable engineering solution has not yet been established. The reported failure of the Ocean Sun-based project in the Shandong Peninsula, where membrane water accumulation and drainage pump failure led to structural damage, indicates that flexible membrane platforms still face substantial engineering challenges in exposed marine environments. This case also highlights the importance of drainage capacity, buoyancy redundancy, structural robustness, and fault tolerance in offshore applications.

Taken together, OFPV in China is evolving towards array deployment, engineering verification, and multi-scenario integration under increasingly complex sea conditions. Platform concepts are expected to develop towards higher environmental adaptability, improved structural reliability, lower carbon footprint, and reduced life-cycle cost. The co-development of OFPV with offshore wind farms, marine ranching, and other offshore energy systems is also likely to become an important direction [19]. Nevertheless, long-term service reliability, design standards, field monitoring data, and operation and maintenance strategies remain insufficient. These limitations mean that OFPV in China is still some distance from large-scale commercial application.

The current development pattern is therefore characterized by prototype-led verification, parallel exploration of multiple platform routes, and a gradual shift from feasibility demonstration to long-term reliability. Flexible membrane, semi-submersible, steel truss-supported, tensioned floating-island, and composite-material platforms are all being tested, but no unified commercial solution has yet emerged. Wind–PV co-location and hybrid offshore energy systems are gaining importance, while long-term monitoring data, design codes, life-cycle assessment frameworks, and cost-effective offshore operation and maintenance remain insufficient. China has a strong industrial foundation and favorable demonstration conditions, but large-scale deployment will depend on solving coupled problems in structural safety, marine environmental adaptability, array design, mooring reliability, and O&M economy.

3. Structural Concepts and Applicability of OFPV Platforms

The structural concept of an offshore floating photovoltaic (OFPV) platform directly determines its environmental adaptability, motion behavior, structural safety, installation feasibility, and operation and maintenance cost [8]. Unlike inland floating PV systems, OFPV platforms must operate under more complex marine conditions, including waves, wind, currents, tidal variations, corrosion, and biofouling. Accordingly, platform design should not only satisfy the layout requirements of PV modules, but also ensure sufficient buoyancy, stability, structural strength, connector reliability, mooring compatibility, and long-term durability.

According to the buoyancy mechanism, load-bearing system, structural stiffness, and applicable sea states, existing OFPV platform concepts can be broadly classified into four categories: high-density polyethylene (HDPE) modular floating platforms, metallic frame-supported platforms, flexible membrane platforms, and semi-submersible or high-

freeboard platforms. These concepts differ significantly in their hydrodynamic behavior, structural complexity, failure modes, and engineering applicability.

3.1. HDPE Modular Floating Platforms

HDPE modular floating platforms are usually composed of high-density polyethylene floats, supporting members, connectors, and PV modules. This concept has been widely used in inland floating PV projects and represents one of the most mature technical routes for sheltered water bodies. The main advantages of HDPE modular platforms include good corrosion resistance, high modularity, convenient transportation and installation, and relatively low cost. These features make them suitable for reservoirs, lakes, mining subsidence areas, harbors, and nearshore sheltered waters.

However, the application of HDPE modular platforms in open-sea environments remains limited. Because such platforms generally have shallow drafts and relatively large waterplane areas, they are sensitive to wave and wind loads. Under wave action, large rigid-body motions and significant connector forces may occur, especially when the array size increases. In addition, repeated relative motion between adjacent modules may induce local wear, connector fatigue, and progressive damage within the array.

Accordingly, HDPE modular platforms are more suitable for mild nearshore waters or protected marine areas. If they are applied to more energetic sea states, the design should place particular emphasis on array connection strength, mooring restraint, global stability, and fatigue resistance. For large-scale OFPV deployment, conventional inland-style HDPE modular systems cannot be directly transferred to offshore environments without substantial structural and hydrodynamic adaptation.

3.2. Metallic Frame-Supported Platforms

Metallic frame-supported platforms usually adopt an upper steel or aluminum frame as the primary load-bearing structure, while pontoons or buoyancy tanks provide flotation. Compared with HDPE modular platforms, metallic frame-supported platforms generally have higher global stiffness, better load-carrying capacity, and greater flexibility for arranging PV modules, electrical equipment, walkways, and auxiliary facilities. Representative concepts such as the SolarSea system [20] demonstrate the feasibility of using metallic structural frameworks for marine PV applications.

The relatively high stiffness of metallic frame-supported platforms is beneficial for maintaining the alignment and inclination of PV modules, reducing excessive local deformation, and improving operational accessibility. In sea trials, this stiffness also provides a stable reference for instrumentation, reduces uncertainty in measured motion and structural responses, protects cables and module connections from excessive relative deformation, and improves inspection and maintenance safety. In this context, stiffness is not pursued only to increase structural strength, but also to improve measurement reliability, operational safety, and repeatability during offshore testing.

Nevertheless, metallic frame-supported platforms also face several limitations. Marine environments characterized by salt spray, high humidity, splash-zone exposure, and long-term wetting may accelerate corrosion of metallic members and joints. This increases the requirements for anti-corrosion coatings, cathodic protection, inspection, and maintenance. In addition, integrated frame structures may involve higher manufacturing cost, heavier lifting operations, and more complex offshore installation and repair procedures than modular floating systems.

Taken together, metallic frame-supported platforms provide improved structural integrity and engineering operability, but their long-term performance depends strongly on corrosion protection, fatigue design, and cost-effective maintenance strategies. In this re-

view, “medium-energy offshore sites” refer to nearshore or semi-sheltered marine areas where wave, wind, current, and tidal exposure is stronger than that in harbors, reservoirs, or fully protected waters, but lower than that in fully exposed open-sea or typhoon-dominated sites. Therefore, metallic frame-supported platforms are more appropriate for sea trials, nearshore engineering demonstrations, and such medium-energy sites where dimensional stability, module alignment, equipment accessibility, and structural robustness are important design requirements.

3.3. Flexible Membrane Platforms

Flexible membrane platforms generally consist of a peripheral buoyancy ring, a flexible membrane, and connecting components between the membrane and the floating ring. Their defining feature is that PV modules are installed close to the water surface on a flexible membrane. The Ocean Sun concept [21] is a representative example of this type of platform. By allowing the membrane to deform with the water surface, the platform can reduce wave-induced structural loads and benefit from hydrodynamic damping and water-cooling effects.

Flexible membrane platforms have several potential advantages. Their low profile can reduce wind loads, and the membrane surface may distribute local stress through deformation. The direct thermal contact with water may also improve the operating temperature of PV modules. In addition, the lightweight nature of flexible membrane systems may reduce material consumption and facilitate deployment in certain sheltered or moderately exposed environments.

However, the same characteristics also introduce important engineering challenges. Because the freeboard of flexible membrane platforms is very low, they are highly susceptible to overtopping, water accumulation, membrane deformation, and drainage failure under severe wave conditions. The buoyancy capacity, drainage system, membrane tension, and fault tolerance of the platform are therefore critical to its offshore applicability. Moreover, flexible membrane systems require compatibility with flexible or specially adapted PV modules, while the conversion efficiency, long-term durability, and resistance of flexible PV modules to high salinity, humidity, ultraviolet radiation, and cyclic loading still require further verification [22].

Consequently, flexible membrane platforms are attractive for lightweight, low-wind-load, and water-cooled PV applications, but their use in open-sea environments requires careful assessment of overtopping, drainage, membrane fatigue, module durability, and survivability under extreme sea states.

3.4. Semi-Submersible and High-Freeboard Platforms

Semi-submersible and high-freeboard platforms draw more directly from offshore engineering concepts. These platforms usually rely on submerged pontoons, columns, truss structures, or ballast systems to provide buoyancy and stability. By reducing the water-plane area, lowering the center of gravity, or increasing the vertical clearance between the PV deck and the water surface, such platforms can improve their adaptability to higher sea states.

Representative concepts include the Helio configuration [4] and the SolarDuck platform [23]. Compared with low-freeboard or shallow-draft concepts, semi-submersible and high-freeboard platforms generally exhibit better motion performance and improved survivability in open-sea conditions. A higher air gap can also reduce the probability of wave overtopping and slamming on PV modules and supporting structures. These characteristics make such platforms promising for exposed nearshore waters, open-sea demonstration projects, and long-term offshore deployment.

The main limitations of semi-submersible and high-freeboard platforms are their higher structural complexity and cost. They usually require more sophisticated design, fabrication, transportation, installation, and mooring systems. Their larger structural dimensions and heavier components may also increase capital expenditure and offshore construction difficulty. Therefore, these platforms are more appropriate for high-value applications or harsh marine environments where improved survivability and structural robustness can justify the additional cost.

3.5. Comparative Assessment of Platform Concepts

No single OFPV platform concept is universally superior. The suitability of a platform depends on site-specific sea states, water depth, installation scale, maintenance strategy, grid connection, and economic requirements. Table 2 synthesizes the main trade-offs: HDPE modular platforms are better suited to mild and sheltered waters; metallic frame-supported platforms are appropriate for medium-energy sites and engineering demonstrations; flexible membrane platforms offer lightweight and low-wind-load advantages but require careful survivability assessment; and semi-submersible or high-freeboard platforms are more promising for exposed offshore environments and higher sea states.

Table 2. Comparative assessment of representative OFPV platform concepts.

Platform Concept	Suitable Sea Area	Wave-Resistance Capability	Structural Complexity	Cost Level	Main Failure Risks	Representative Platform
HDPE modular floating platform [24]	Reservoirs, harbors, sheltered nearshore waters	Low to moderate	Low	Low	Connector fatigue, large array motion, local wear, mooring overload	
Metallic frame-supported platform [15]	Nearshore and moderate offshore sites	Moderate to high	Moderate to high	Moderate to high	Corrosion, fatigue at joints, heavy installation, maintenance difficulty	
Flexible membrane platform [12]	Sheltered or moderately exposed waters	Moderate, depending on membrane and drainage design	Moderate	Moderate	Overtopping, water accumulation, membrane fatigue, drainage failure, module durability	
Semi-submersible and high-freeboard platform [13]	Open-sea and harsher offshore environments	High	High	High	Structural fatigue, mooring loads, high fabrication and installation cost	

In addition to structural applicability, the technological readiness and commercial maturity of different OFPV concepts are also important for evaluating their near-term deployment potential. Table 3 provides an indicative assessment of representative concepts based on available demonstration projects, reported sea trials, structural complexity, field validation, and remaining barriers. The assessment is qualitative rather than a formal certification of technology readiness level, because publicly available long-term operational data for OFPV systems remain limited. It should also be noted that the maturity of a basic floating technology may differ from its maturity in offshore PV applications. For example, HDPE modular floats are commercially mature in inland floating PV, while their direct application to exposed offshore environments still requires substantial structural and hydrodynamic adaptation.

Table 3. Indicative assessment of technological readiness and commercial maturity of representative OFPV concepts.

Technology Route	Indicative Readiness for OFPV	Commercial Maturity	Main Evidence or Basis	Main Barriers to Wider Deployment
HDPE modular floating platforms	Medium for sheltered or mild nearshore waters; low to medium for exposed offshore waters	High in inland FPV; low to medium in OFPV	Extensive inland FPV applications; potential use in harbors and protected nearshore waters	Large wave-induced motions, connector fatigue, local wear, mooring overload, limited survivability in energetic sea states
Metallic frame-supported platforms	Medium	Low to medium	Several sea-trial and engineering demonstration platforms in China; relatively high structural stiffness and good accessibility	Corrosion, fatigue at welded or bolted joints, high structural weight, installation cost, maintenance requirements
Flexible membrane platforms	Medium for sheltered or moderately exposed waters; low for harsh open-sea environments	Low to medium	Demonstration of Ocean Sun-type concepts and wind–PV co-location trials; lightweight and low wind-load characteristics	Overtopping, water accumulation, drainage failure, membrane fatigue, durability of flexible PV modules, low fault tolerance under extreme sea states
Semi-submersible or high-freeboard platforms	Medium	Low	Offshore engineering principles are mature; OFPV-specific prototypes and sea trials have been reported	High fabrication and installation cost, complex mooring design, structural fatigue, need for long-term full-scale validation
Tensioned floating-island and cable-supported platforms	Low to medium	Low	Early-stage MW-scale prototype testing; attractive for large-area lightweight deployment	Cable–membrane coupling, pretension control, hydroelastic response, fatigue of cable and membrane systems, lack of long-term operation data
Composite-material or low-carbon platforms	Low to medium	Low	Early demonstration of bamboo-based or composite-material concepts	Material durability, salt-spray ageing, fatigue, fire safety, manufacturing repeatability, certification
Offshore wind–PV co-location systems	Medium at demonstration level	Low to medium	Demonstration projects in offshore wind-farm scenarios; potential sharing of substations, export cables, sea space, and O&M resources	Integrated layout optimization, turbine wake and safety distance, cable routing, mooring interference, typhoon survivability, grid dispatch and O&M coordination
PV–wave energy/PV–breakwater hybrid systems	Low to medium	Low	Conceptual designs, numerical studies, and model tests showing potential wave attenuation and multi-energy integration	Coupled hydrodynamics, PTO reliability, increased system complexity, cost, maintenance, lack of full-scale validation

Overall, the selection of OFPV platform concepts should be based on a comprehensive assessment of environmental conditions and engineering objectives. For early-stage nearshore demonstrations, low cost, modularity, and installation convenience may be the dominant design considerations. For open-sea and large-scale applications, however, platform stability, structural reliability, mooring safety, air-gap protection, and survivability under extreme sea states become the controlling factors. As OFPV develops from small-scale prototypes to large-scale arrays, structural design should evolve from single-platform optimization towards integrated array design, connector reliability, mooring coordination, and life-cycle performance assessment.

4. Marine Environmental Loads and Hydrodynamic Challenges

Compared with inland floating photovoltaic systems, offshore floating photovoltaic (OFPV) platforms are exposed to more complex and uncertain marine environments. Their structural safety and operational stability are governed by the combined effects of waves, wind, currents, tidal variations, and extreme weather events. Owing to their low freeboard, lightweight configuration, multi-module connection, and array-based layout, environmental loads may not only induce rigid-body motions of individual platforms, but also cause multi-body hydrodynamic interactions, amplified connector loads, mooring tension redistribution, and hydroelastic deformation of flexible or large-scale structures. Therefore, hydrodynamic performance is a key factor controlling the transition of OFPV from prototype verification to engineering application.

4.1. Characteristics of Marine Environmental Loads

OFPV platforms are mainly subjected to wave, wind, and current loads [25], as shown in Figure 1. Among these, wave loading, wave–structure interaction, and mooring design are generally regarded as fundamental issues in OFPV structural design [26]. Waves are the primary external excitation for platform motion and local impact. They affect heave, pitch, roll, and other motion responses, and may also induce overtopping, slamming, local pressure concentration, and increased connector forces. For low-freeboard and flexible membrane platforms, wave-induced overtopping, water accumulation, and membrane deformation are particularly important [27]. For semi-submersible and high-freeboard platforms, the main concerns are wave excitation, air-gap safety, and local loading on columns, braces, and supporting structures.

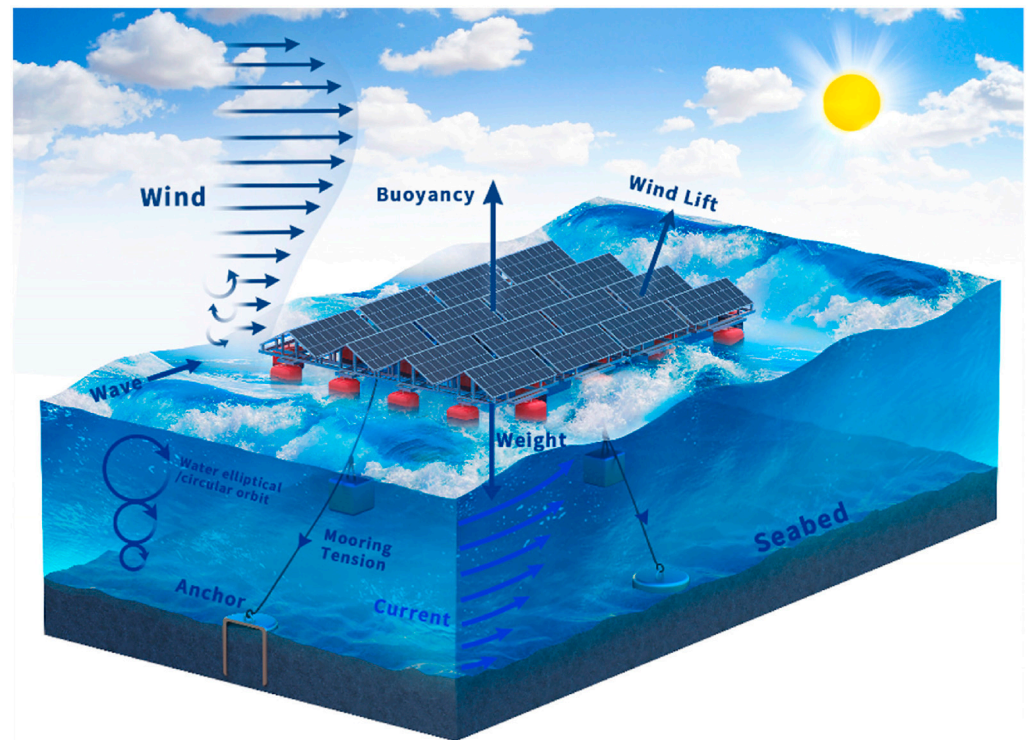


Figure 1. Schematic illustration of environmental loads acting on an offshore floating photovoltaic platform, including wave, wind, current, tidal, and mooring effects, reproduced from [25].

Wind loads mainly act on PV modules, support frames, and exposed structural components. They influence the mean platform attitude, low-frequency drift, and loads on the upper structure [28]. Because PV panels are usually installed at an inclination angle, the effective wind attack angle varies with platform pitch and roll. As a result, wind loading on OFPV systems is inherently time-dependent and coupled with wave-induced motion. In large arrays, wind may also contribute to non-uniform load distribution among modules and increase the demand on connectors and mooring lines.

Currents and tidal flows generally act as sustained horizontal loads. They can change the equilibrium position of a floating platform, increase horizontal drift, and redistribute mooring tensions. For lightweight and large-area OFPV arrays, current loads may not always dominate the dynamic response, but they have a continuous influence on station-keeping performance and mooring safety. Previous studies on flexible multi-floater OFPV arrays have shown that combined wave–current action can lead to global array drift and increase the motion response, connector tension, and mooring tension of upstream and edge floaters [29]. Moreover, the response under combined wave–current conditions may differ

significantly from a simple superposition of wave-only and current-only effects. In shallow nearshore sites, tidal variation, shallow-water effects, and uneven seabed conditions may further alter the boundary conditions of platform motion and the initial state of mooring systems. Coupled wave–wind–current modelling and basin testing under superimposed environmental conditions are already well established in offshore engineering. For OFPV systems, the key issue is therefore not the general need to move beyond single-wave analysis, but the systematic application and validation of such coupled-load approaches for OFPV-specific configurations, including low-freeboard platforms, lightweight multi-module arrays, flexible or semi-rigid connectors, mooring-boundary effects, and site-specific Chinese coastal conditions.

4.2. Platform Motion Response

The motion response of an individual platform is the basis for OFPV hydrodynamic analysis. It generally includes six-degree-of-freedom motions, response amplitude operators (RAOs), resonance characteristics, air-gap safety, and mooring tension variation. Platform response is controlled by wave height, wave period, wave direction, draft, platform scale, mass distribution, structural stiffness, and mooring configuration. Different platform concepts exhibit distinct motion characteristics. HDPE modular platforms usually have shallow drafts and large waterplane areas, making them sensitive to wave and wind loads. Semi-submersible platforms can improve offshore adaptability by reducing waterplane area and increasing air gap. Flexible membrane platforms rely on membrane deformation and hydroelastic effects to adapt to waves, but their very low freeboard makes overtopping, water accumulation, and drainage failure critical issues.

Several studies have investigated the seakeeping performance of individual OFPV platforms. Jin et al. [30] studied a SolarDuck-type triangular platform supported by three columns and equipped with retractable heave plates at the column bottoms (Figure 2). A frequency-domain AQWA model was used to analyze the response under regular waves. The results showed that column spacing and heave-plate parameters significantly affect the motion response, indicating that floater arrangement and additional damping devices can be effective for improving seakeeping performance. Zhang et al. [15] conducted field tests on a semi-submersible steel-frame OFPV platform in the Yellow Sea and obtained platform motion and mooring tension data under different wave and tidal conditions. Their results showed that the platform operated stably overall, but tidal variations had a marked influence on mean mooring tension. When the wave period approached the natural period of the platform, the RAO range increased, suggesting the possibility of response amplification.

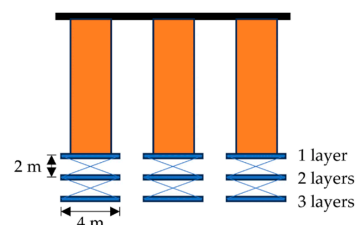


Figure 2. Schematic of the modified SolarDuck-type offshore floating photovoltaic platform equipped with retractable heave plates, showing configurations with one-, two-, and three-layer heave plates, reproduced from [30].

Platform motion may also affect PV power-generation performance. Ji et al. [31] conducted model tests on a twin-floater OFPV system and simultaneously examined platform motion, mooring tension, and power-generation efficiency. The results suggested that, under the tested wave conditions, platform motion had a limited influence on power-generation efficiency, even under relatively unfavorable conditions. This finding indicates

that moderate platform motion does not necessarily lead to significant power loss if the system is properly designed. However, large attitude variations, water accumulation, shading, and rapid changes in PV module inclination may still affect output stability and should be considered in integrated performance assessment. Therefore, single-platform motion analysis is not only important for structural safety, but also provides a foundation for subsequent array layout, connector design, and mooring optimization.

4.3. Hydrodynamic Interaction in Large Arrays

Array deployment is essential for the large-scale application of OFPV. However, the dynamic response of a multi-module array cannot be regarded as a simple linear superposition of individual platform responses [8,32]. As waves propagate through an array, diffraction, radiation, and sheltering effects modify the local wave field. Meanwhile, the motion of each module further influences the surrounding fluid field, resulting in different response characteristics for upstream, downstream, edge, corner, and interior modules. Array layout, module spacing, floater geometry, wave incident angle, and the relationship between array scale and wavelength all affect the global response and local load distribution [33].

Another important issue for large OFPV arrays is wave-field inhomogeneity. Many numerical studies assume that all floating modules are subjected to the same incident wave spectrum, wave direction, and phase relationship. This homogeneous-wave assumption may be acceptable for small arrays in open and relatively uniform sea states, but it can become invalid for very large arrays, semi-sheltered waters, nearshore sites with complex bathymetry, or layouts protected by islands, reefs, breakwaters, or offshore wind-farm infrastructure. In such cases, the incident wave height, peak period, wave direction, phase, spectral shape, and spatial coherence may vary across the array. These spatial variations can modify the relative motions between modules, shift the locations of peak connector loads, redistribute mooring tensions, and change the fatigue exposure of edge and interior modules. Therefore, array-level hydrodynamic assessment of OFPV systems should consider not only multi-body diffraction and radiation under idealized uniform waves, but also the possible influence of spatially varying wave fields.

Li et al. [34] investigated a four-module hexagonal floating PV system (Figure 3) and showed that multi-body interaction can increase the motion response of individual modules, while reducing the oscillation amplitude and peak value of mooring tension. This indicates that the dynamic behavior of an OFPV array cannot be directly inferred from the response of a single module. Zhang et al. [35] compared different array layouts and floater shapes under nearshore long-period waves and found that array configuration had a greater influence on global motion response than local floater geometry. In some cases, triangular arrays showed better stability. These findings confirm that multi-body interaction, array layout, and floater arrangement are key factors in determining the hydrodynamic performance of OFPV arrays [36].

The coupled action of wind, waves, and currents further increases the complexity of array response. Fu et al. [32] studied a hinged multi-body floating PV system using a potential-flow-based time-domain coupling framework and compared the responses under wave-only and co-directional wind-wave conditions. The results showed that wind loads had limited influence on surge and pitch RAOs, but could significantly amplify low-frequency surge response and increase mooring forces and horizontal connector loads. Wind-induced lift may also alter the mean vertical position of the platform, increasing the risk of platform submergence or local instability. These results suggest that safety problems under combined environmental loads are not limited to increased motion amplitude; they may also arise from changes in platform attitude, connector load amplification, and mooring tension redistribution.

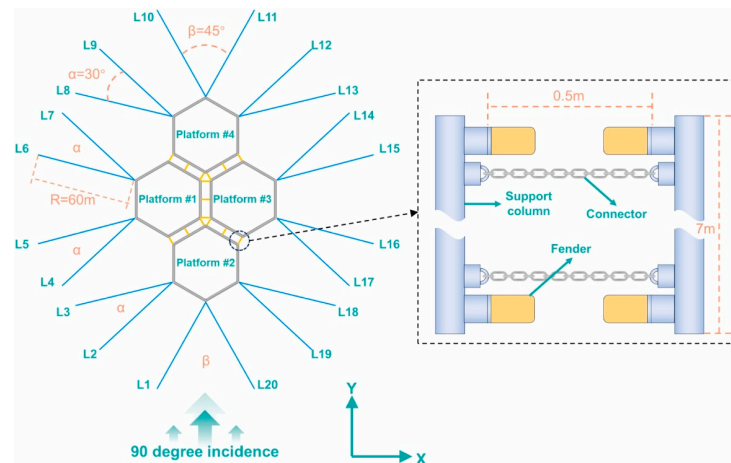


Figure 3. Layout of a hexagonal multi-module floating photovoltaic array, showing the arrangement of floating modules, mooring lines, and wave incident direction, reproduced from [34].

As the array scale increases, boundary effects and local response differences become more pronounced. Upstream modules may experience stronger wave excitation, edge and corner modules may be more vulnerable to asymmetric constraints and load concentration, and interior modules may be influenced by wave sheltering. For large-scale OFPV farms, hydrodynamic design should therefore shift from single-platform seakeeping assessment to integrated evaluation of array-level dynamic behavior, local load distribution, and possible failure propagation paths.

4.4. Connector and Mooring Responses

Connectors and mooring systems jointly determine the constraint conditions, load-transfer paths, and station-keeping capacity of OFPV arrays [29,30,34,35,37–41]. Connectors maintain the relative positions of adjacent modules and transfer environmental loads throughout the array. Common connection types include rigid, hinged, flexible, and semi-rigid connections. Rigid connections can improve global integrity but may generate large local bending moments and stress concentrations. Hinged connections can release part of the rotational constraint but may produce large shear or contact forces under certain wave conditions. Flexible and semi-rigid connections can improve wave-following capability, but relative displacement, collision risk, wear, and fatigue accumulation must be carefully controlled.

Existing studies show that connector loads exhibit strong location dependence and wave-direction sensitivity [42]. Zou et al. [37] compared rigid, hinged, flexible, and semi-rigid connections in a 3×3 multi-body array (Figure 4) and analyzed the motion and structural response of central, edge, and corner modules. They found that peripheral floaters and corner connectors were more sensitive to wave direction, while rigid connections could produce a pronounced outer-frame effect, influencing both array stability and local fatigue. Ji et al. [41] investigated a six-module semi-submersible OFPV system using ANSYS-AQWA (Version 19.0) and showed that connection schemes significantly affect platform motion, mooring tension, and PV-panel air gap. Optimizing connector design can therefore directly improve both operational and survival performance. Studies on hinged multi-module systems further indicate that connector parameters and module scale influence pitch response, resonance characteristics, peak contact forces, and effective array length, with the front-row modules and first hinge connections often experiencing larger connector forces [30,38].

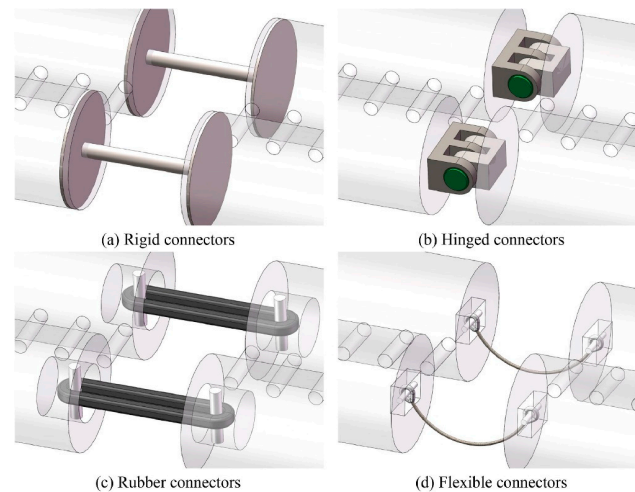


Figure 4. Typical connection concepts for floating photovoltaic modules, reproduced from [37].

Local connector safety is also affected by nonlinear hydrodynamics and multi-body coupling. Bai et al. [43] developed a fully coupled model for a two-module OFPV system and showed that hydrodynamic interaction and second-order sum-frequency wave loads can significantly increase structural loads on connectors. Neglecting these nonlinear effects may underestimate both strength and fatigue risks. He et al. [44] combined two-module model tests with numerical simulations and found that the maximum connector load and maximum mooring tension may occur under different wave directions. They also showed that, after mooring failure, the tension in remaining lines may increase substantially. Lian et al. [39] studied semi-rigid connection joints and mooring forces through 1:14 scale model tests and found that wave steepness strongly controls joint stress and mooring force. When wave steepness exceeds a certain threshold, joint loads and cable tensions increase rapidly. Connection joints near the center of an array may also experience higher stress concentration because they transfer loads from surrounding floaters.

Mooring systems restrict platform drift and provide restoring forces (Figure 5). Their response is influenced by water depth, tidal variation, line stiffness, wave and current conditions, and array boundary configuration. For lightweight and large-scale OFPV platforms, mooring systems not only provide station keeping but also affect platform motion, connector loads, and global array stability [25,45]. Studies on wave–current coupling have shown that upstream and edge floaters usually experience higher mooring tensions [29]. Time-domain analyses of moored and hinged multi-body platforms under irregular waves and wind have further shown that wind loads can increase the instability of surge and sway motions and redistribute mooring tensions among different lines [30,40]. Comparative studies of all-chain, chain–polyester–chain, and chain–high-modulus polyethylene (HMPE)–chain mooring systems indicate that mooring stiffness significantly changes platform motion response, while high water levels generally increase mooring tensions [46]. In sites with large tidal variations, hybrid mooring systems require a careful balance between motion control, tension level, and air-gap safety [47].

In essence, connector and mooring responses are both associated with array constraints and load transmission. For large-scale OFPV deployment, connectors, mooring systems, and array layouts should not be designed independently. Instead, they should be co-optimized within a unified dynamic analysis framework that accounts for mooring failure, connector fatigue, local damage evolution, and array-level redundancy [48].

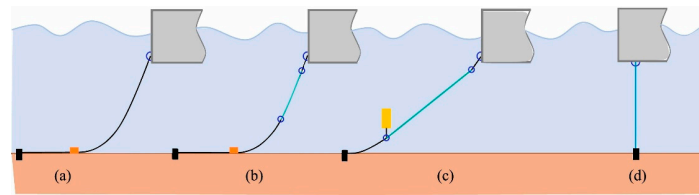


Figure 5. Typical mooring configurations for offshore floating photovoltaic platforms: (a) catenary chain mooring; (b) hybrid catenary mooring; (c) semi-taut mooring; and (d) taut mooring, reproduced from [49].

4.5. Hydroelastic Response of Flexible and Large-Scale Structures

Hydroelasticity is a critical issue for flexible membrane platforms and large-scale interconnected OFPV arrays [11]. For structures with large horizontal dimensions, small thickness, or flexible connections, wave action may induce not only rigid-body motions such as heave, pitch, and roll, but also structural bending, membrane deformation, internal force redistribution, and local stress concentration [50,51]. As platform size increases or structural stiffness decreases, the rigid-body assumption becomes less appropriate, and the coupling among hydrodynamic loads, structural flexibility, and connection constraints must be explicitly considered.

Chen et al. [50] conducted a hydroelastic analysis of a 5 MW interconnected floating box-type offshore PV platform and examined the effects of module size, hinge arrangement, and equivalent structural stiffness. The results showed that appropriate module division and hinge arrangement are necessary to control vertical displacement and hinge shear force. Unless unrealistically high elastic stiffness is assumed, such large-scale arrays cannot be accurately simplified as rigid bodies. Shi et al. [52] developed a hydroelastic analysis framework applicable to complex connections and non-uniform wave fields. Their results indicated that non-uniform wave conditions can significantly amplify equivalent structural stress, with stress levels much higher than those under idealized uniform waves. This suggests that analyses based only on uniform wave fields may underestimate structural risks in real deployment conditions.

For flexible membrane platforms, hydroelastic response is mainly governed by membrane pretension, elastic modulus, bending stiffness of the floating ring, membrane size, and wave frequency. Zhang et al. [53] incorporated both in-plane and out-of-plane modes of the flexible floating ring and membrane into a coupled dynamic equation, and analyzed platform response under regular waves based on potential-flow theory and three-dimensional hydroelastic theory. The results showed that, at low frequencies, the flexible ring and membrane can follow wave-surface motion reasonably well. As wave frequency increases, the influence of ring stiffness becomes more significant, and the platform exhibits pronounced three-dimensional coupled behavior. Zhang et al. [54] further developed a fully coupled time-domain hydroelastic method for membrane-type OFPV structures and validated it through towing-tank experiments. Their work revealed complex interactions among rigid-body motion, membrane deformation, and pitch resonance in irregular waves.

In addition to frequency- and time-domain hydroelastic methods based on potential-flow theory, high-fidelity fluid–structure interaction methods provide useful tools for analyzing flexible floating structures. Jiang et al. [55] developed a numerical approach coupling free-surface Navier–Stokes equations with flexible multibody dynamics. The method revealed strong coupling between rigid-body motion and structural deformation, as well as the influence of high-order nonlinear fluid effects and structural nonlinearity on flexible floating-body response. Although this work was not specifically focused on OFPV, the

methodology provides useful reference for future studies of flexible PV platforms under extreme waves, strong free-surface deformation, and viscous-dominated conditions.

Hydroelastic analysis is also becoming increasingly relevant to hybrid offshore energy systems and protective structures. Tay [56] investigated the hydroelastic response of an offshore floating PV farm combined with a floating breakwater and wave energy converters, showing that the structural response of large OFPV farms may be coupled with surrounding protective structures, wave-energy devices, and the overall field layout. Therefore, hydroelastic research is expanding from the local deformation of flexible membrane platforms to the integrated design of large-scale arrays, connector layouts, and hybrid offshore energy systems [57].

Overall, OFPV hydrodynamic research is evolving from single-platform motion analysis to coupled array dynamics, connector–mooring interaction, and hydroelastic response of flexible and large-scale structures. For future large-scale applications, the key issue is not the response calculation of a single component or a single load case, but the development of integrated analysis frameworks that can simultaneously account for wind–wave–current coupling, multi-body interaction, nonlinear connection behavior, mooring constraints, and structural flexibility.

5. Research Methodologies for Hydrodynamic Analysis

The hydrodynamic behavior of offshore floating photovoltaic (OPFV) systems involves platform motion, multi-body interaction, connector loads, mooring response, and hydroelastic deformation. Because these phenomena occur across different spatial and temporal scales, no single method can resolve all relevant mechanisms with sufficient accuracy and efficiency [7,19]. Existing studies usually select research methods according to the design stage, structural concept, environmental condition, and target response. Analytical and semi-analytical methods are useful for identifying fundamental mechanisms and key parameters. Potential-flow-based frequency- and time-domain methods are efficient for platform motion, array interaction, and mooring-coupled analysis. Computational fluid dynamics (CFD) can resolve viscous effects, slamming, overtopping, and strongly nonlinear free-surface phenomena. Physical model tests and field measurements are essential for model validation and engineering verification. More recently, hybrid numerical methods and data-driven approaches have been introduced to improve predictive capability and computational efficiency.

5.1. Analytical and Semi-Analytical Methods

Analytical and semi-analytical methods provide the theoretical basis for OFPV hydrodynamic research. They are mainly used to formulate governing equations, clarify the coupling between wave loads and structural response, and identify the influence of key parameters. Compared with high-fidelity numerical simulations, these methods are computationally efficient and physically transparent. They are therefore suitable for conceptual design, parametric studies, and mechanism-oriented analysis, especially for simplified flexible structures and idealized boundary conditions.

For flexible and very-large floating structures, analytical methods are often used to establish simplified fluid–structure interaction models. Xu and Wellens [58] idealized a large polymer offshore floating PV structure as an Euler–Bernoulli–von Kármán beam, as shown in Figure 6, and combined it with linear potential-flow theory to derive a second-order analytical solution for wave–structure interaction. This work provided a theoretical framework for analyzing the dynamic response of flexible OFPV-type structures. Similar analytical or semi-analytical approaches based on linear potential theory and eigenfunc-

tion expansion have also been applied to floating elastic disks and flexible plates, demonstrating their usefulness for regular geometries and simplified constraints [59].

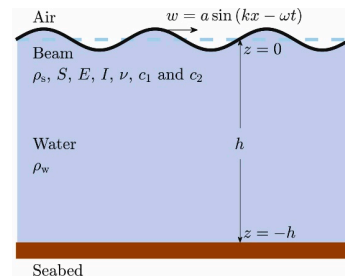


Figure 6. Two-dimensional wave–structure interaction model of a large polymer offshore floating photovoltaic structure idealized as an Euler–Bernoulli–von Kármán beam, reproduced from [58].

Analytical modelling has also been extended from structural response to power-generation performance. Peng et al. [60] proposed a dynamic two-dimensional coupled model that considers platform motion and environmental factors, linking PV module attitude, irradiance, temperature, and electrical output. Such studies indicate that theoretical analysis of OFPV should not be limited to hydrodynamic response alone, but should gradually incorporate power-generation performance and operational state assessment.

Nevertheless, analytical and semi-analytical methods usually rely on simplified geometry, linear assumptions, and idealized boundary conditions. Their applicability is limited when dealing with complex platform configurations, large multi-body arrays, nonlinear connectors, irregular mooring systems, strong nonlinear waves, or overtopping. Therefore, in engineering-oriented studies, these methods are more commonly used for mechanism interpretation and preliminary model development, and are often combined with potential-flow simulations, CFD, or physical experiments.

5.2. Potential-Flow-Based Frequency- and Time-Domain Methods

Potential-flow-based numerical methods are currently among the most widely used tools for OFPV hydrodynamic analysis [40]. These methods usually assume that the fluid is incompressible, inviscid, and irrotational, and describe the flow field using a velocity potential. The governing equation can be written as

$$\nabla^2 \phi = 0 \quad (1)$$

where ϕ is the velocity potential. By applying the free-surface boundary conditions and body-surface boundary conditions, hydrodynamic coefficients such as added mass, radiation damping, wave excitation forces, and response amplitude operators can be obtained. Owing to their high computational efficiency, potential-flow methods are particularly suitable for regular and irregular wave analysis, multi-body interaction, connector–mooring coupling, and preliminary design of large OFPV arrays.

Frequency-domain methods are mainly used to identify the fundamental dynamic characteristics of floating platforms. Under the linear assumption, the frequency-domain equation of motion can be expressed as

$$\left[-\omega^2 (M + A(\omega)) + i\omega B(\omega) + C \right] \xi = F(\omega) \quad (2)$$

where M is the structural mass matrix, $A(\omega)$ is the added mass matrix, $B(\omega)$ is the radiation damping matrix, C is the restoring stiffness matrix, $F(\omega)$ is the wave excitation force vector, and ξ is the complex motion response amplitude. This formulation enables the calculation of response amplitude operators, resonance frequencies, and main hydrodynamic coeffi-

cients. It is therefore useful for the preliminary assessment of single platforms, multi-body systems, and flexible floating structures.

Several OFPV studies have adopted frequency-domain potential-flow methods. Zhang et al. [53] developed a frequency-domain hydroelastic model for membrane-type OFPV platforms based on potential-flow theory and three-dimensional hydroelastic theory. The model used modal expansion to describe the deformation of the floating ring and membrane, and analyzed the influence of membrane pretension, elastic modulus, and floating-ring bending stiffness. Xiong et al. [61] established a numerical model of a flexible membrane PV platform using SESAM and calculated frequency-domain hydrodynamic parameters and response amplitude operators. Their comparison with experimental results showed that potential-flow damping alone may overestimate the response near resonance, indicating the need for additional viscous damping correction. For multi-module systems, Zheng et al. [38] used a higher-order boundary element method to calculate coupled hydrodynamic coefficients and examined the effects of module length, connector parameters, and wavelength on pitch response and connector forces.

Time-domain methods are more suitable for analyzing irregular waves, multi-field environmental loads, nonlinear connectors, and mooring-coupled responses. A commonly used formulation is the Cummins equation:

$$(M + A_{\infty})\ddot{x}(t) + \int_0^t K(t-\tau)\dot{x}(\tau)d\tau + Cx(t) = F(t) \quad (3)$$

where A_{∞} is the infinite-frequency added mass, $K(t-\tau)$ is the retardation function representing the radiation memory effect, $x(t)$ is the displacement vector, and $F(t)$ is the external force vector. By transforming frequency-domain hydrodynamic coefficients into the time domain and coupling them with mooring forces, connector forces, damping devices, wind loads, and current loads, time-domain analysis can provide response histories that are closer to engineering operating conditions.

Wang et al. [62] developed a time-domain coupled model for a taut-moored floating PV array system by combining three-dimensional potential-flow theory with a lumped-mass mooring model. First-order wave forces and second-order difference- and sum-frequency wave loads were included. The results showed that taut mooring could reduce mooring-line and connecting-cable tensions, whereas high pretension and second-order sum-frequency loads may enhance high-frequency tension components and increase the risk of line failure. Jin et al. [40] used ANSYS-AQWA to analyze a moored and hinged multi-body platform under irregular waves and wind loads, revealing the influence of wind on surge and sway instability as well as mooring tension redistribution.

In recent years, frequency–time-domain coupled frameworks have become increasingly important for OFPV array analysis. As illustrated in Figure 7, added mass, radiation damping, wave excitation forces, response amplitude operators, and second-order wave loads are first obtained in the frequency domain based on potential-flow theory. These hydrodynamic quantities are then introduced into time-domain simulations, where they are coupled with connector forces, mooring systems, damping devices, wind loads, current loads, and, where necessary, structural deformation models. This approach provides an efficient way to analyze the dynamic response of large multi-module OFPV systems under irregular waves and combined environmental loads. It has been applied to flexible connector tension, mooring response, hydroelastic analysis of membrane platforms, multi-body interaction, connector loads, and second-order wave effects [34,42,43,54]. Despite its efficiency, this framework still has limited capability in representing viscous damping, slamming, overtopping, green-water effects, and strongly nonlinear free-surface phenom-

ena. When these effects become important, potential-flow-based analysis should be complemented by CFD simulations, physical model tests, or empirical correction methods [63].

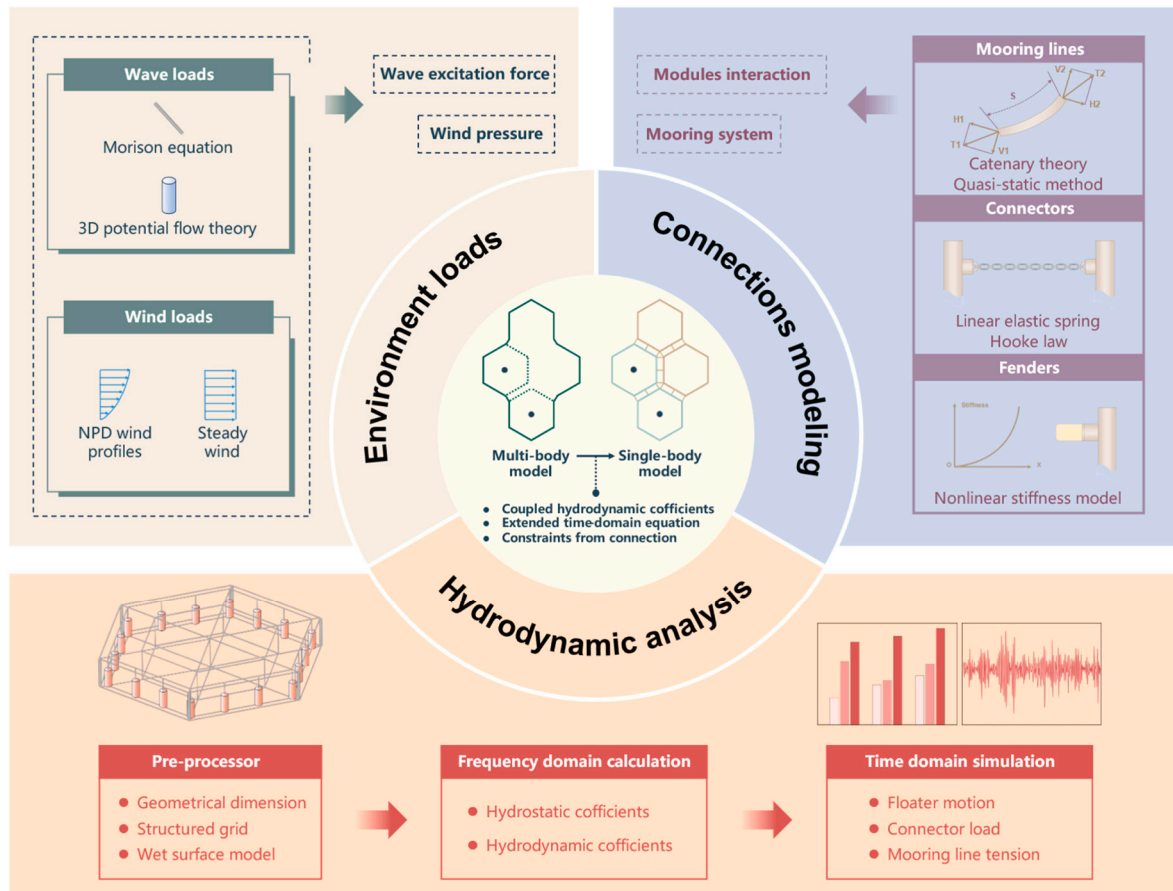


Figure 7. Frequency–time-domain coupled framework for hydrodynamic analysis of multi-module offshore floating photovoltaic systems based on potential-flow theory, reproduced from [34].

For large OFPV arrays, potential-flow-based and time-domain frameworks should also be extended to account for spatially inhomogeneous wave fields. Instead of prescribing a single uniform incident wave condition for the entire array, the wave excitation of each module may be defined using location-dependent wave spectra, wave directions, phases, and coherence functions. Similar issues have been extensively studied in the very-long floating bridge community, where kilometer-scale floating structures may be exposed to spatially varying wave conditions. Rodrigues et al. [64] developed hydroelastic model tests for truncated floating bridges, while Rodrigues [65] proposed a numerical procedure for calculating first-order wave–structure interaction loads in wave farms and other multi-body structures subjected to inhomogeneous waves. These studies provide useful methodological references for future OFPV array analysis, especially when OFPV arrays are deployed in semi-sheltered nearshore waters, complex bathymetry, or hybrid layouts involving breakwaters, offshore wind farms, and other marine infrastructure.

5.3. CFD Simulations

CFD methods directly solve viscous flow and free-surface evolution, making them suitable for hydrodynamic phenomena that are difficult to capture using potential-flow theory. These include viscous damping, flow separation, local pressure distribution, wave slamming, overtopping, vortex shedding, and strongly nonlinear wave–structure interaction. Most existing studies use Reynolds-averaged Navier–Stokes equations, the volume-

of-fluid method for free-surface tracking, and turbulence models such as $k-\omega$ SST or RNG $k-\epsilon$ to predict platform motion, pressure distribution, local impact, and mooring loads.

CFD has first been applied to the seakeeping analysis of single platforms or simplified floating bodies. Ou et al. [66] used STAR-CCM+ to simulate the hydrodynamic responses of barge-type and catamaran-type floaters under regular waves, and validated the results through wave-flume tests. Their study showed that CFD can reasonably capture heave and pitch response amplitude operators, as well as differences in mooring forces between upstream and downstream floaters. Shu et al. [67] investigated the hydrodynamic characteristics of a nearshore floating PV platform under regular waves using a VOF-based numerical model, which was validated against physical model tests. The results showed that mooring forces may increase significantly with increasing wave height and wavelength, and that notable slamming may occur around pontoons under large wave steepness.

For multi-module arrays and complex platform concepts, CFD is often used as a complementary tool rather than a standalone design method. Tang et al. [47] introduced viscous damping obtained from STAR-CCM+ free-decay simulations into an AQWA–OrcaFlex coupled model to improve the prediction of hydrodynamic and mooring-coupled responses of semi-submersible floating PV platforms. Zhang et al. [63] further incorporated CFD-derived viscous damping coefficients into a potential-flow solver to establish a hybrid numerical method for hinged multi-module floating PV arrays. Their results showed that the calibrated potential-flow model was more consistent with high-fidelity simulations in predicting motion amplitudes and connector loads.

CFD is also useful for analyzing protective structures and local configuration optimization. Lu et al. [68] developed a two-dimensional numerical wave flume in FLOW-3D to investigate a curved-plate double-pontoon wave-attenuation structure. Their parametric study revealed the effects of pontoon draft, curved-plate span, and relative freeboard on wave attenuation and horizontal wave forces. Such studies demonstrate the advantage of CFD in resolving local flow details and supporting structural optimization. However, CFD remains computationally expensive and is sensitive to mesh resolution, time-step selection, turbulence modelling, and numerical wave-generation strategies. Full CFD simulation is therefore not practical for large-scale OFPV arrays under long-duration random sea states.

5.4. Physical Model Tests and Field Measurements

Physical model tests provide direct measurements of platform motion, local loads, connector forces, mooring tensions, overtopping, and deformation. They are essential for validating numerical models, identifying weak structural components, and assessing platform behavior under extreme or complex sea states. Compared with numerical simulations, experiments can more realistically capture free-surface nonlinearity, local impact, structural connections, and flexible deformation, especially for novel platform concepts and array systems [69].

Although this review is centered on OFPV development in China, OFPV model testing should be interpreted within the broader international context of very large floating structures, offshore floating solar systems, and floating-breakwater-protected arrays. Several recent European test campaigns provide important methodological benchmarks. For example, the Norwegian soft-connected lattice-type floating solar concept was tested for harsh offshore conditions, highlighting the importance of module compliance, rope-type connections, array integrity, and survivability under severe waves [70]. In the Netherlands, wave-basin tests of a multi-body floating PV system sheltered by a floating breakwater were conducted at a scale of 1:10, with measurements of relative motions, hinge loads, buckling risk, and wave-attenuation performance. These studies represent an important step from isolated small-scale platform tests towards array-level and protection-

oriented validation. They also provide useful references for future Chinese OFPV experiments, particularly in terms of similitude design, irregular and directional wave conditions, connector-load measurement, mooring-boundary effects, and failure-mode identification.

For single platforms and simplified floaters, Ou et al. [66] conducted wave-flume tests to compare the seakeeping performance of catamaran-type and barge-type floating bodies under regular waves, obtaining heave response, pitch response, and mooring-force variation. Ji et al. [71] carried out experimental and numerical investigations of a novel OFPV platform and validated its global motion and local load characteristics under regular and irregular waves. For flexible membrane platforms, Ren et al. [10], Le et al. [27], and Xiong et al. [61] performed model tests to study the motion, deformation, and power-generation behavior of membrane-type or flexible floating PV systems under different wave conditions. These studies show that flexible platform response is not limited to rigid-body motion, but is closely related to membrane deformation, water accumulation, and local loading.

For multi-module arrays and connector performance, model testing is particularly important. He et al. [44] combined two-module model tests with numerical simulations to investigate dynamic response, connector loads, and mooring tension under different wave directions. Their results indicated that the maximum connector load and maximum mooring tension may not occur under the same wave condition, and that mooring failure can substantially increase the tension in the remaining lines. Lian et al. [46] tested a multi-floater system with semi-rigid connection joints and found that connection joints near the center of the array are more prone to stress concentration, while increased water level can significantly amplify mooring tension. Lu et al. [72] conducted regular- and irregular-wave tests on a novel floating-box array, measuring response amplitude operators and observing pitch-response attenuation along the wave propagation direction as well as array sheltering effects.

Experimental studies have also been extended to special structural concepts and hybrid application scenarios. Jiang et al. [70] conducted model tests on a flexibly connected lattice-type OFPV concept and showed that the flexible array had good wave-following capability and maintained array integrity under severe conditions. Mi et al. [73] studied a rope-net modular floating PV platform and found that this type of flexible platform could follow wave motion effectively, but that global drift and boundary constraints were strongly dependent on the mooring system. Xie et al. [74] investigated a fishery–PV complementary floating structure and showed that auxiliary aquaculture-related facilities can further modify platform motion and mooring response. Saitov and Jiang [75] used model tests to calibrate frequency–time-domain coupled analysis results for a modular floating PV array, improving the prediction reliability of platform motion, mooring response, and rope tension.

Field measurements are a critical link between model-scale tests and engineering application. Unlike laboratory experiments, field tests reflect real sea conditions, including combined wind–wave–current action, tidal variation, irregular waves, marine corrosion, biofouling, and actual operation and maintenance constraints [76]. Several Chinese OFPV demonstration projects have been designed partly to obtain field data on platform motion, mooring tension, structural response, and power-generation performance. Such data are indispensable for validating numerical models, calibrating design parameters, and developing engineering standards. Nevertheless, field measurements are costly, site-dependent, and often limited in duration. They should therefore be combined with numerical simulations and physical model tests to form a closed validation loop; representative model-test configurations reported in the literature are summarized in Figure 8.

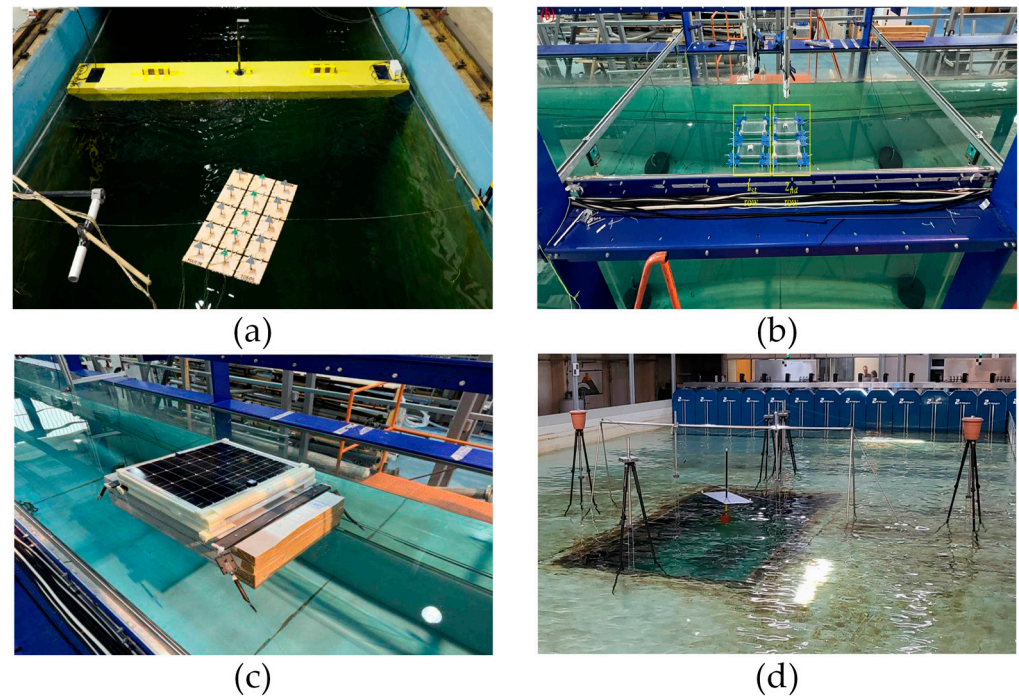


Figure 8. Physical model tests of representative floating photovoltaic systems. (a) 5×3 floating photovoltaic array sheltered by a floating breakwater [77], (b) 2×2 scaled floating photovoltaic array [73], (c) high-freeboard ship-shaped floating photovoltaic platform [66], (d) HelioSea concept platform [78].

5.5. Hybrid Methods and Data-Driven Analysis

As OFPV systems move towards large-scale arrays and more complex marine environments, the limitations of individual research methods become increasingly evident. A practical research strategy is to develop hybrid analysis frameworks in which potential-flow methods provide efficient array-scale dynamic prediction, CFD supplies corrections for local viscous and nonlinear effects, physical model tests validate key responses, and field measurements feed back into engineering design. Such frameworks can balance computational efficiency and prediction accuracy, making them suitable for multi-body interaction, connector–mooring coupling, hydroelastic response, and complex environmental loading.

In this context, hybrid numerical and data-driven methods should be benchmarked against high-quality experimental datasets rather than calibrated only against small-scale or simplified domestic tests. The international basin-test campaigns on soft-connected floating solar arrays, floating-breakwater-sheltered FPV systems, and hydroelastic large floating structures provide valuable validation data for array-level motion, connector forces, hinge loads, mooring response, wave attenuation, and failure modes [64,70,77]. For OFPV applications in China, these datasets can serve as methodological references for improving potential-flow models, calibrating CFD-derived viscous damping, validating connector and mooring models, and developing machine learning-based rapid prediction tools. Therefore, future hybrid-method development should combine domestic sea-trial data with international benchmark experiments to improve both engineering relevance and model generality.

Potential-flow–CFD hybrid methods are a representative direction. Potential-flow solvers can efficiently analyze global responses of large arrays, whereas CFD can be used to estimate additional viscous damping, verify slamming and overtopping, and resolve local flow details. Studies by Tang et al. [47] and Zhang et al. [63] showed that potential-flow models calibrated using CFD-derived damping can more accurately predict plat-

form response amplitudes and connector loads. Numerical–experimental hybrid validation is also important, especially for flexible platforms, multi-module arrays, and nonlinear connection systems. Model tests can be used to calibrate damping, connector stiffness, contact parameters, and mooring properties, thereby improving the reliability of engineering calculations.

Data-driven approaches are mainly used for rapid prediction, operational monitoring, and health management. Liu et al. [48] generated array-motion and cable-tension datasets using OrcaFlex and compared neural-network models such as back-propagation neural networks, gated recurrent units, and long short-term memory networks for mooring-tension prediction. The results suggested that data-driven models have potential for fast response prediction and operational state identification as array scale and environmental complexity increase. In the future, the integration of field monitoring data, physics-based numerical models, and machine learning algorithms may support the development of digital twins and structural health management systems for OFPV farms.

Overall, hydrodynamic research methodologies for OFPV have developed into a multi-level framework that includes analytical modelling, potential-flow-based numerical analysis, CFD simulation, physical model testing, field measurement, and data-driven prediction. Potential-flow-based frequency- and time-domain methods remain the main tools for engineering analysis. CFD is most valuable for local nonlinear effects and viscous correction. Physical model tests and field measurements provide validation and engineering feedback. Future research should further strengthen multi-physics coupling, high-fidelity local modelling, numerical–experimental validation, and rapid engineering assessment methods suitable for China's nearshore and offshore OFPV applications.

6. Reliability, Durability, and Survivability Challenges

Although offshore floating photovoltaics (OFPVs) in China have made initial progress in platform concepts, sea trials, and hydrodynamic analysis, the technology is still in the transition stage from prototype verification to engineering application. Compared with inland floating PV systems, OFPV platforms must maintain safe and reliable operation over long service periods under waves, wind, currents, tidal variations, salt-spray corrosion, biofouling, material ageing, and extreme weather events. Therefore, the main engineering challenge is not merely whether PV modules can be supported on floating structures, but whether the entire system can remain structurally safe, operationally stable, electrically reliable, and economically maintainable throughout its life cycle.

From an engineering perspective, the reliability of OFPV systems is governed by multiple coupled mechanisms. Extreme sea states control platform survivability; long-term cyclic loads dominate fatigue damage; corrosion, biofouling, and material degradation affect structural and operational durability; and insufficient design standards and full-scale validation restrict the translation of research outcomes into engineering practice. These issues are closely related to the hydrodynamic problems discussed in previous sections, particularly array interaction, connector loads, mooring response, and hydroelastic deformation.

6.1. Survivability Under Extreme Sea States

Survivability under extreme sea states is one of the most critical requirements for the engineering application of OFPV. In exposed marine environments, floating PV platforms may experience strong wave impact, large relative motion, overtopping, local collision, connector failure, and mooring overload. Unlike normal operating conditions, platform safety under extreme conditions depends not only on the strength of individual floaters, but also on array layout, connection strategy, wave-energy dissipation, redundancy, and the possible use of protective structures.

Improving structural flexibility and modularity is an important approach to reducing extreme environmental loads. Dai et al. [79] proposed a flexibly connected modular floating PV concept, in which weakly connected modules were used to mitigate the effects of environmental loading. Model tests showed that the array could follow wave motion under operating conditions and retain a certain level of survivability under extreme wave heights exceeding 10 m. This finding indicates that flexible modular arrays may help reduce local load concentration associated with rigid connections. However, large relative motion may also cause local collision between modules, suggesting that wave-following capability and array integrity must be carefully balanced.

Protective structures provide another possible route for enhancing OFPV survivability. For offshore floating PV systems, using external wave-attenuation facilities may be more cost-effective than continuously increasing the strength of the floating platform itself [80]. Van der Zanden et al. [77] investigated a multi-body floating PV system sheltered by a floating breakwater through wave-basin experiments. Their results showed that the breakwater reduced the high-frequency wave energy responsible for relative module motion, thereby decreasing hinge loads and buckling risk. Gomis et al. [76] also studied a floating PV system with a surrounding floating barrier and demonstrated its ability to improve the local wave environment and dissipate wave energy, especially under short-wave conditions.

These studies suggest that flexible modular arrays, floating breakwaters, and peripheral protective structures can all contribute to reducing platform response and local failure risk under extreme waves. Figure 9 illustrates this protection-oriented design logic for a floating breakwater integrated with an OFPV system. However, most existing studies remain limited to scaled model tests, specific structural concepts, and selected environmental conditions. Systematic survivability assessment under typhoons, storm surges, extreme waves, and their coupled effects is still insufficient. For China's southeastern coastal waters and future deep-sea applications, extreme environmental statistics, array-level dynamic response, connector failure, mooring redundancy, and protective-structure design should be incorporated into an integrated survivability framework.

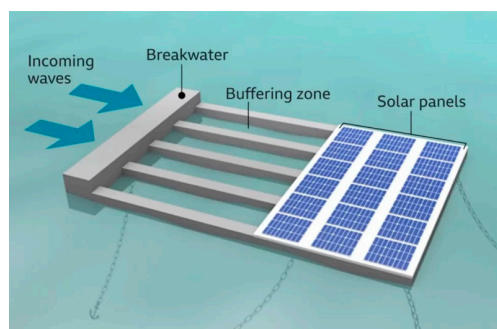


Figure 9. Conceptual integration of a floating breakwater with an offshore floating photovoltaic system for wave attenuation and platform protection, reproduced from [7].

6.2. Fatigue Reliability of Large-Scale Arrays

As OFPV develops from single-platform demonstrations to large-scale arrays, structural reliability and fatigue become increasingly important. Large arrays involve stronger multi-body hydrodynamic interactions, more complex connection networks, and longer load-transfer paths. Under long-term wave, wind, and current actions, connectors, mooring lines, flexible membranes, supporting frames, and local joints may all experience continuous cyclic loading. Fatigue damage is usually not governed by a single extreme event, but by the accumulation of long-term low-amplitude cyclic response, local stress concentration, and material degradation.

Previous hydrodynamic studies have shown that edge modules, corner modules, front-row connectors, and mooring-boundary regions are more likely to experience amplified loads. Connector axial forces, hinge shear forces, local contact forces, and mooring tensions vary significantly with wave direction, array layout, module spacing, and connection stiffness [44]. For flexible or membrane-type platforms, stress concentration may also occur near the connection between the membrane, supporting cables, and peripheral floating ring [57]. Therefore, fatigue reliability in large OFPV arrays should not be treated as a component-level strength problem alone. It is instead a system-level issue involving global platform motion, local structural details, connection boundary conditions, and long-term environmental evolution.

Zou et al. [81] pointed out that offshore floating PV systems are continuously exposed to combined wind, wave, and current actions, with wave loading being a major source of fatigue damage. Fatigue cracks are particularly likely to initiate at connection joints and other structural discontinuities. Their study further incorporated the influence of climate change on future sea-state statistics into fatigue assessment, indicating that reliability evaluation of OFPV systems should not rely solely on historical environmental data. Instead, possible changes in environmental conditions over the service life should also be considered.

Array configuration and connection strategy strongly influence fatigue reliability. Flexible and soft-connection arrays can reduce part of the environmental load, but they may also increase relative motion, collision risk, wear, and connector fatigue [46]. Rigid or semi-rigid connections can improve global integrity, but may lead to local bending moments and stress concentration. The damage patterns further underline the need to treat fatigue and storm damage as array-level reliability problems rather than isolated component failures. For large-scale engineering applications, structural reliability design should therefore move beyond conventional strength checks and include life-cycle fatigue assessment, connector damage evolution, mooring redundancy, progressive failure, and array-level failure propagation.

6.3. Corrosion, Biofouling, and Material Degradation

Corrosion, biofouling, and material degradation are important durability problems that distinguish OFPV from floating PV systems deployed in inland waters. Offshore platforms are exposed to high humidity, high salinity, ultraviolet radiation, cyclic wetting and drying, and long-term mechanical loading. Floats, metallic connectors, mooring components, electrical accessories, membranes, cables, and support structures may therefore undergo different forms of performance deterioration [7]. Metallic members are vulnerable to salt-spray corrosion and splash-zone degradation, whereas polymers and composite materials may suffer from ultraviolet ageing, hydrothermal degradation, water absorption, creep, and cyclic stress effects.

Biofouling can further modify the mass distribution, surface roughness, hydrodynamic drag, and added weight of floating structures. These changes may affect platform motion, mooring tension, connector loads, and long-term structural response. For low-freeboard and flexible membrane platforms, biological attachment, salt deposition, bird guano, and surface contamination may also influence PV module transmittance, heat dissipation, cleaning frequency, and power-generation performance. Therefore, biofouling should not be regarded only as a maintenance issue; it should also be incorporated into hydrodynamic performance and structural reliability assessment.

Compared with platform motion, connector loads, and mooring response, corrosion, biofouling, and material degradation have not yet formed a mature research framework in OFPV studies. Existing work is still mainly limited to conceptual discussion, material selection, and accelerated ageing tests. Systematic studies on performance degradation,

structural safety, and maintenance strategies under real marine service conditions remain insufficient. OFPV platforms usually consist of multiple materials, including HDPE, composites, metallic frames, membrane materials, ropes, cables, and electrical devices. These materials may exhibit different degradation mechanisms under salt spray, ultraviolet radiation, immersion, temperature variation, and cyclic loading. Wei et al. [7] noted that biofouling and corrosion remain insufficiently studied and that effective mitigation strategies are still lacking in floating PV development.

Future research on OFPV durability should therefore further integrate material-level ageing tests with life-cycle performance assessment of multi-material structural systems. Particular attention should be paid to the coupling between material degradation and cyclic loads, the influence of biofouling on hydrodynamic performance, the long-term effectiveness of anti-corrosion and anti-fouling measures, and offshore maintenance strategies such as inspection, cleaning, repair, and component replacement.

6.4. Lack of Design Standards and Full-Scale Validation

The lack of dedicated design standards and full-scale validation is another major barrier to the engineering development of OFPV. Offshore floating PV platforms involve structural configuration, hydrodynamic response, connectors, mooring systems, electrical safety, operation and maintenance, and environmental adaptability. However, systematic design standards specifically developed for open-sea OFPV systems are still lacking. Existing guidelines mainly focus on inland or nearshore floating PV applications. For example, DNVGL-RP-0584 provides recommendations for the design, development, operation, and decommissioning of floating PV plants [82], but it does not fully address the specific technical requirements of offshore floating PV. Similarly, the Chinese design specification for floating PV systems indicates that floating PV sites should not be located in distant offshore waters, and a dedicated standard framework for OFPV has not yet been established [83].

Because of this gap, current OFPV research and engineering design often borrow experience from offshore structures, inland floating PV, and offshore wind engineering [84]. However, OFPV platforms have distinctive features, including lightweight structures, large horizontal dimensions, low freeboard, multi-module connections, array deployment, and strong coupling between structural and electrical systems. They cannot be designed simply by applying standards from conventional offshore platforms or inland floating PV systems. Issues such as air-gap safety, connector fatigue, array boundary effects, hydroelastic response, waterproofing and insulation of PV modules, corrosion protection, and offshore operation and maintenance all require more targeted design criteria and safety assessment methods.

Full-scale engineering validation is also insufficient. Existing studies are still dominated by numerical simulations, scaled model tests, and conceptual prototypes, while long-term field data remain limited. Claus et al. [78] validated the conceptual feasibility of the HelioSea configuration through prototype testing, demonstrating the value of prototype experiments for early-stage concept screening. Zhang et al. [15] conducted field tests on a semi-submersible OFPV platform in the Yellow Sea, providing important data on platform motion, mooring tension, and environmental adaptability under real sea conditions. Their study showed that the platform operated stably in waters of approximately 20 m depth, while tidal variation had a significant influence on mean mooring tension. Such field data are valuable for validating numerical models and improving design reliability.

Nevertheless, most existing field tests are short-term, small-scale, or limited to single-platform verification. They are not yet sufficient to support large-array design, life-cycle fatigue assessment, commercial operation, or standard development. Future work should establish a closed-loop validation system that integrates numerical simulation, physical

model testing, prototype trials, and long-term field monitoring. Dedicated design standards for Chinese nearshore, typhoon-prone, and offshore environments should also be developed progressively. For OFPV systems, standardization should cover not only structural safety, but also site selection, environmental load assessment, array layout, connectors and moorings, material durability, electrical safety, operation and maintenance, monitoring, and decommissioning.

Overall, the reliability challenges of OFPV are systematic in nature. Extreme sea states determine platform survivability, cyclic environmental loads control fatigue damage, corrosion and biofouling affect material and operational durability, and the lack of standards and full-scale validation limits the transformation of research findings into engineering design practice. Future OFPV development in China should therefore shift from individual technology verification towards life-cycle, system-level, and full-scale reliability assessment.

7. Hybrid Offshore Renewable Energy Systems and Future Development Pathways

The long-term development of offshore floating photovoltaics (OFPVs) is unlikely to rely on isolated PV platforms alone. In marine environments, the use of sea space, grid connection, offshore transmission, installation vessels, operation and maintenance resources, and environmental protection requirements all impose strong constraints on single-purpose energy projects. A more plausible development pathway is to integrate OFPV with other offshore activities and renewable energy systems, such as offshore wind power, wave energy, floating breakwaters, aquaculture, marine ranching, energy storage, and hydrogen production [85]. In this context, OFPV should be viewed not only as a floating power-generation technology, but also as a component of future integrated offshore energy systems.

Hybridization can improve the utilization efficiency of marine space and shared infrastructure. Offshore substations, export cables, maintenance vessels, monitoring systems, and mooring areas are costly resources. If several energy technologies can share part of this infrastructure, the system-level cost may be reduced. Hybrid systems may also benefit from the temporal complementarity among solar, wind, and wave resources, which can help smooth power output and improve the utilization of transmission capacity [86]. The representative integration mode in Figure 10 shows that these benefits are accompanied by more complex engineering problems, including structural coupling, hydrodynamic interaction, power management, ecological impacts, navigation safety, and multi-system maintenance.

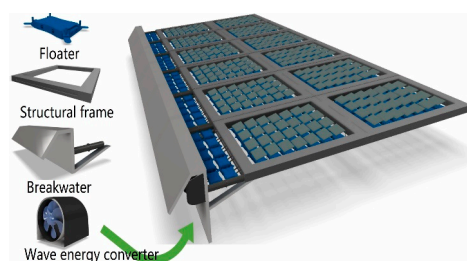


Figure 10. The combined floating breakwater, wave energy converter, and floating PV system, reproduced from [8].

International experience shows that hybrid offshore renewable energy systems should be assessed not only at the conceptual level, but also through array-scale hydrodynamic testing and coupled numerical validation [77]. In particular, floating-breakwater-sheltered FPV tests in the Netherlands have demonstrated how protective structures can reduce high-frequency wave energy, relative motions, hinge loads, and buckling risk in interconnected

PV modules. Norwegian soft-connected floating solar studies have further shown that compliant modularity and flexible load-transfer paths are important for harsh offshore conditions [70]. These international developments provide useful benchmarks for China's emerging wind–PV co-location, PV–breakwater, and PV–wave energy concepts. The key task for Chinese OFPV development is therefore to adapt these state-of-the-art methods to domestic site conditions, including shallow nearshore waters, typhoon-prone regions, offshore wind-farm infrastructure, and large-scale marine-space planning.

7.1. Offshore Wind–PV Co-Location

Offshore wind farms represent one of the most practical scenarios for the near-term development of OFPV [87]. China has already established a relatively mature offshore wind industry, including engineering construction, grid connection, offshore substations, transmission routes, and operation and maintenance systems. Deploying floating PV arrays within or around offshore wind farms may allow shared use of sea space, electrical infrastructure, and maintenance resources, thereby improving marine-space utilization and reducing the overall cost of offshore renewable energy development. Existing demonstration projects, such as the Shandong Peninsula South No. 3 project and the Dongtai wind–PV co-location project, have already reflected this development direction.

From the perspective of power generation, wind and solar resources show a certain degree of temporal complementarity. PV output is mainly controlled by solar irradiance, cloud cover, and day–night variation, whereas wind power output depends on wind speed and meteorological processes. Their combined operation may reduce the variability associated with a single energy source and improve the utilization of offshore transmission systems. However, offshore wind–PV co-location is not a simple addition of floating PV arrays into wind farm areas. It requires integrated consideration of wind turbine wakes, safety distance, navigation and maintenance corridors, mooring boundaries, submarine cable routing, and extreme-sea-state interactions.

For floating PV platforms deployed inside offshore wind farms, additional constraints may arise from turbine foundations, inter-array cables, offshore substations, installation vessels, and maintenance activities. International studies on hybrid offshore wind–solar systems have gradually shifted from resource-complementarity assessment to field-level integrated design. López et al. [88] investigated the potential of combined floating offshore wind and solar PV using the Asturias region in Spain as a case study. Bi and Law [89] further analyzed the influence of high wind and wave conditions on floating PV performance in wind–solar co-location scenarios, showing that the relative variation in PV output may remain limited under the studied conditions. Ali et al. [90] summarized site-selection factors for offshore wind–solar projects, including environmental regulations, resource conditions, economic feasibility, social acceptance, and technology maturity.

Future research on offshore wind–PV co-location should move from single-device design towards field-level optimization. Key issues include the joint layout of wind turbines and PV arrays, capacity allocation of shared transmission systems, coordinated operation and maintenance, safety distance under typhoon conditions, multi-energy power forecasting, and dispatch strategies. For China, offshore wind–PV co-location is likely to be one of the most realistic pathways for early OFPV commercialization, particularly in nearshore and offshore wind-farm regions with established infrastructure.

7.2. Integration with Wave Energy and Floating Breakwaters

The integration of OFPV with wave energy has strong ocean-engineering relevance. Unlike wind–PV complementarity, which mainly concerns energy output and infrastructure sharing, wave–PV integration may also provide hydrodynamic synergy [91]. On the

one hand, wave energy converters or floating breakwaters can be arranged around floating PV arrays to attenuate incident waves and reduce wave-induced excitation inside the array. On the other hand, floating PV platforms may provide structural space and shared support systems for wave energy devices, thereby improving the overall energy-capture capability of the offshore system.

Yang et al. [85] proposed a hybrid system integrating floating PV, floating wind turbines, and wave energy devices within a shared floating platform and mooring system. This concept reflects the development direction of integrated offshore renewable energy platforms. Zheng et al. [92] explored wave energy utilization within a floating PV array by combining box-type modules and semi-submersible modules and introducing power take-off (PTO) damping at the connection locations. The design used the hydrodynamic characteristics of different floaters to reduce array motion, while optimized PTO damping further suppressed pitch and heave responses and enabled wave energy capture.

These studies indicate that wave–PV integration should not be regarded merely as the superposition of two energy sources. Instead, it should be understood as a coupled problem involving energy capture, wave attenuation, platform motion control, structural loads, and fatigue reliability. PTO damping, floater arrangement, connector stiffness, and mooring parameters not only affect wave-energy absorption efficiency, but also change the motion response, connector loads, and fatigue characteristics of floating PV platforms [93]. Therefore, the design of wave–PV hybrid systems requires a balance among energy capture, platform stability, structural safety, and operation and maintenance complexity.

For China's nearshore and future deep-sea OFPV applications, the integration of wave energy devices and floating PV arrays may provide a promising pathway for wave attenuation, platform protection, and multi-energy output stabilization. However, the additional mechanical systems, control strategies, and maintenance requirements of wave energy converters may also increase system complexity. Future studies should therefore focus on the co-design of floating PV arrays, wave energy devices, floating breakwaters, mooring systems, and power management strategies.

7.3. Integration with Aquaculture and Marine Ranching

Fishery–PV complementarity and marine ranching are important application scenarios for OFPV. Compared with large deep-sea energy bases, nearshore aquaculture areas, marine ranches, and offshore fishery facilities have more direct demand for distributed clean electricity. Floating PV systems can provide power for aeration equipment, monitoring devices, feeding systems, aquaculture platforms, lighting, communication facilities, and marine ranching operations. When combined with energy storage, such systems can improve power-supply stability under off-grid or weak-grid conditions [94].

The main advantage of fishery–PV and marine-ranching applications is that they can improve the comprehensive utilization of marine space while supporting the coordinated development of marine energy and fishery production. However, these applications are also highly complex. Shading from PV arrays may change local light conditions, water temperature, and primary productivity. Platform layout may affect water exchange, aquaculture operations, and vessel navigation. Mooring lines and anchoring systems may also conflict spatially with cages, nets, and marine ranching structures. Therefore, fishery–PV integration should not be evaluated only from the perspective of energy yield. Ecological impacts, aquaculture suitability, maintenance accessibility, navigation safety, and sea-use coordination must also be considered.

For fishery–PV and marine-ranching scenarios, environmental impact and ecological compatibility are key factors determining long-term sustainability. Future studies should quantify the influence of floating PV coverage on light penetration, dissolved oxygen, wa-

ter exchange, nutrient distribution, plankton communities, and aquaculture productivity [95]. In addition, integrated design methods are required to coordinate platform layout, mooring arrangement, aquaculture facilities, maintenance routes, and ecological monitoring [96]. For China, where coastal aquaculture and marine ranching are widely developed, this scenario may provide an important pathway for distributed OFPV applications, especially in sheltered or moderately exposed waters.

7.4. Energy Storage, Hydrogen Production, and Offshore Energy Islands

As OFPV deployment moves from small-scale demonstrations to larger offshore systems, energy storage and power conversion will become increasingly important. The output of floating PV is inherently variable because of diurnal cycles, cloud cover, platform motion, and marine weather conditions. When OFPV is integrated with offshore wind and wave energy, the combined power output may become more stable than that of a single source, but it will still require energy storage, power smoothing, and coordinated dispatch to meet grid-connection requirements [97].

Battery energy storage can support short-term power smoothing, frequency regulation, and off-grid supply for marine ranches, islands, and offshore facilities. For larger offshore energy bases, hydrogen production may provide a pathway for long-duration energy storage and large-scale energy conversion. Excess electricity from offshore wind, floating PV, and wave energy could be used for seawater desalination, electrolysis, hydrogen storage, and transport. In such a system, OFPV would no longer be an independent generation unit, but part of an integrated offshore energy chain involving power generation, conversion, storage, transmission, and consumption [94].

The concept of offshore energy islands may further expand the role of OFPV. Floating PV arrays could be combined with offshore wind turbines, wave energy converters, floating breakwaters, substations, storage systems, hydrogen-production facilities, and maintenance bases. Such systems may be particularly relevant for deep-sea or remote-island applications where conventional grid connection is difficult or expensive. However, offshore energy islands also introduce substantial technical and economic uncertainties. The coupled design of floating structures, mooring systems, power systems, safety systems, and maintenance strategies remains at an early stage.

For future Chinese applications, energy storage and hydrogen production should be considered according to site conditions and development scale. For nearshore aquaculture or island supply, distributed PV-storage systems may be more realistic. For offshore wind-PV co-location, shared transmission and grid-support functions are likely to be more important. For deep-sea integrated energy bases, hydrogen production and multi-energy conversion may become long-term development directions. In all cases, techno-economic assessment, safety analysis, marine environmental impact, and life-cycle carbon evaluation are needed to determine the feasibility of different pathways.

7.5. Future Research Priorities for China

The future development of OFPV in China should be guided by both engineering demand and scientific challenges. The most immediate need is site-specific platform selection. Nearshore sheltered waters, offshore wind-farm regions, typhoon-prone coastal areas, and deep-sea sites cannot rely on a single structural route; each requires design criteria that balance environmental adaptability, structural robustness, installation feasibility, and life-cycle cost.

Array-scale hydrodynamic analysis should become a central research focus. Large OFPV farms involve multi-body interaction, connector-load amplification, mooring tension redistribution, and hydroelastic deformation. Future models need to account for wind-

wave–current coupling, nonlinear connectors, mooring failure, local damage propagation, and array-level redundancy rather than treating modules as independent floating units.

Long-term reliability and durability also need to enter the early design stage. Fatigue, corrosion, biofouling, material ageing, waterproofing, electrical insulation, and offshore maintenance should not be handled as secondary issues after structural design has been fixed; they should be embedded in life-cycle reliability assessment and operation and maintenance planning from the outset.

Field measurements and full-scale validation remain particularly urgent. Existing sea trials are limited in both scale and duration, and long-term monitoring under real marine environments is still scarce. Future demonstration projects should systematically measure environmental conditions, platform motion, connector loads, mooring tension, structural strain, power output, corrosion, biofouling, and maintenance events, because such datasets are essential for model validation, design-code development, and commercial risk assessment.

OFPV should also be developed within a broader framework of hybrid offshore renewable energy systems. Research on offshore wind–PV co-location, wave–PV coupling, fishery–PV complementarity, energy storage, hydrogen production, and offshore energy islands should focus not only on how to install PV modules offshore, but also on how to integrate floating PV into marine energy systems that are safe, reliable, economical, and environmentally compatible.

The future of OFPV in China will depend on the transition from single-platform demonstration to array-scale design, from short-term sea trials to life-cycle reliability assessment, and from isolated PV systems to integrated offshore renewable energy platforms. This transition requires coordinated progress in structural design, hydrodynamic analysis, material durability, power-system integration, environmental assessment, and engineering standardization.

8. Conclusions

Offshore floating photovoltaics (OFPVs) offer a promising route for extending solar energy development from land and inland waters to marine environments. In China, this technology is particularly relevant because of the strong electricity demand in coastal regions, limited land availability, abundant nearshore sea space, a mature photovoltaic manufacturing industry, and the rapid expansion of offshore wind infrastructure. This China-centered review has examined the development status, structural concepts, hydrodynamic challenges, research methodologies, reliability issues, and future development pathways of OFPV from the perspective of marine structures and hydrodynamic performance.

The development of OFPV in China has advanced from conceptual exploration to prototype testing, sea trials, and early engineering demonstration. Recent projects have investigated a wide range of structural concepts, including flexible membrane platforms, semi-submersible platforms, steel truss-supported platforms, tensioned floating-island systems, and composite-material platforms. These demonstrations indicate strong industrial interest and engineering potential. At the same time, they also show that OFPV has not yet reached a mature commercial stage. Long-term field data, full-scale validation, standardized design procedures, and replicable engineering solutions remain limited. The indicative maturity assessment further shows that most OFPV concepts in China remain at the prototype, sea-trial, or early demonstration stage, although some enabling technologies, such as HDPE modular floats and semi-submersible offshore structures, have higher maturity in inland FPV or conventional offshore engineering contexts.

The diversity of existing platform concepts reflects both the vitality and the uncertainty of current OFPV development. HDPE modular platforms are more suitable for sheltered or mild nearshore waters, whereas metallic frame-supported platforms provide

higher stiffness and better operational accessibility. Flexible membrane platforms offer advantages in terms of low wind exposure, lightweight design, and water-cooling potential, but their offshore reliability is strongly affected by overtopping, drainage, membrane deformation, and module durability. Semi-submersible and high-freeboard platforms are more promising for exposed marine environments, although their structural complexity and cost are higher. Platform selection should therefore be based on site-specific sea states, installation scale, maintenance strategy, and life-cycle performance, rather than on a single structural criterion.

Hydrodynamic coupling remains one of the central scientific and engineering challenges for OFPV. Waves, wind, currents, tides, and extreme weather may induce platform motion, multi-body interaction, connector-load amplification, mooring tension redistribution, and hydroelastic deformation. As OFPV systems develop from single-platform prototypes to large-scale arrays, the dominant design concern will shift from the motion response of individual platforms to the coupled dynamics of array-scale systems. Future hydrodynamic analysis needs to account for environmental-load coupling, nonlinear connectors, mooring constraints, local damage evolution, and structural flexibility within an integrated framework.

A range of research methods has been applied to OFPV hydrodynamics, including analytical modelling, potential-flow-based frequency- and time-domain analysis, CFD simulation, physical model testing, field monitoring, hybrid methods, and data-driven prediction. Potential-flow methods remain efficient tools for engineering-scale analysis, particularly for platform motion, multi-body interaction, and mooring-coupled response. CFD is more suitable for local nonlinear phenomena such as viscous damping, slamming, overtopping, and complex free-surface deformation. Physical model tests and field measurements are indispensable for validating numerical models and calibrating design parameters. Further progress will depend on the integration of numerical simulation, experimental validation, and long-term monitoring data.

Reliability, durability, and survivability are likely to determine whether OFPV can progress from demonstration projects to large-scale deployment. Extreme sea states control platform survivability, while long-term cyclic loading governs fatigue damage in connectors, mooring systems, supporting structures, and flexible components. Corrosion, biofouling, material ageing, waterproofing, and electrical insulation also need to be considered as part of the system-level reliability problem. At present, dedicated design standards for open-sea OFPV remain insufficient, and existing field tests are still limited in scale and duration. More systematic work is required on full-scale monitoring, life-cycle reliability assessment, material degradation, anti-corrosion and anti-fouling strategies, and standard development.

OFPV should also be viewed within the broader context of hybrid offshore renewable energy systems. Co-location with offshore wind farms is one of the most realistic near-term pathways for China, because it allows shared use of sea space, transmission facilities, substations, and operation and maintenance resources. In the longer term, integration with wave energy, floating breakwaters, marine ranching, energy storage, hydrogen production, and offshore energy islands may further improve marine-space utilization and energy-supply stability. These hybrid systems will require coordinated design of floating structures, mooring systems, power conversion, environmental protection, and offshore maintenance.

Future research on OFPV is expected to concentrate on several key hotspots. Array-scale hydrodynamics, including wave-field inhomogeneity, multi-body interaction, connector-mooring coupling, and hydroelastic deformation, will be crucial for the design of large offshore PV farms. Reliability and survivability will also become dominant research themes, particularly life-cycle fatigue, corrosion, biofouling, material degradation, progressive failure, and typhoon-resilient design. In parallel, full-scale monitoring, digital

twins, and data-driven prediction are likely to play an increasing role in model validation, health management, and standard development. From an engineering-development perspective, OFPV in China is likely to evolve from nearshore prototype demonstrations to offshore wind–PV co-location, semi-exposed offshore arrays, and eventually integrated offshore renewable energy bases combining PV, wind, wave energy, floating breakwaters, storage, hydrogen production, and marine ranching. These trends suggest that OFPV research should increasingly shift from component-level feasibility verification to system-level design, life-cycle reliability, and multi-energy offshore infrastructure integration.

It should also be noted that the scope of this review is intentionally centered on China. The development status, demonstration projects, structural concepts, environmental conditions, and future pathways discussed in this paper are closely related to China's coastal energy demand, nearshore sea-space availability, offshore wind infrastructure, typhoon-prone environments, and domestic engineering practice. Therefore, some conclusions may not be directly transferable to other countries or regions without site-specific assessment. In addition, economic aspects are considered only to a limited extent in this review. Issues such as life-cycle cost, operation and maintenance economy, shared offshore infrastructure, and hybrid-system development are discussed qualitatively, but a quantitative techno-economic assessment involving capital expenditure, operation expenditure, levelized cost of energy, insurance risk, grid-connection cost, and decommissioning cost is beyond the scope of this paper. These topics should be further investigated in future studies.

China has favorable industrial conditions and strong application demand for OFPV, but large-scale deployment will require more than isolated prototype demonstrations. The next stage of development should therefore focus on transforming these research directions into validated design methods, engineering standards, and scalable deployment solutions. Addressing these issues will be essential for transforming OFPV from an emerging demonstration technology into a reliable component of China's offshore renewable energy system.

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