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Review

Research Status and Development Trend of Floating Photovoltaic Structure System

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ABSTRACT: Under the guidance of the dual carbon goals, the development and utilization scale of new energy in China, including photovoltaics and wind power, has steadily increased. Particularly, the floating photovoltaic technology in inland waters has been developing quickly over the past decade because it could compensate for certain shortcomings of traditional terrestrial photovoltaics. The offshore floating photovoltaic (FPV) pilot projects are also continuously emerging due to the advantages of longer daylight hours, higher radiation levels, and enhanced efficiency of light utilization in marine environments compared to terrestrial settings under identical solar irradiance conditions. To comprehensively understand the development prospects of offshore FPV systems, the development progress of FPV systems was traced, and an analysis was conducted on the forms of various types of floating structures, their technical characteristics, and their applicability in the marine environment. Summarization was carried out on the floating photovoltaic mooring system in terms of the classification of the mooring, the chain deployment mode, the form of the mooring foundation, *etc.*, and a few new types of mooring systems were put forward. Finally, the development trend of the offshore FPV system was predicted.

Keywords: Floating photovoltaic; Floating structure system; Offshore FPV; Mooring system; Wind-solar complementarity

1. Introduction

Promoting renewable energy development and implementing substitution initiatives are crucial for ensuring national energy security. They are also significant measures to advance China's energy revolution and build a clean, low-carbon, safe and efficient energy system [1].

Developing and utilizing solar energy is a crucial pathway for China's transition towards renewable energy, with immense potential to meet global energy demand. Over the past decade, the photovoltaic (PV) industry has expanded at an average annual growth rate of 133% [2]. Global solar PV capacity rose from about 10.5 GW in 2008 to nearly 125 GW by 2018 [3].

While solar energy is widely recognized as a key renewable resource for global decarbonization, existing land-based photovoltaic systems face critical challenges in China, including land scarcity and grid integration bottlenecks. These challenges drive the emergence of floating offshore photovoltaic (FPV) systems. FPV systems are key to achieving China's carbon goal and promoting green development. They also enhance grid interconnection with neighbouring countries and boost the internationalization of China's new energy sector, demonstrating its active role in global energy transformation.

2. Development History of FPV System

The history of floating photovoltaic (FPV) power generation can be traced back to the early 20th century. An American Navy ship, named Jacona, which participated in the First World War, was converted into a floating power

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plant by the British in the 1830s [4], marking the birth of the first water-based power generation technology. The first FPV project in the world was located in Aichi Prefecture, Japan [5], with a capacity of 20 kW. It was researched and built by the National Institute of Advanced Industrial Science and Technology (AIST) in 2007, with comparison on the power efficiency of power generation under water-cooling and air-cooling systems. Following the success of this research project, many FPV systems were installed all over the world, including in the United States, South Korea, France, Spain, Italy, China, India and others, and Japan has become the country with the most extensive application of FPV technology. The first grid-connected commercial FPV project was constructed by SPG Solar in the USA in 2008 [6], with a generation capacity of 400 kW, primarily to supply power to the Far Niente Winery. In 2012, Ciel and Terre, a French company, completed the world's first-megawatt FPV project in Okegawa, Japan [7].

Subsequently, more and more FPV systems were installed in various inland waters such as lakes, canals, ponds, irrigation reservoirs, coal mining subsidence areas, *etc.* There has been a significant growth in the installed capacity of FPV power plants globally, from 100 MW in 2016 to more than 3 GW by 2021 [8]. According to the report by Wood Mackenzie, the global installed FPV capacity will exceed 6 GW by 2031.

Inland FPV technology and experience have laid the foundation for expanding PV power plants into marine environments. Initial projects were launched nearshore with low-wind and wave conditions, gradually expanding into more challenging marine conditions. In 2017, six Dutch institutions jointly developed the world's first offshore FPV project: Zon-op-Zee [9], as illustrated in Figure 1. It can maintain stable operation in marine environments with wave heights up to 10 m, wind speeds up to 32 m/s, and current velocities of 2.1 m/s. The successful demonstration of Zon-op-Zee has encouraged global energy companies to conduct in-depth research on marine FPV systems. In 2021, Norway's Moss Maritime developed a modular marine FPV platform called Solar Duck [10], as shown in Figure 2. It is designed with a 30-year lifespan and can withstand wave heights up to 5 m and wind speeds up to 30 m/s. A 1:13 scale FPV model was tested at 1.0-km off the coast of Trondheim. In 2022, the world's first marine hybrid FPV-Wind project was constructed by the State Power Investment Corporation (SIPC) in Yantai, Shandong Province, China [11], as shown in Figure 3. It is the world's first floating offshore PV project demonstrated in the 'double 30' marine environment of 30 km offshore, 30-m water depth and 10-m extreme wave height, which provides valuable technology and experience for the development of the deep-sea offshore photovoltaic industry. In 2023, SIPC and Tianjin University of Technology jointly developed China's first indigenous hexagonal cable-stayed floating island-type FPV test platform, as shown in Figure 4. It achieved off-grid power generation in offshore waters with wave height of 5 m, water depth of 12 m, and wind speed of 30 m/s. In 2024, China Huaneng invested in the construction of a large-scale offshore wind-scenic integration floating photovoltaic platform named 'Yellow Sea No. 1', which has begun to collect and analyse operational data from sea trials, as shown in Figure 5. At present, many offshore floating PV pilot projects have been put into operation, proving the feasibility of the technology. This indicates that the transition of floating PV systems from inland waters to the deep-sea large-scale development is the key direction for the future of the photovoltaic industry. The vital development history is illustrated in Figure 6, and only representative projects are highlighted.

Figure 1. Zon-op-Zee in the Netherlands.

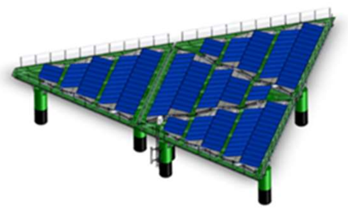


Figure 2. Solar Duck in Norway.

Figure 3. 500kW FPV in Shandong Province, China [11].

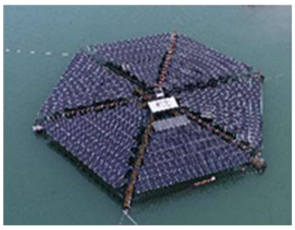


Figure 4. Hexagonal Tensioned Floating Island FPV Platform in Tianjin, China.

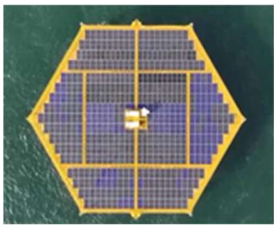


Figure 5. Yellow Sea No.1 FPV Platform of China Huaneng.

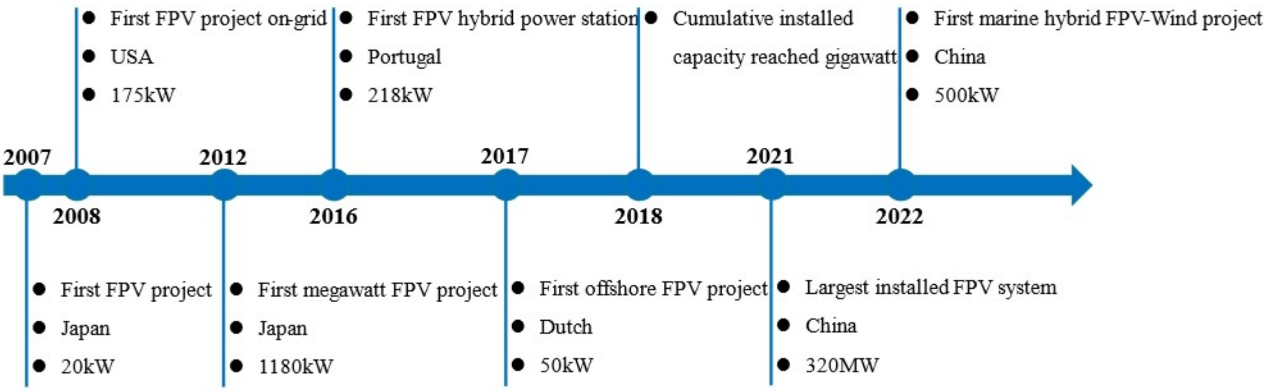


Figure 6. Development history of representative projects of FPV systems.

3. Classification and Current Development Status of Float Structure for FPV System

A typical floating photovoltaic (FPV) system mainly consists of four parts: the floating structure, the PV modules, the electrical system and the anchoring and mooring system [12], as shown in Figure 7. After the PV modules convert solar energy into electricity, the electrical system collects the power output from the PV modules through a convergence box, which is then boosted by inverters and box transformers and transmitted to land via cables. The anchoring and mooring system provides proper limitation of the entire floating platform system, and the floating structure provides buoyancy for the entire PV system, supporting the PV modules, inverters and other equipment, as well as facilitating construction and maintenance. Since the offshore FPV system is subjected to a variety of complex loads such as wind, wave, current and ice, as well as a high salt spray environment for a long period of time, the stability and safety of the floating body structure and the durability of the equipment are critical factors determining the success or failure of the FPV technology [13].

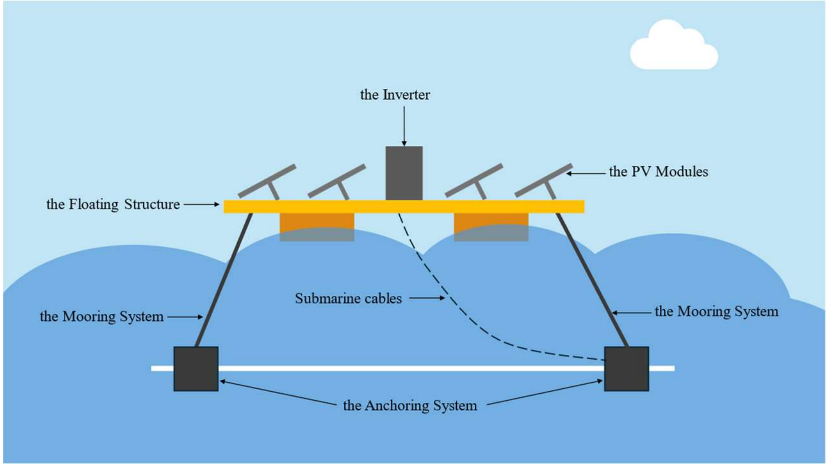


Figure 7. Composition of a typical FPV system.

Since 2008, with the increasing construction of FPV projects, the floating structure has also developed towards a more diverse. In 2021, Det Norske Veritas (DNV) issued the recommended specification DNV-RP-0584, which classifies the floating system into three main types [14]: pure floats, pontoon and truss assembled type, and membranes type. According to the discussions of scholars both domestically and internationally in recent years, common FPVs can be classified into three types based on waterline surface and structural characteristics: pontoon/float tube type [15], semi-submersible type, and membrane type.

3.1. Pontoon/Tube-Type Floating Structure

In the pontoon/float tube floating structure, a modular pontoon or float tube made of high-density polyethylene (HDPE) is used to create a stable floating platform for the PV modules.

3.1.1. Pure Pontoon-Type Floating Structure

The pure pontoon-type floating structure employs a specially engineered pontoon system to support the PV modules directly. The pontoons provide sufficient buoyancy for self-floating and are designed to bear external loads effectively, with the advantages of maintenance-free, excellent UV resistance and superior corrosion resistance.

This concept was first proposed by Ciel&Terre in 2011 [16], with the product name Hydrelio®. Since then, several companies have developed similar designs. For instance, China's Sunshine Power Company has created a modular pontoon system made of HDPE [17], as shown in Figure 8. This float system consists of two types of pontoons. The primary pontoons are utilized to support the PV module and provide the optimal tilt angle. The secondary float ensures the connection between the primary pontoons and provides enough space to ensure that surrounding modules do not obscure the PV module. They also serve as a maintenance channel while providing additional buoyancy. The pontoons are connected to each other with pins or bolts to form an integral PV platform, as shown in Figure 9.

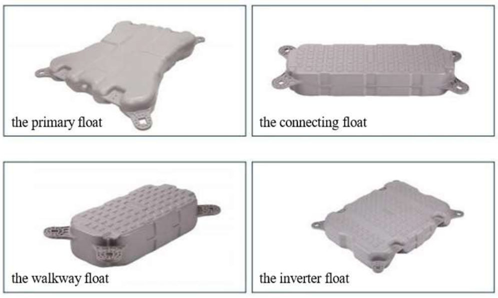


Figure 8. Pontoons products of Sunlight Power Company.

Figure 9. Pontoons bolted connection.

The pontoons developed by Sumitomo Mitsui in Japan are filled with polystyrene foam internally to reduce the risk of sinking if the pontoons are damaged. The restraining straps are used to minimize the likelihood of connections failing [18].

Pure pontoon-type floating structures are the most common type of FPV system in inland waters and are highly recognized for their cost-saving advantages. The 'Barrel River Water Solar' [19] in Barrel River City, Saitama Prefecture, Japan, with a capacity of 1.18 MW, is a water-based solar power plant constructed in a local reservoir, as shown in Figure 10. This project was completed in only six weeks, achieving the goal of having 4500 solar panels floating on 12,400 square meters of water, with a 10% increase in power generation compared to rooftop or ground-mounted photovoltaic systems. From 2016 to date, hundreds of megawatts of such FPVs have been installed in China and Southeast Asia, among which the most representative one is the 150-MW floating PV on a water project in Huainan, Anhui Province, China [20], as shown in Figure 11. This project was constructed using unused water from the coal mining subsidence area. Its electrical system has been connected to the National Grid and is expected to generate 77,693 MWh of electricity per year. Huaneng Dezhou Dingzhuang Reservoir 320-MW floating photovoltaic power plant is currently the world's largest single floating photovoltaic power plant. Through the stereoscopic use of the reservoir, nearly 8000 acres of construction land were saved, as shown in Figure 12. With the reservoir's north bank of the Dingzhuang 100-MW wind power project and 8 MW high-efficiency energy storage device, the Huaneng Dezhou Dingzhuang 'FPV-Wind-Storage integrated power generation' project was formed, which can provide 550 million kWh of clean electricity annually.

Figure 10. The 1.18-MW 'Barrel River Water Solar' in Japan [19].

Figure 11. The 150-MW floating PV in Huainan, Anhui Province, China [20].

Figure 12. The 320-MW FPV of Huaneng Dezhou Dingzhuang Reservoir.

A pure pontoon-type structure is relatively easy to fabricate, transport and install. Through non-rigid connections, the overall platform can move with the undulations of waves, and the internal load of the system is reduced. For floating photovoltaics in inland waters, a pure pontoon-type structure is the most suitable solution in the short term. However, for complex marine environments, it has non-negligible disadvantages. HDPE floats have relatively low strength, low self-weight, and a low center of buoyancy. They are connected by lugs and connecting pins. Even in the case of low wind or waves, the loads borne in the structure may be excessive, risking damage to individual floats or the entire structure [21]. High winds and strong waves in marine environments can generate dynamic loads on the structure, which may lead to float overturning and stress concentration at the connection points and ultimately lead to the failure and disintegration of the whole system. Therefore, this structure is not suitable for marine environments with harsh conditions, and it is only suitable for small waves with a peak height of about 1 m [13]. Zhao et al. [22] have carried out research on the foundation form of the bracket for an on-water photovoltaic power station and pointed out that the maximum allowable wave height of the purely float-based floating body structure is generally within 1.0–1.5 m, and that a breakwater needs to be constructed around the periphery when the design wave height exceeds the maximum allowable value.

3.1.2. Pontoon or Tube and Metal Combination Floating Structure

The pontoon or tube and metal combination floating structure, which is the earliest form of floating structures, incorporates special support structures—typically made of steel, aluminum, or other composite materials—designed on HDPE floats to elevate the photovoltaic modules. Some typical projects are described as follows.

(1) The FPV floating structure in Korea

This type of floating structure was applied to an FPV platform installed in South Korea in 2009 [23]. As illustrated in Figure 13, the float tube is fabricated from polyester plastic and alkali-free glass fiber and is filled with polystyrene foam to safeguard against buoyancy loss in the event of damage to the float tube. The supporting structure is constructed from fiberglass reinforced plastics (FRP), with stainless steel bolted connections incorporated.

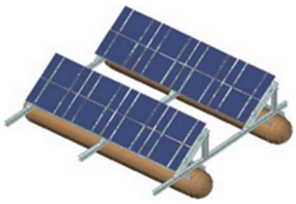


Figure 13. The FPV floating structure in Korea.

(2) The FPV scheme proposed by Terra Moretti

The FPV scheme proposed by Terra Moretti in 2010 [21] consists of HDPE cylinders arranged in parallel as floats and a support structure made of steel, aluminum or FRP material. As illustrated in Figure 14, this structure has a low contact surface with the water, allowing for the easy integration of the single-axis tracking system and the compressed air energy storage system. The advantages of this structure include ease of fabrication, convenient transportation, and the elimination of wear from relative movement between PV modules enabled by the fixation of the upper rigid truss. However, the rigid truss structure cannot move along with the undulation of the waves, leading to stress concentration at certain points and structural damage. Therefore, it is only applicable to small-scale water areas.

Figure 14. The FPV scheme proposed by Terra Moretti.

(3) The offshore FPV system in Tokyo Bay, Japan

In the offshore FPV system in Tokyo Bay, Japan [24], the solar panels are fixed at a height of more than 3 m above the water surface, and the system is designed to withstand coastal sea conditions and typhoon impacts. Its foundational floating platform is a triangular structure measuring 16 m × 16 m × 16 m, similar to offshore floating wind power platforms or floating Ishii platforms, which can be flexibly connected to form large-scale power stations, as shown in Figure 15.

Figure 15. The offshore FPV system in Tokyo Bay, Japan.

This type of floating structure also has its limitations in the marine environment. Kim [25] investigated the safety of this floating structure under high wave impact conditions. They found that incident waves could induce excessive bending moment loads, while hinge connections could minimize the transfer of bending moments, allowing the structure to respond sensitively to water surface movements.

3.2. Semi-Submersible Floating Structure

The semi-submersible offshore platform [26] was first applied in the fields of oil and gas exploration and exploitation in deep and ultra-deep waters. As shown in Figure 16, the platform is elevated above the water surface at a certain height to avoid wave impact. The lower floating tank provides the main buoyancy and is submerged underwater to minimize wave disturbance forces. The columns linking the platform and the lower floating tank exhibit a minimal waterline surface profile. To ensure the platform's stability, the main columns are spaced at a certain interval, which is why they are referred to as column-supported pontoons.

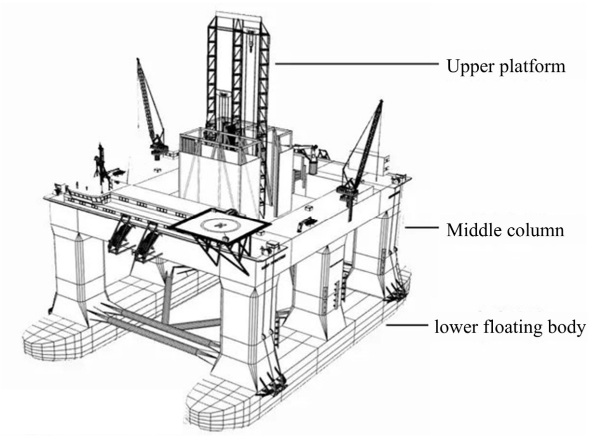


Figure 16. The Semi-submersible offshore platform.

During the development process of FPV from inland lakes and reservoirs to the ocean, the semi-submersible structure platform, which can withstand greater wave loads and achieve larger dimensions, represents a mainstream technical route being developed both domestically and internationally. Relevant demonstration pilot projects are underway to validate these platforms, but further verification of their wind and wave resistance performance is still required [27].

(1) Solar Sea Offshore FPV System

The Austrian company Swimsol, in collaboration with the Vienna University of Technology and the Fraunhofer Institute, has developed the Solar Sea offshore FPV system [28]. A pilot project for this system has been launched at LUX South Ari Atoll in the Maldives, as shown in Figure 17. The single module of this system has an installed capacity of 24 kW, and it can withstand wave heights of 1.5 to 2 m and typhoon force 12. However, this floating structure faces several challenges when deployed in offshore situations: Due to its limited freeboard, the structure is more susceptible to wave overtopping, potentially causing damage to PV modules from wave impact. Additionally, constrained by the rigid truss configuration, it can only accommodate a series of small-scale systems rather than being integrated into a large platform, which poses significant challenges for electrical system configuration.

Figure 17. Solar Sea offshore FPV system.

(2) SolarDuck Semi-submersible FPV Platform

Dutch company SolarDuck has designed a triangular semi-submersible FPV platform, as illustrated in Figure 2. The platform is connected through a modular connection method, with each module having a design capacity of 16 kW, and four triangular modules can be assembled into a large triangular platform. Featuring a lightweight marine-grade aluminum frame, the platform has its deck positioned over 3 m above the water surface, avoiding direct contact between PV modules and water. It can maintain high overall stability in sea waves under 5 m.

(3) The First Semi-submersible Offshore FPV Platform in China

In China, CIMC Energy has developed the first semi-submersible offshore FPV platform with a capacity of 400 kWp, which completed its launch and towing in April 2023 [29]. As shown in Figure 18, a semi-submersible truss structure is applied to this platform. Equipped with four single floating body arrays, the platform can operate safely in open seas with wave heights up to 6.5 m, wind speeds of 34 m/s, and tidal ranges of 4.6 m. Compared to SolarDuck's triangular design, this platform has a rectangular layout that maximizes the utilization of sea surface area and optimizes resource usage. Additionally, its underwater structure is stronger, enabling it to withstand harsher marine conditions. This FPV platform represents China's first successful demonstration project for semi-submersible offshore floating PV, validating the feasibility of such systems and paving the way for their deployment in deeper and more distant waters.

Figure 18. The first semi-submersible offshore FPV platform in China.

3.3. Flexible Membrane Floating Structure

The flexible membrane floating structure primarily consists of PV modules, hydro-elastic flexible membranes, buoyancy rings, and damping lines [30]. As shown in Figure 19, the PV modules are surface-mounted and securely fixed onto the flexible membrane.

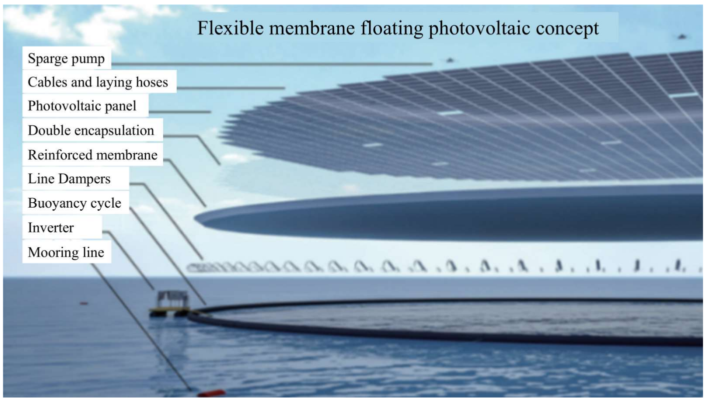


Figure 19. Schematic diagram of flexible membrane floating PV structure.

The flexible membrane floating structure was originally conceptualized in 2014 by Trapani and Millar, drawing inspiration from marine aquaculture cage designs [31]. This innovative configuration leverages the membrane's hydroelastic properties and damping characteristics to mitigate wave-induced forces on the floating structure, reducing system impact and enhancing overall stability. The direct surface mounting of PV modules on the membrane facilitates efficient water cooling, significantly improving power generation efficiency. This technology has achieved commercial viability through OceanSun, with notable installations including a 200-kW pilot project at Magat Reservoir in the Philippines (2019) [32], a 2-MW system at an Albanian hydropower station (2019) [33], and a 500-kW demonstration project in the coastal waters of Shandong, China (October 2022) [11].

(1) Magat Project (Philippines)

As shown in Figure 20, the Magat project represents the Philippines' first 200-kW floating PV installation, featuring a single floating unit with a 50-m diameter capable of withstanding Category 4 typhoon conditions (270 km/h).

Figure 20. Magat FPV Project in Philippines.

(2) Banja Project (Albania)

The Banja project in Albania, illustrated in Figure 21, comprises four floating units with a combined capacity of 2 MW.

Figure 21. Banja FPV Project in Albania.

(3) Shandong Peninsula South No. 3 Offshore Wind Farm Project (China)

A significant milestone was achieved in October 2022 with the commissioning the 500-kW deep-sea floating PV demonstration project at the Shandong Peninsula South No. 3 Offshore Wind Farm (Figure 22). This pioneering project represents the world's first FPV-Wind co-located floating PV demonstration. The system consists of two annular floating structures with heights ranging from 0.6 to 0.8 m, fabricated from HDPE piping. Each floating unit, measuring 53 m in diameter and housing 250 kW of installed capacity, accommodates 770 PV modules. The mooring system employs four sets of 12 mooring lines for station-keeping. However, operational challenges have emerged due to the absence of water pumps in the membrane platform combined with the significant wave heights characteristic of the Yantai sea area. The intrusion water accumulated within the flexible membrane through wave overtopping may lead to membrane perforation or catastrophic rupture, combined with buoyancy ring failure, ultimately resulting in the structural collapse of both the membrane and PV modules.

Figure 22. 500kW FPV in Shandong Province, China.

(4) New Dynamic FPV Device Proposed by DNV in 2012 (Norway)

In 2012, DNV (Det Norske Veritas) proposed an innovative dynamic offshore FPV system [12], as illustrated in Figure 23. This system features a hexagonal array configuration comprising 4200 thin-film solar panels. The hexagonal geometry was strategically designed to minimize the number of required anchor points. Compared to conventional rigid glass-based modules, this technology offers enhanced flexibility and reduced weight, enabling the entire system to respond to wave motions dynamically. While this wave-following capability significantly reduces wave-induced structural loads, it introduces additional complexity in the fatigue limit state design of mooring cables.

Figure 23. New Dynamic FPV Device Proposed by DNV.

(5) Fully Flexible Offshore FPV System Proposed by Ocean Sun (Norway)

Norwegian company Ocean Sun has developed an innovative, fully flexible offshore FPV system [34], as depicted in Figure 24. This design incorporates a circular buoyancy ring that tensions a specially engineered material to form the marine-grade high-strength flexible membrane. PV modules are mounted directly onto this membrane, enabling the entire system to respond to wave motions dynamically. The direct thermal contact between PV modules and water facilitates efficient heat dissipation, enhancing system performance. The technology demonstration began with a prototype featuring a single 20-m diameter flexible membrane unit installed off the western coast of Norway in 2017. Subsequently, Ocean Sun has deployed larger-scale systems, including circular configurations with diameters of 50 m (200-kW capacity) and 72 m (500-kW capacity) and rectangular systems for streams and rivers with a capacity of 100 kW.

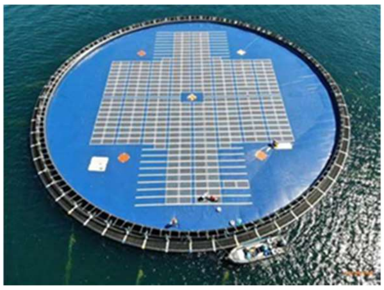


Figure 24. Ocean Sun in Norway.

The flexible membrane demonstrates exceptional wave-adaptive characteristics, enabling the entire system to synchronize with wave motions. Additionally, the surface-proximity configuration leverages effective water-cooling dissipation, thereby enhancing photovoltaic conversion efficiency. The simplified structural design, devoid of complex connectors, ensures high system reliability and facilitates maintenance operations. Notably, the HDPE-based membrane structure has gained global adoption due to its foldable design, significantly reducing transportation costs and simplifying installation procedures.

However, cyclic loading from wave, wind, and current actions may induce component deflection and stress accumulation in PV modules. This mechanical fatigue can lead to microcracking, potentially affecting both power output and service life. Sahu et al. [12] noted that membrane floating structures' lightweight and flexible nature may provide better resilience in harsh marine environments. Nevertheless, further research is required to optimize these systems' structural integrity and long-term performance.

3.4. Other New Floating Structures

Under national policy initiatives, offshore photovoltaic systems have emerged as a strategic priority in marine energy development. In recent years, several new floating structures have evolved that cannot yet be clearly categorized according to existing classification standards.

(1) Tianjin Pilot Project

In May 2023, the 2-MW offshore FPV project in the Lingang Industrial Zone (Binhai New Area, Tianjin) commenced operations, marking a significant milestone in offshore FPV deployment. The project successfully achieved module fabrication, installation, and deployment. The floating structure employs a tension-braced island configuration, utilizing a steel truss structure that serves as the primary support platform for PV module installation and power generation, as illustrated in Figure 25.

Figure 25. Tianjin Pilot Project.

(2) Global First Bamboo-Based Composite FPV Platform

In October 2023, "Jilin-1"—the world's first bamboo composite-based offshore floating photovoltaic system (as shown in Figure 26)—successfully completed its launch, towing, and offshore installation procedures, initiating empirical testing protocols for marine PV operations. This pioneering platform represents the first global application of a jointly developed bamboo-based marine engineering material as the primary structural component, marking the initiation of new material testing in FPV platform technology.

Figure 26. Global First Bamboo-Based Composite FPV Platform.

(3) Domestic Large-Scale Offshore FPV Platform "Yellow Sea No.1"

In August 2024, "Huanghai-1" (China's inaugural large-scale offshore FPV platform) completed its terrestrial fabrication phase. This hexagonal steel truss structure, with principal dimensions of 25 m × 25 m × 9 m, currently demonstrates China's current maximum wave resistance capacity by withstanding wave heights up to 10 m, as illustrated in Figure 27. The platform is scheduled for deployment as a test unit at the Shandong Peninsula South No. 4 Offshore Wind Farm, where it will undergo field testing in an offshore environment characterized by 30-km distance from shore and 30-m water depth.

Figure 27. Domestic Large-Scale Offshore FPV Platform "Yellow Sea No.1".

4. Mooring and Anchoring Systems for FPV

FPV systems are inherently susceptible to complex environmental loads, including wind, current, and wave forces, which can induce translational and rotational movements. These movements disrupt normal operation and cause structural damage, posing significant safety risks to the system. The mooring system, which connects the floating structure to seabed anchors through mooring lines, plays a critical role in maintaining system stability. By utilizing cable tension, it effectively limits the movement of the floating structure within predefined operational boundaries, ensuring stable system performance. Given its fundamental importance in ensuring the safety and stability of floating structures, comprehensive research on mooring systems will provide essential technical support for the advancement of aquatic renewable energy development.

4.1. Classification of Mooring Systems

The mooring system can be categorized into two types according to the fixed form of the floating body's position: the mooring cable-fixed type and the vertical guide pile-fixed [35].

4.1.1. The Mooring Cable-Fixed

Mooring systems fixed by mooring cables can be further classified into various types, as illustrated in Figure 28. Based on the number of connection points between the anchor ropes and the floating structure, it can be divided into single-point mooring systems and multi-point mooring systems. According to the geometrical characteristics of the anchor rope form, it can be categorized into catenary curve mooring systems and tension mooring systems.

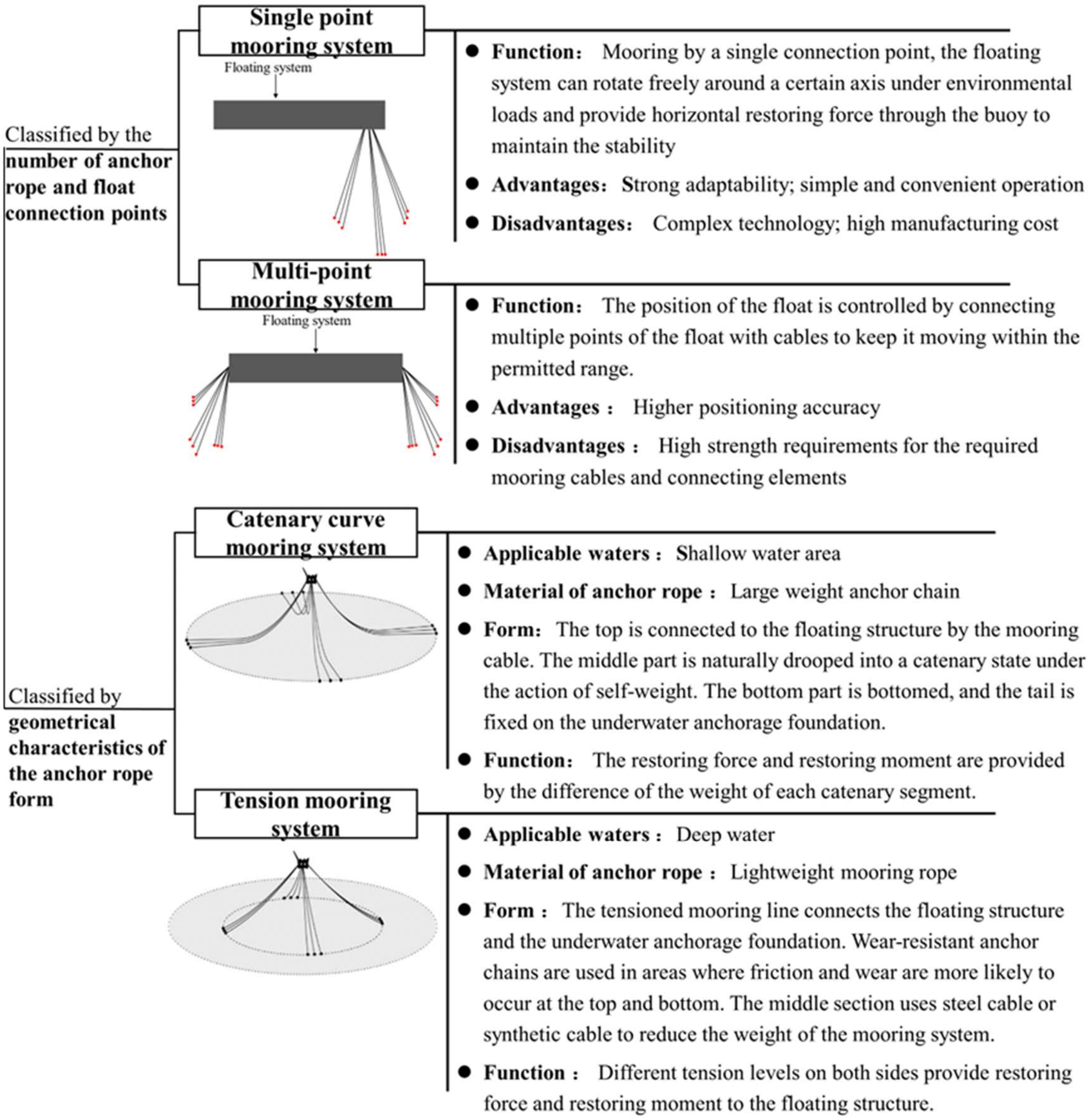


Figure 28. The Classification of Mooring Cable Fixed Mooring System.

4.1.2. The Vertical Guide Pile Fixed

The vertical guide pile-fixed mooring system is particularly suitable for shallow water applications. In this configuration, vertical guide piles penetrate through the floating structure and are embedded into the seabed foundation, restricting the structure's movement to vertical displacement along the piles. Under wave action, the floating structure undergoes heave motion along the guide piles while being constrained from horizontal translation and rotation, as illustrated in Figure 29.

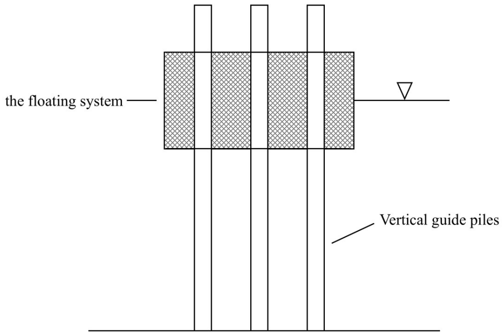
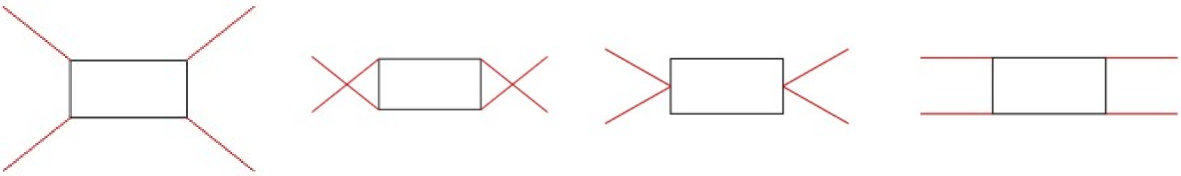


Figure 29. Schematic diagram of vertical guide piles.

Compared to the mooring cable-fixed type, the vertical pile-fixed type provides superior motion restraint and wave attenuation capabilities while eliminating risks associated with line breakage and enhancing operational safety and reliability. However, the strong structural constraints the guide piles impose result in significant load responses under extreme environmental conditions. This necessitates higher structural requirements for pile fixation, consequently increasing system costs [36].

4.2. The Chaining Method of Mooring System

The chain configuration methods for mooring systems are diverse, with four primary configurations: "character '八' shaped" "Cross-shaped" "V-shaped" and "Parallel-shaped" [35], as shown in Figure 30. These basic configurations have been extensively studied and are well-understood in current research.



(**a**) (**b**) (**c**) (**d**)

Figure 30. Schematic diagram of vertical guide piles. (**a**) character '八' shaped; (**b**) Cross-shaped; (**c**) V-shaped; (**d**) Parallel-shaped.

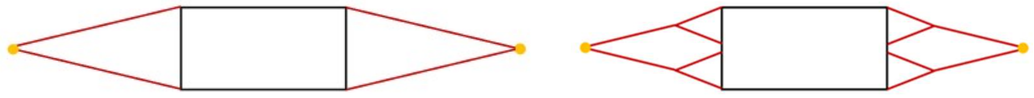
Zhao et al. [37] conducted numerical simulations using AQWA software to analyze the motion responses and mooring forces of mooring systems under various anchor configurations. The results demonstrated that the chain configuration significantly affects the surge and sway of the pontoons. The parallel mooring systems are unsuitable for floating pier applications. Additionally, V-shaped configurations with excessive divergence angles or insufficient angles exhibited comparable instability issues in motion control.

Chen et al. [38] theoretically derived expressions for the roll and yaw restoring moments provided by anchoring systems under different mooring configurations. Their study identified key factors influencing these restoring moments, concluding that mooring chains primarily control the yaw motion of floating structures, and the magnitude of the yaw-restoring moment determines the oscillation amplitude. Since mooring chains exhibit limited effectiveness in roll motion control, the research recommends the cross-shaped configuration as the superior mooring pattern.

Using physical model tests, Liu [39] investigated the wave attenuation performance and mooring forces of a permeable floating breakwater with front and rear openings under regular wave conditions. The study employed V-shaped and cross-shaped mooring configurations. Results indicated that both configurations showed no significant variation in transmission and reflection coefficients with wave height under identical wave periods. The V-shaped mooring demonstrated relatively better wave attenuation performance in most wave conditions. Under shallow water depths, the V-shaped configuration generally experienced greater mooring forces compared to the cross-shaped configuration, with both forces becoming comparable as water depth increased.

Wang et al. [40] employed the Smoothed Particle Hydrodynamics (SPH) method to simulate the hydrodynamic characteristics of a twin-barge floating breakwater with parallel-shaped and cross-shaped mooring configurations. Their computational results revealed comparable heave motion responses between the two configurations. However, the cross-shaped mooring exhibited greater surge motion, roll motion, and mooring forces compared to the parallel-shaped mooring configuration.

Beyond the fundamental mooring configurations discussed above, this paper proposes a new configuration method—the single-point multi-chain anchoring. In this method, chains connected to a single anchor foundation are attached to multiple points on the floating structure, contrasting with traditional single-point single-chain configurations (as illustrated in Figure 31). The hydrodynamic performance of this novel mooring system remains a subject for further investigation.



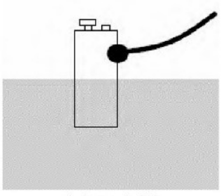
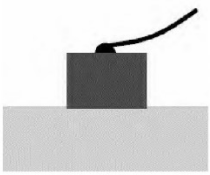
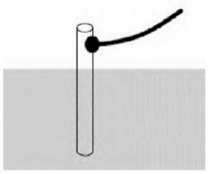
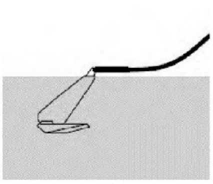
(**a**) (**b**)

Figure 31. The new chaining methods of mooring system. (**a**) Single point double chain; (**b**) Single point multi-chain.

4.3. Underwater Anchorage Foundation Form

Mooring systems connect floating structures to seabed anchors through cables. To maintain structural positioning within permissible ranges under environmental loads, anchor foundations must resist displacement caused by combined forces from cables and environmental conditions. Common anchor types include embedded anchors, pile foundations, suction cylinders and gravity anchors. These vary in respective working mechanisms, characteristic advantages and disadvantages, and scope of application [41,42], as summarized in Table 1.

Table 1. Forms of underwater anchorage foundations.

Types	Diagram	Function, Advantages, Disadvantages and Scope of Application
suction anchor		During the installation process, the suction anchor is firstly inserted into the seabed soil through itself gravity, and then the water inside the cylinder is extracted so that the structure sinks to the design depth under the pressure difference between inside and outside the cylinder. Simple and efficient to install, reusable, low impact on seabed soils, but not suitable for loose sandy soils and stiff seabed soils.
gravity anchor		Gravity anchors are often made of concrete cast in large blocks of volume and mass and rely on their own gravity to provide tension to the mooring cable while resisting other environmental loads. Suitable for medium hardness and hard soil seabed, its installation method is simple, but due to the large size and weight, the crane and other equipment load-bearing capacity requirements are high.
pile anchor		Commonly used in mooring systems for tension-legged platforms, where the horizontal tensile resistance is weaker than the vertical pull-out resistance. The cost of underwater piling with pile anchors rises sharply with increasing water depth, so pile anchors are not suitable for mooring systems in large water depths.
embedded anchor		Embedded in the submerged soil by means of a barbed hook element attached to the end of the mooring cable, which relies on the barbed hook catching the soil to provide the mooring cable pulling force. The construction operation is flexible and convenient, and the equipment can be reused many times at low cost. However, the construction accuracy is difficult to grasp, and it is only suitable for temporary or less demanding mooring systems.

4.4. New Types of Mooring System

With the continuous advancement of engineering practices, traditional mooring systems often encounter operational limitations due to their specific application conditions. When faced with new environmental challenges or emerging requirements, these systems may demonstrate inadequate adaptability. Consequently, some scholars and engineers have proposed innovative mooring configurations and conducted corresponding feasibility studies.

Wu [43] developed a hybrid mooring system integrating pile-anchor and floating elements, as schematically depicted in Figure 32. By arranging pile foundations beneath floating structures and connecting them via mooring cables, this system shortens the length of the mooring cables, effectively restricts the movement of floating structures, reduces the spacing between multiple floating structures, and improves water area utilization. It is particularly suitable for environments with shallow water depths and restricted surface areas. Compared to catenary and tension mooring systems, this configuration provides superior motion response for floating structures.

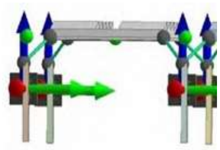


Figure 32. New mooring system [43].

Yuan et al. [44] proposed a novel multi-body mooring system comprising a "platform-connector- anchor chain - tension leg" configuration, as illustrated in Figure 33. Through comprehensive time-domain coupled analysis, the study revealed that this design most significantly affects the heave motion of the floating structure, followed by pitch motion, with minimal impact on surge motion.

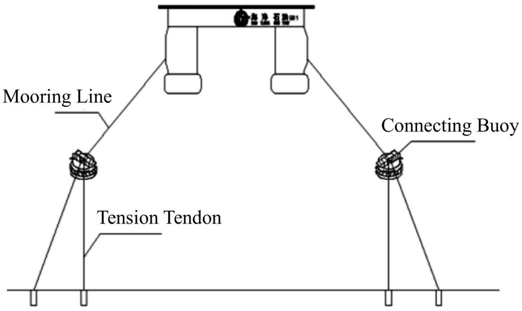


Figure 33. Multi-floating system [44].

The DTP platform is a new type of deepwater floating structure primarily consisting of decks, floating tanks, risers, and mooring system, as shown in Figure 34. Deng et al. [45] studied the motion response, mooring cable forces, and broken cable response of the DTP platform using a combination of experiments and numerical modeling. They found that compared to traditional semi-submersible platforms, the arrangement of lower flotation tanks and heave plates on the DTP platform increases vertical added mass, effectively reducing heave motion. When a mooring cable breaks, the platform's horizontal motion and mooring cable forces increase immediately, but the impact on heave and sway motion is minimal.

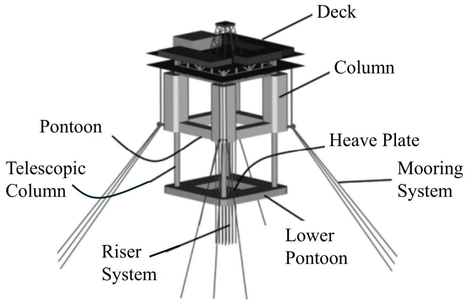


Figure 34. DTP Platform Mooring System [45].

5. Future Development Trend of Offshore FPV

5.1. Offshore Hybrid Photovoltaic Power System

The inherent variability of single renewable energy sources presents significant challenges due to their spatial-temporal distribution inconsistencies and weather dependency, resulting in discontinuous power generation efficiency. Therefore, hybrid offshore photovoltaic power systems have been developed to simultaneously utilize solar energy in combination with one or more additional energy sources, enhancing the system's performance and ensuring stable power supply [46].

Offshore photovoltaic systems offer significant potential for utilizing diverse marine spaces, including tidal flats, islands, offshore, and even open-sea areas, and alleviate land resource constraints. In recent years, coastal provinces such as Shandong [47] and Zhejiang [48] have implemented policy initiatives to promote offshore PV development, with key strategies focusing on site-specific adaptation, integrated development, and stereoscopic comprehensive utilization. Cui Lin, Deputy Director of the Ocean Energy Development Center at the National Ocean Technology Center, emphasizes that offshore PV is poised for substantial expansion with the implementation of marine spatial policies. The future development trajectory suggests that offshore PV will increasingly integrate with various marine industries to maximize its comprehensive value.

Offshore FPV systems can synergize and integrate with other offshore renewable energy or marine activities, such as offshore wind power [49], offshore oil and gas [50], marine aquaculture [51], and seawater desalination [52]. This collaboration enables spatial sharing, infrastructure co-utilization, and energy complementarity, thereby promoting comprehensive marine resource development and facilitating the scalable advancement of offshore clean energy. Currently, two predominant models have emerged in China's offshore renewable energy integration: the "Wind-PV complementation" system and the "Aquaculture -PV complementation" system.

5.1.1. Wind-PV Complementation

In recent years, offshore wind-PV co-generation has become a critical research focus. Leveraging the relatively mature offshore wind industry infrastructure and supply chain, offshore FPV commercialization can benefit from established energy systems. The advantages of integrating offshore photovoltaics with offshore wind power are evident:

(1) Cost Efficiency: Shared grid connection infrastructure and equipment reduce overall construction costs.
(2) Enhanced Energy Yield: Increased renewable energy output per unit of marine spatial allocation.
(3) Stabilized Power Supply: Complementary wind-PV generation profiles mitigate intermittency, ensuring a more consistent renewable electricity supply.
(4) Operational Synergy: Shared maintenance personnel and equipment resources optimize operational costs. Offshore installations can mitigate wave impacts on wind farms.

Offshore wind turbines, with rotor diameters ranging from 30 to 170 m, typically require spacing of 5 to 15 times their diameter between each unit, leaving substantial unused sea surface areas within existing wind farms. Integrating FPV plants into these operational offshore wind farms could significantly enhance the areal density of marine renewable energy production, as illustrated in Figure 35. As validated by López et al. [53], a Wind-PV complementation system is found to increase the capacity and the energy production per unit surface area by factors of ten and seven compared to a typical offshore wind farm.

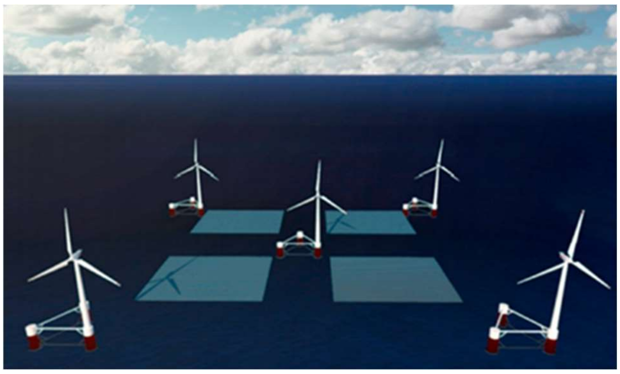


Figure 35. Wind-PV complementation.

Golroodbari et al. [54] assessed the feasibility of retrofitting FPV systems into existing wind farms in the Dutch North Sea, demonstrating that hybrid plants achieve smoother total power output and higher marginal solar contributions to the power grid compared to standalone wind farms.

López et al. [53] investigated wind-FPV synergy off northern Spain, showing that co-location not only boosts energy yield per unit area but also improves power generation quality.

Costoya et al. [55] simulated hybrid wind-FPV deployments along the Iberian Peninsula's western coast from 2000 to 2040, concluding that combined solar-wind systems increase renewable energy volumes while reducing spatiotemporal variability, enabling more efficient resource utilization.

Bi et al. [56] modelled FPV performance under high wind-wave conditions at three offshore sites, confirming stable power generation even in extreme weather and underscoring the resilience of hybrid systems.

The integration of offshore FPV systems with wind power also faces numerous challenges, as no successful commercial hybrid projects have yet been reported. During the planning phase, it is particularly challenging to select suitable sites that meet the requirements for both offshore wind and solar installations. Typically, areas with abundant wind resources demand more rigorous design specifications for wave and wind resistance in floating structures. The co-located system design must also comprehensively address the dual operational and maintenance requirements of both wind turbines and FPV systems, ensuring adequate inspection channels for maintenance vessels and collision prevention measures between FPV structures and wind turbine foundations under extreme weather conditions.

The installation of new FPV facilities within existing offshore wind farms may potentially impact established infrastructure. A significant portion of the cost for offshore FPV lies in the design of floating structures to resist wind and waves. Therefore, future wind-solar co-located designs could consider integrating breakwater structures with wind turbine foundations to provide overall protection, reducing the costs associated with individual floating structure designs and enhancing the survivability of FPV systems.

5.1.2. Aquaculture-PV Complementation

The Aquaculture-PV complementation system, a novel aquaculture approach originating in China in the 21st century, integrates PV panels atop aquaculture facilities to generate electricity for underwater farming operations [57]. Marine aquaculture systems currently face challenges in power supply, as high-power demand and costly grid connectivity often force reliance on diesel generators. These systems struggle with equipment instability and maintenance inefficiencies. The integration of photovoltaic technology into aquaculture systems offers a sustainable solution through renewable energy self-sufficiency [58], enabling the realization of Aquaculture-PV complementation and meeting the energy demands of these integrated systems.

Small-scale pilot projects combining offshore wind, photovoltaic, and aquaculture have been implemented in coastal regions like Shandong Province (China), as illustrated in Figure 36.

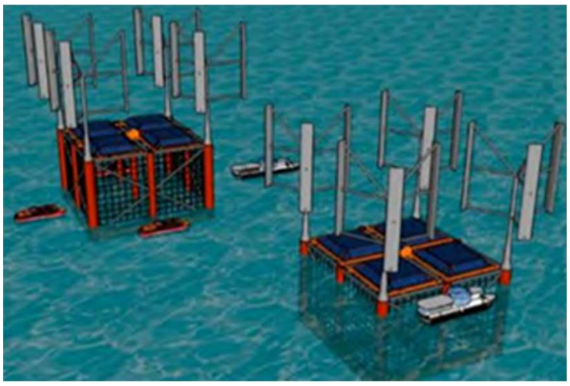


Figure 36. Aquaculture -PV complementation.

Zhang et al. [59] developed a coupled hydrodynamic-water quality-ecosystem-engineering model for the Liuyanji Reservoir, demonstrating that Aquaculture-PV implementation caused no fundamental degradation of water quality or ecological status.

Tang et al. [60] compared phytoplankton communities in PV-equipped (Guanhu Reservoir Upper Lake, Fenglin Reservoir) and non-PV lakes (Guanhu Reservoir Lower Lake, Xitan Reservoir). The results indicated that PV systems increased phytoplankton density and biomass but showed minimal effects on species diversity.

Wang [61] utilized PVsyst software to optimize panel tilt angles and spacing in large-scale AV plants, analyzing how the arrangement of PV modules changes power generation.

Zheng et al. [62] proposed a novel wind-solar-aquaculture triad system combining turbines with floating steel fish cages and PV arrays. Hydrodynamic simulations revealed superior seakeeping performance compared to OC3Hywind and OC4DeepCwind platforms, validating its viability for mid-depth offshore deployments.

The directions and advantages of the Aquaculture-Photovoltaic Complementary System are reflected in the following aspects.

(1) Shared Marine Space for Ecological Synergy

PV power generation and marine aquaculture can achieve multilayered marine space utilization. Subsea anchoring systems stabilize the infrastructure and enhance marine biodiversity by creating habitats, improving marine environmental conditions, restoring ecosystems, and promoting fishery yield and stock enhancement.

(2) Shared Infrastructure for Structural Integration

Pile foundations of the equipment can serve as dual-purpose fixed structures for both fish farming and energy installations. FPV structures and aquaculture facilities (e.g., cages and rafts) can be co-designed for synergistic functionality.

(3) Unified Operation for Integrated Management

Intelligent offshore monitoring platforms enable coordinated management of aquaculture and FPV operations, enhancing fisheries and energy production efficiency. By continuously monitoring meteorological and hydrological data (e.g., weather patterns, ocean currents) can enhance the resilience of marine ranches and FPV to cope with extreme natural disasters such as typhoons, spring tides, and high temperatures [63].

The hydrodynamic challenges associated with the Aquaculture -PV complementation system are notably more complex than those of the Wind-PV complementation system. This complexity integrates hydrodynamics from

FPV systems, floating wind turbines [64–66], and floating aquaculture net cages [67–69]. Additionally, the system must address technical challenges related to power grid integration and cable management.

5.2. New Structural Systems for Offshore FPV

5.2.1. Wave-Adaptive Flexible Structures

(1) Flexible Membrane Photovoltaic System

The flexible membrane FPV system developed by Norway's Ocean Sun consists of a buoyancy ring and a flexible polymer membrane. The buoyancy ring, prefabricated from HDPE piping, is connected to the flexible membrane through tensioned lines. The solar modules are securely mounted on the membrane surface for power generation. This innovative configuration maintains direct membrane-water contact, effectively suppressing module temperature rise and consequently enhancing power output. This system offers multiple advantages, including cost-effectiveness, low wind resistance, and exceptional typhoon resilience, which have garnered increasing research attention in recent years.

The flexible membrane floating structure exhibits significantly larger horizontal dimensions compared to its vertical scale, coupled with relatively low bending stiffness, resulting in primarily elastic deformation under wave action.

Kristiansen et al. [70] conducted model tests on an air-cushioned flexible photovoltaic platform supported by buoyancy rings, investigating its motion characteristics and mooring system forces under both regular and irregular wave conditions, while also exploring the failure conditions caused by air cushion leakage.

Aas-Hansen [71] performed seakeeping tests on the flexible membrane photovoltaic system developed by Norway's Ocean Sun, comparing the structural motion responses and mooring line forces with and without PV modules. The experiments revealed significant wave overtopping phenomena due to the low handrail height on the buoyancy rings.

Sigstad [72] studied the hydroelastic response of an FPV platform, which is supported by multiple buoyancy rings through physical model tests. This platform employs interconnected concentric flexible buoyancy rings to support the flexible membrane.

Schreier [73] measured the deformation of floating flexible rubber sheets in regular waves for floating flexible photovoltaic structures.

(2) Offshore Fishing Raft Off-grid Photovoltaic Power Station

Offshore aquaculture industry is predominantly located in coastal areas, where fishermen conduct both production activities and daily living on offshore residential platforms and cage structures. Given the remote offshore locations, conventional power supply solutions have typically relied on either submarine cable installations or diesel generators to meet their electricity demands. Therefore, the offshore aquaculture industry in land-remote power-challenged areas demonstrates optimal compatibility with small-scale off-grid photovoltaic systems to achieve self-sufficiency and synergistic fishery-solar co-location. A practical example can be found in Fujian Province, where wind-powered street lights have been installed on aquaculture platforms, complemented by over 200 PV panels on rooftops to provide a green and stable electricity supply for fishing rafts [74].

Aquaculture zones typically lack natural protective barriers, making fishing equipment particularly vulnerable to safety risks under extreme weather conditions. Hydrodynamic performance and mooring systems are critical determinants for ensuring the operational safety of aquaculture equipment.

Cui et al. [75] conducted numerical simulations to investigate raft-type aquaculture facilities' displacement and maximum mooring line forces under varying wave periods and heights. Their results exhibit periodic motion without entanglement of buoys or cages, demonstrating the structure's safety in wave conditions.

Cheng [76] developed a numerical model to analyze the dynamic response of aquaculture structures, focusing on sheltering effects between farming units and the influencing factors of mooring line forces. The results reveal that current flow increases mooring tension on the upstream side, and maximum tension decreases with the increase of the incident angle. Mooring lines on the wave-facing side experience greater forces than those on the leeward side when waves parallel the raft's main axis. Maximum tension shows an approximately linear increase with relative wave height. The research results can provide valuable technical support for safety and reliability assessments of aquaculture structures.

Fu et al. [77] performed frequency-domain analysis of a floating aquaculture fishery's dynamic response using three-dimensional hydroelastic theory. Results showed rigid motion dominance on the wave-facing side and flexible motion contribution on the backside.

(3) New Floating Block Floating Structures

In inland water systems, floating block structures have gained popularity due to their excellent wave-following capabilities. However, material strength and connection joint durability limitations restrict their applicability in offshore environments. To address this technological barrier, scholars are investigating innovative material solutions and intelligent connection technologies to develop floating block structures capable of stable operation in harsh marine environments while maintaining effective wave-following performance, which represents a promising future research direction.

Tian et al. [78] investigated the motion responses and wave loads of FPV platforms using AQWA. They calculated the mooring forces and structural strength under combined wind-wave conditions with 10-year and 25-year return periods, revealing that weak zones were identified at the wave-facing edge and the connection plates between floating units.

Zhang et al. [79] explored dual-floating systems' motion responses and mooring tensions under wave loads. The study indicated that shorter connectors intensify hydrodynamic interference between dual floating boxes, while increasing connector stiffness reduces both pitch and roll motions. Interestingly, mooring tension variations exhibited an inverse relationship with motion responses. These findings provide insights for designing multi-floating structures in marine environments.

Da et al. [80] performed systematic numerical analysis on FPV platforms, evaluating the impacts of rigid connectors with different rotational constraints and flexible connectors with different tensile stiffness on motion responses. The results indicate that rigid connectors significantly reduce relative motions between platforms but induce higher connection loads, whereas flexible connectors reduce loads but allow greater relative motions. Engineering applications thus require balanced solutions considering both platform motion and connector load limitations.

Consequently, the design and optimization of floating block structures must account for wave conditions, material properties, and connector reliability to enhance performance and safety under severe wind and wave conditions.

5.2.2. Large Scale Rigid Floating Structures

Current floating structures typically have relatively small dimensions close to frequently occurring wavelengths, leading to poor motion responses. Existing studies demonstrate a significant correlation between structural length and wave length in dynamic responses.

Ding et al. [81] investigated the effects of geometric dimensions and physical properties of Very Large Floating Structures (VLFS) on hydroelastic dynamic responses under typical sea states and analyzed the hydroelastic response of floating structures with different lengths, thicknesses and materials. The results indicate that structures exhibit sufficient safety performance in small-wave environments with minimal response. However, when wave lengths approximate structural dimensions, elastic deformation increases substantially, potentially inducing plastic failure. In scenarios where wavelength exceeds the structure length, rigid-body motion dominates the response profile, drastically raising overturning risks.

Wang et al. [82] calculated the dynamic responses of box-type VLFS in sinusoidal regular waves using three-dimensional linear hydroelasticity theory. Analysis results indicated that maximum vertical displacements occur when wave lengths match structural lengths, necessitating avoidance of such wave conditions in the design or implementation of breakwaters.

Huang [83] compared static responses, including vertical displacements and axial stresses, under two wave-load calculation methods. The results showed that central vertical displacements decreased with the decrease in the ratio of the wavelength to the structure length.

Consequently, developing ultra-large FPV structures exceeding regional frequently occurring maximum wave lengths appears a viable direction for floating systems.

6. Conclusions

Compared to land-based and inland FPV systems, offshore FPV offers significant advantages in marine resource utilization, enhanced solar energy efficiency, and land conservation. Its potential for synergistic integration with other offshore renewable energy projects or maritime activities presents substantial development opportunities. Successful demonstration projects such as Solar Duck, Solar Sea, and Ocean Sun have validated the technical feasibility of offshore FPV systems. Consequently, continued research and development in offshore FPV technology will play a crucial role in addressing global energy shortages and mitigating the impacts of climate change.

However, the development and application of offshore FPV systems are still facing significant challenges. Firstly, floating structure design lacks authoritative theoretical guidelines and standards, leading to insufficient accuracy in analyzing motion characteristics, load distributions, and power performance under the action of wind, wave and current. Secondly, most existing offshore FPV structures exhibit limitations in wave resistance, weather endurance, and wave-following capabilities. New structural systems examined in this study– including flexible membrane photovoltaics, offshore fishing raft off-grid photovoltaic power stations, modular floating block structures, and large-scale rigid structures–demonstrate promising prospects in these aspects, representing critical future research directions. Additionally, mooring systems are crucial for ensuring structural stability. Further investigations should focus on chain configuration arrangements and hydrodynamic performance of anchoring systems under different mooring strategies.

Hybrid offshore FPV systems represent a promising alternative solution for enhancing both the performance and economic competitiveness of marine PV installations. Existing research has verified the technical feasibility of such hybrid systems. Compared with conventional standalone PV systems, this development mode not only reduces operational costs and improves commercial viability through synergistic industrial complementarity but also expands application domains. Currently, "Wind-PV complementation" and "Aquaculture-PV complementation" models have emerged as critical research priorities. It is projected that Hybrid offshore FPV systems will become a driving force in advancing the FPV industry and supporting the achievement of China's 3060 dual-carbon targets.

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Author Contributions

Conceptualization, X.Y. and J.L.; Methodology, Y.Y. and X.G.; Investigation, X.Y. and C.D.; Writing—Original Draft Preparation, C.D.; Writing—Review & Editing, X.Y. and C.D.; Supervision, J.L. and H.L.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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Declaration of Competing Interest

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

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