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Review

Review of Recent Offshore Floating Photovoltaic Systems

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Abstract: Photovoltaic (PV) power generation is a form of clean, renewable, and distributed energy that has become a hot topic in the global energy field. Compared to terrestrial solar PV systems, floating photovoltaic (FPV) systems have gained great interest due to their advantages in conserving land resources, optimizing light utilization, and slowing water evaporation. This paper provides a comprehensive overview of recent advancements in the research and application of FPV systems. First, the main components of FPV systems and their advantages as well as disadvantages are analyzed in detail. Furthermore, the research and practical applications of offshore FPV systems, including rigid floating structures and flexible floating structures, are discussed. Finally, the challenges of offshore FPV systems are analyzed in terms of their stability and economic performance. By summarizing current research on FPV systems, this overview aims to serve as a valuable resource for the development of offshore FPV systems.

Keywords: renewable energy; offshore floating photovoltaic; floating structure; thin film structure

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1. Introduction

With the growth of the global population and the development of economy and society, human demand for energy is increasing. Traditional fossil energy plays a leading role in energy consumption, and the burning of fossil energy causes serious problems such as greenhouse effect and atmospheric pollution. It is imperative to exploit renewable energy in order to alleviate the contradiction between energy supply and demand, reduce greenhouse gas emissions and protect the ecological environment [1]. Typical renewable energy sources mainly include solar, wind and hydro energy, among which solar energy is highly favored for its broad, sustainable and environmental advantages. Photovoltaic (PV) power generation represents a widely adopted method for utilizing solar energy. This technology effectively converts solar radiation into direct current electrical energy. In recent years, there has been a notable increase in the development of large-scale grid-connected solar photovoltaic power generation systems, particularly in regions characterized by abundant solar radiation [2]. This accelerated growth reflects the growing recognition of solar power as a viable and renewable resource for electricity generation, which is crucial for meeting future energy demands.

Conventional PV power generation systems are generally built on mountains or on the ground, requiring a substantial land area which significantly raises installation costs, and relevant statistics show that 1.6 hectares of land area is required for the installation of a PV system with a capacity of 1 MWp [3–6]. In addition, land-based PV systems face challenges such as temperature rise, partial shading, and dust accumulation on the modules, all of which can reduce power generation efficiency [7–9]. In contrast, floating photovoltaic (FPV) systems deploy PV modules on the water surfaces of lakes, ponds, water treatment plants, and oceans using floats that are secured by anchoring systems. This approach conserves land resources while enhancing power production efficiency and light utilization compared to land-based systems, yielding approximately 10% greater benefits from FPV systems [10–16]. The relevant literature shows that the deployment of FPV systems is experiencing rapid global growth, with notable increases in installed capacity in China, the United States, South Korea, Japan, France, India, Spain, Singapore, and Italy [4,17–22]. It is projected that global power generation from FPV systems will experience a substantial increase by 2030, with estimates reaching 710 terawatt hours (TWH) [23,24]. For certain islands and countries with restricted land availability, FPV systems could potentially emerge as their primary source of renewable energy [25].

The majority of FPV systems are typically situated in inland bodies of water, including lakes, water ponds, water reservoirs, and canals [20], while offshore FPV systems have received less attention due to the harsh marine environment. Despite this, the ocean covers over 70% of the Earth's surface and offers abundant solar energy resources, making offshore FPV a promising avenue for future PV power plant development [26–30]. This paper aims to provide a detailed overview of the main components, advantages, and disadvantages of FPV systems. It will also analyze the research and practical applications of offshore FPV systems with rigid floating structures and flexible floating structures, while discussing the primary challenges faced by the offshore FPV systems.

2. Overview of FPV Systems

2.1. The Composition of FPV Systems

The primary components of the FPV system include floats, PV modules, related electrical equipment, as well as mooring and anchoring devices, as depicted in Figure 1.

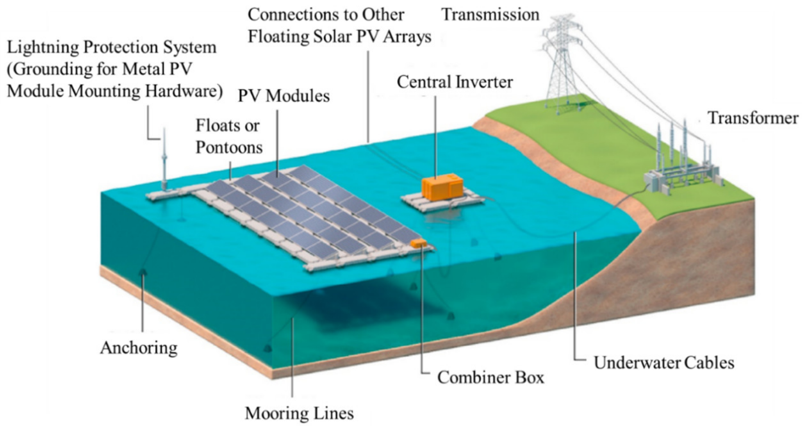


Figure 1. Main components of the FPV system [31].

Floating structures are utilized to provide buoyancy for FPV systems, supporting PV modules and electrical equipment, and these structures are typically of the floating tube or floating pontoon type [27]. Currently, a single floating structure is commonly used for FPV systems, and high-density polyethylene (HDEP) is widely selected as the manufacturing material for the float due to its high tensile strength, good UV and corrosion resistance [18]. Additionally, the floating body can also serve as an installation and maintenance channel during assembly or repair of the FPV system [29]. Individual floats are designed with a highly modular structure for easy assembly, often featuring special shapes to aid in connecting neighboring floats [4,12,26]. Semi-rigid or flexible connections between individual floats are usually adopted [32], and a certain degree of rotation between floats is allowed at the connection point. This rotation helps reduce stress concentration under wave action and facilitates the installation and launching of the FPV system [33,34]. The FPV device with single float structure is mainly used in inland lakes and reservoirs. In harsh marine environments, multiple floats are typically used to jointly support a floating platform with fixed brackets that support the PV modules, and these platforms can be flexibly connected to expand the scale of the FPV system [35]. Alternatively, a buoyant ring can be utilized to support a reinforced thin film on which PV modules are positioned [21,26].

PV modules can directly convert solar energy into electrical energy through the photovoltaic effect. Currently, crystalline silicon PV modules are predominantly used in solar energy systems, typically in rigid flat form [36]. In FPV systems, PV modules are often treated with emerging technologies to adapt to various operating environments [37]. These modules are usually affixed to the float using supporting devices made of galvanized metal or HDEP [38]. There is generally an optimal tilt angle between the PV modules and the float, which is determined by the geographic location of the FPV system. This tilt angle ensures adequate light intensity, prevents the accumulation of dust onto the PV modules, and aids in the cooling of the modules [39–41]. To protect against corrosion in wet and salt spray environments, PV modules are commonly sealed with glass components and aluminum alloy or polymer frames. Amorphous silicon (a-Si) thin-film PV modules have gained increasing attention in recent years. These thin-film modules can float on water surfaces and move with the waves. They are cost-effective, lightweight, easy to install, and can directly interact with water, making them a promising option for offshore FPV systems [17,42,43].

Mooring and anchoring devices in FPV systems can keep the float structure in a relatively stable position to limit the float from rotating or drifting under wind, wave and currents, which can prevent damage to the float structure and electrical equipment [44,45]. The design of mooring and anchoring devices should take into account factors such as water level fluctuations, wind pressure loads, fluid dynamics, and geological conditions to ensure that the strength of the mooring line and the load carrying capacity of the anchoring are sufficient to meet the working requirements of the FPV system under different operating conditions [34,46,47]. Mooring lines are usually made of steel wire rope or synthetic fiber rope, and the types of anchoring mainly include drag anchors, pile anchors, and gravity anchors. Among them, gravity anchors are mainly composed of concrete blocks or steel blocks, which are convenient for construction and relatively low cost and are often used in small FPV systems [4,35]. With the development of offshore FPV systems, the requirements for the design and installation of mooring and anchoring devices will continue to increase.

The FPV system's electrical equipment mainly consists of the inverter and the cable line [26]. The function of the inverter is to transform the direct current power generated by the PV modules into alternating current power, which facilitates the integration of electrical energy into the power grid. The inverter can be mounted on the float or on the shore closer to the FPV system and should be well waterproofed [26,31]. The effect of the cable line is to deliver the power generated by the FPV system to the grid or the storage battery. Presently, most FPV systems do not install the cables underwater but lay them on the water surface. To ensure the longevity of the cable line, the cable sheath should be waterproof, corrosion-resistant, and sturdy, requiring regular inspection and maintenance due to prolonged operation in a wet environment and constant exposure to wind and wave loads [4,48]. Moreover, the cable design should consider a margin for cable length adjustments in response to fluctuations in water levels.

2.2. Advantages and Disadvantages of FPV Systems

In comparison with land-based PV systems, FPV systems exhibit a number of advantages.

- Saving land resources.

The acquisition and exploitation of land resources significantly contribute to the overall cost of installing land-based PV systems [4]. In contrast, FPV systems do not require agricultural or mining land resources, which eliminates the costs associated with constructing civil works and reduces the construction costs to a certain extent. This advantage is especially significant in densely populated countries and regions where land resources are scarce and demand for agricultural land is high [5,17,48].

- Enhancing power generation efficiency.

The functioning of photovoltaic systems is accompanied by a consistent increase in the temperature of the solar modules, which in turn leads to a reduction in power generation efficiency. In FPV systems, the PV modules are directly or indirectly in contact with water, which results in the cooling of the system, maintains lower temperatures for the PV modules, and improves the power generation efficiency of the system [49–52]. Research indicates that FPV systems operate at temperatures 2.7–3.5 °C lower than land-based PV systems, resulting in approximately 2.3–2.6% higher energy output per day [53,54]. Additionally, there is almost no sunlight shading in FPV systems and the water can easily clean the dust accumulated on the PV modules, which will also increase the efficiency of FPV systems [55].

- Reducing evaporation of water.

The FPV system has the beneficial effect of covering the surface of the water, which directly leads to a reduction in the amount of solar radiation that reaches the water's surface. This decreased exposure to sunlight plays a crucial role in mitigating water loss caused by evaporation [56–61]. Research conducted at the Passaúna reservoir in Brazil demonstrated that installing an FPV system with a capacity of 0.13 MWp and an area of 1265.14 m^2 resulted in a 60.20% reduction in the evaporation rate of water in the covered area. In the case where the capacity of the FPV system was increased to 5 MWp, the water saved by covering the FPV system was enough to supply more than 196 people for one year [62].

- Improving water quality.

The discharge of nutrients, such as nitrogen and phosphorus, can cause rapid reproduction of algae and other plankton in lakes and seas, leading to eutrophication and deterioration of water quality. Installing an FPV system can reduce the amount of solar radiation on the water surface, weakening the photosynthesis of algae in the water body and slowing down the process of eutrophication, which can improve water quality and reduce the expenses associated with water treatment [48,63–65].

The main disadvantages of FPV systems are as follows.

- Harsh working environment.

Prolonged exposure to aqueous environments makes the components of FPV systems susceptible to rust and corrosion, leading to a significant reduction in the operational lifespan of the PV module [66]. This phenomenon is particularly prevalent in offshore FPV systems, where the presence of salt in seawater serves to accelerate the processes of rusting and corrosion [4,67]. As a result, the levelized cost of electricity (LCOE) for FPV systems is around 2.5% higher than that of land-based PV systems [68]. In offshore FPV systems, the support floats are easily damaged in certain severe sea conditions due to the combined effects of wind and wave loads and mooring forces during operation.

- Impact on the growth of aquatic organisms.

The installation of FPV systems has been shown to reduce eutrophication and improve water quality. However, in the case of offshore FPV systems, the large area coverage of the water body can prevent sunlight penetration into the water, which can have an impact on the growth of aquatic organisms [40,69,70]. In addition, the interaction between the mooring cable and the water bottom, as well as the electromagnetic effect of the FPV system, may also affect the growth of aquatic organisms [16,71,72].

3. Research on Offshore Floating Photovoltaic Systems

The design of offshore FPV systems is fundamentally analogous to that of FPV systems in inland lakes or reservoirs. However, the challenging conditions of the marine environment present more significant obstacles, resulting in heightened requirements for offshore FPV systems. Factors such as reliability, maintainability, overall cost-effectiveness, and potential impact on the marine ecosystem must be carefully considered during the design and manufacturing process, and these considerations have limited the widespread deployment of maritime FPV systems [6,18,33,73,74]. Nonetheless, offshore FPV projects have been developed and practiced in several countries with some achievements [35].

These systems can be categorized into rigid and flexible floating structures based on their float composition.

3.1. Offshore FPV with Rigid Floating Structures

3.1.1. Research Status of Rigid Floating Structures

The inland lake FPV systems are basically rigid floating structures, and some researchers have made improvements to adapt them to the marine environment.

Lee et al. developed and deployed an offshore FPV system using fiberglass reinforced plastic (FRP) components at the sea site in Korea [38]. The safety of the FPV system was confirmed through tensile and shear tests of pultruded fiberglass reinforced plastic (PFRP) members, finite element analysis of the FPV module, and fluid-structure coupling analysis of the FPV module. The comparison between the offshore FPV system and the land-based PV system showed that the offshore FPV system produced significantly more electricity from June to August. However, during September and October, the power generation of the offshore FPV system was comparatively lower, which may be attributed to typhoon-related damage to the system's electrical equipment.

Ghigo et al. developed an offshore FPV system comprising multiple independent platforms supported by HDPE floats [44]. Rectangular support structures made of steel and aluminum alloy are mounted on the floats to hold the photovoltaic modules. Each independent platform is equipped with four catenary lines connected with four drag-embedded anchors to prevent the platform from excessive movement. The hydrodynamic response of the FPV system was analyzed using Matlab-Simulink software (https://www2.mathworks.cn/en/) under the action of three different sets of common waves when the wind speed was 8 m/s and the relevant technical requirements of the mooring and anchoring device were determined.

Jiang et al. developed a rigid FPV system specifically designed for rough sea conditions [75]. The standard float of the system measures 4.7 m in length and 2.9 m in width, comprising a combination of one porous rectangular float and six cylindrical floats. The porous design of the rectangular floats enhances the cooling effect of the PV panels, and the hollow interior reduces float weight. The floats are made of recyclable, corrosion-free carbon-fiber-reinforced material based on high-density polyethylene. Each standard float can support four PV panels, and the floats are flexibly connected to each other by elastic ropes to reduce environmental loads and mitigate fatigue damage.

3.1.2. Properties and Application of Rigid Floating Structures

The most commonly utilized materials for rigid floating structures include FRP and HDPE. The interior of the float can be filled with polystyrene foam, which provides necessary buoyancy even in the event of damage to the float itself [38]. To ensure the corrosion resistance of the support structure, it is essential to minimize welding between the support structure and the floating body, as well as within the support beam of the support structure. Instead, bolted connections are preferred [38,44]. Furthermore, the use of flexible rope connections between adjacent rigid floats enhances the ability of the FPV array to adapt to wave motion, thereby preventing collisions among neighboring floats [75].

The application of rigid floating structures to offshore FPV systems has been indicated by research to be a viable solution. However, in the case of large-scale offshore FPV systems with rigid floating structures, the requirements for the strength of the floating structure and the mooring and anchoring devices are necessarily higher in order to withstand the challenging sea conditions that are a common feature of offshore operations. This can significantly increase the manufacturing cost of FPV systems. Currently, various conceptual models for offshore FPV systems with rigid floating structures have been proposed and tested by some marine energy companies globally. The designs by Swimsol, Moss Maritime, and Oceans of Energy are particularly notable and representative, as depicted in Figure 2 [28,76].

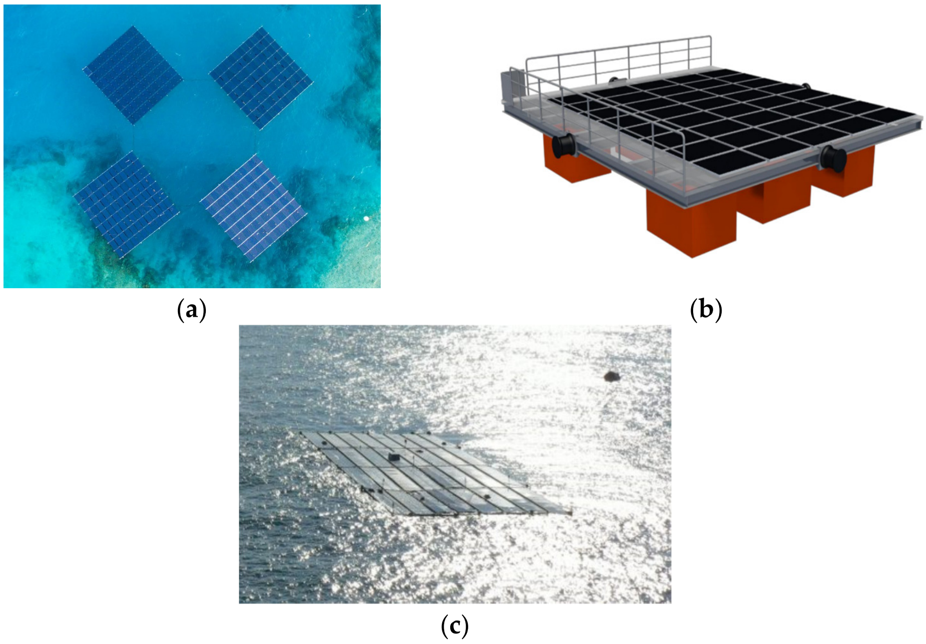


Figure 2. Offshore FPV systems with rigid floating structures [28,76,77]. (a) Offshore FPV project by Swimsol. (b) Offshore FPV project by Moss Maritime. (c) Offshore FPV project by Oceans of Energy.

3.2. Offshore FPV Systems with Flexible Floating Structures

3.2.1. Research Status on Flexible Floating Structures

Recent studies have indicated that flexible floating structures are more suitable in harsh sea environments compared to rigid floating structures [17,35,78]. Offshore FPV systems with flexible floating structures can be categorized into two types, flexible floating structures supporting flexible thin film PV panels and flexible floating structures supporting rigid crystalline silicon PV panels [43].

Trapani et al. developed a flexible thin film FPV system prototype designed for large-scale power generation in harsh sea conditions [43]. The system prototype uses a customized flexible thin film PV panel measuring 3.45 m in length and 0.69 m in width, with a power rating of 94 Wp. The outer layer of the PV panel is covered with ethylene tetrafluoroethylene (ETFE) sheets, to constitute a standard PV module with a thickness of less than 1 mm. The selected ETFE sheet has high transparency and self-cleaning performance, ensuring the panel's power generation efficiency. To maintain the buoyancy of the system, the standard PV modules are affixed to the neoprene mesh on their backside, and the adjacent modules are connected through the mesh to form the FPV array.

Det Norske Veritas (DNV) has proposed a flexible thin film FPV system named SUNdy [4,76]. In this system, the thin film solar panels attached with a three phase micro-inverter are mounted on a flexible floating mat, and the marine grade connectors embedded in the edge of the floating mat facilitates the connection of neighboring PV panels to form a standard PV module. By connecting a series of standard PV modules, a 20 MWp hexagonal FPV array is formed, with a transformer placed in the center of the hexagon and maintenance access between the center and each vertex. It is feasible to connect multiple FPV arrays to establish a solar farm with a capacity of 50 MWp or greater, which would be capable of supplying energy to approximately 30,000 individuals.

Ravichandra et al. designed a flexible floating structure offshore FPV system equipped with thin-film PV modules [17]. To minimize the impact of wind and wave current loads, the system is no longer supported by floats. Instead, the flexible thin-film PV modules are directly paste onto a foam plate made of neoprene rubber, and the ends of the adjacent thin-film PV modules are connected to each other through the foam plate. The foam plate has holes at both ends to connect the mooring and anchoring system. The number and location of foam plates can be adjusted to ensure the overall strength and rigidity of the offshore FPV system, based on wind and wave loads. By eliminating the need for float support, this system is lighter in weight, has a simpler mooring and anchoring design, and is more cost-effective compared to onshore FPV systems.

3.2.2. Properties and Application of Flexible Floating Structures

The FPV systems with flexible floating structures offer a simpler structure and lower cost in comparison to that with rigid floating structures. The flexible film can effectively adapt to the movement of the water surface, so that the whole FPV system follows the waves, reducing the interaction between the waves and the system, which reduces the mooring loads and improves the reliability of the system [17,21,73,78,79]. In addition, the flexible thin film support allows the PV module to be situated in close proximity to the water surface, thereby enhancing the cooling effect and maintaining the cleanliness of the PV module. As a consequence, the power generation efficiency of the solar module is improved, which in turn leads to enhanced environmental benefits [80,81].

Currently, there are limited practical applications of offshore FPV systems with flexible floating structures. The available products on websites and in literature are mainly Ocean Sun's products, all of which are flexible floating structures supporting rigid crystalline silicon PV panels. The Solar@Sea II project trial was conducted by the Netherlands Organization for Applied Scientific Research (TNO) in the Oostvoornse Meer near the port of Rotterdam [82], as shown in Figure 3, which used a flexible floating structure to support flexible ultra-thin copper-indium-gallium-selenide (CIGS) PV panels, with a total project power of 20 kW using 144 flexible thin film PV panels. The project concentrated on the energy generation capacity of the flexible PV panels and the performance of the FPV system in the presence of waves and strong winds. Following the trial, TNO plans to build an offshore FPV facility with a capacity of up to 5 MWp in the North Sea and coordinate it with existing offshore wind farms to create a wind–solar co-located project.

Figure 3. The Solar@Sea II project [82].

4. Application of Offshore FPV System

At present, the deployment of FPV systems on inland waterways is relatively common, whereas the application of offshore FPV systems remains relatively limited. Table 1 lists some of the offshore FPV system projects that have been installed in recent years.

Table 1. Part of offshore FPV system projects in recent years [4,21,28,35,76,77,83–91].

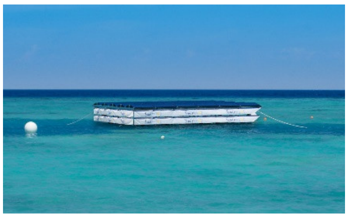
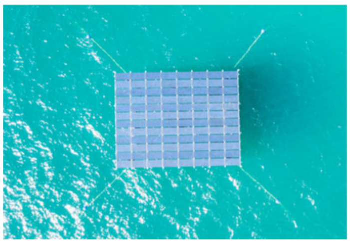
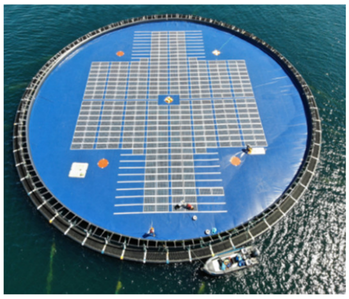
Producer	Float Structure	Capacity (KWp)	Features	Date	Location	The Physical Picture
Swimsol	Rigid floating structures	15	The inaugural offshore FPV system globally, along with the first floating solar platform at sea. This platform is robust enough to guarantee the safety of the photovoltaic modules. Every component in the system is designed to resist corrosion and has a lifespan of up to three decades.	2014	Maldives	
Swimsol	Rigid floating structures	24	This project serves as a preliminary effort for the offshore floating solar platform, with the goal of acquiring experience that will facilitate the future installation of a more extensive offshore floating solar system.	2017	Maldives	
Ocean Sun	Flexible floating structures	100	The individual float of the system is 50 m in diameter, and the system employs flexible thin film to support the rigid crystalline silicon PV panels, with the inverters placed on a nearby barge. The floats, thin film and PV panels of the system remained in good condition after surviving several winter storms.	2018	West Coast of Norway	
Oceans of energy	Rigid floating structures	50	The system was installed 15 km offshore from the coast and successfully withstood severe sea conditions, including wave heights up to 9–10 m and hurricane winds in excess of 110 km/h. It is designed and tested to withstand waves up to 13 m high.	2020	The North Sea	
Sunseap	Rigid floating structures	5000	The FPV system comprises 13,312 photovoltaic panels, 40 inverters, and over 30,000 floats. Based on Sunseap's estimates, the system will generate 6,022,500 kWh of energy per year, leading to a reduction of around 4258 tons of CO_2 emissions.	2021	Straits of Johor, Singapore	
Solarduck	Rigid floating structures	65	The system's individual float is triangular in shape, measuring 16 × 16 × 16 m, and it can be connected in a flexible configuration to form a large floating solar platform. It is lightweight, highly stable, and can withstand wind, waves, and currents, including sea breezes of up to 30 m/s.	2021	Rhine inshore waters	

Table 1. *Cont.*

Producer	Float Structure	Capacity (KWp)	Features	Date	Location	The Physical Picture
Swimsol	Rigid floating structures	35	The system is a PV-LPG hybrid power system installed near fish farms in the coastal waters of Chile, which provides power to the fish farms.	2022	Chile	
Ocean Sun	Flexible floating structures	500	This project represents the inaugural offshore FPV undertaking to be operational within the "double 30" marine environment. This environment is defined by an offshore distance of 30 km, a water depth of 30 m, and an extreme wave height of 10 m. The project combines wind and PV power generation in the same field to reduce engineering, operating and maintaining costs. It explores technical routes for future offshore FPV systems to achieve scale, commercialization and standardization, and aims to realize value symbiosis with the industrial chain.	2022	Yantai, China	
CIMC Raffles	Rigid floating structures	400	The offshore FPV power generation platform is semisubmersible and equipped with four single floating arrays. Its overall net deck area spans approximately 1900 square meters and includes eight systems, such as floating structural support system, buoyant material system, multi-body connection and mooring system, fender collision avoidance system, photovoltaic power generation and inverter system, intelligent monitoring system, dynamic cable transmission system and power consumption system. This platform is engineered to function safely in open ocean environments, capable of withstanding wave heights of up to 6.5 m, wind speeds reaching 34 m/s, and tidal ranges of as much as 4.6 m.	2023	Yantai, China	

5. Challenges of Offshore FPV Systems

In recent years, there has been a rapid development in inland water FPV systems. Simultaneously, more and more scholars are focusing on offshore FPV systems due to the abundant solar energy resources in the sea. Nevertheless, the operational conditions for offshore FPV are notably harsh, particularly due to the interaction of wind, waves, and currents during adverse maritime conditions. Consequently, the FPV system is subjected to considerable additional loads, which must be taken into account in the design process. Moreover, offshore FPV systems are located far from land, making maintenance challenging, and prolonged exposure to salt spray increases material corrosion. These factors pose higher requirements for offshore FPV systems [16,21,26,28,35]. The challenges of offshore FPV systems can be discussed in terms of the stability and the economic performance of the system.

5.1. Stability of FPV Systems

In the marine environment, the stability of the system is the primary determinant of the lifespan of FPV systems. The stability is primarily influenced by several factors, including the type of float, the configuration of the float structure, the arrangement of the anchoring device, the selection of materials, and other related aspects. In recent years, researchers have focused their efforts on investigating the stability of large-scale FPV systems [44,54,92].

For rigid floating structures, a single floating platform provides good stability and can withstand the impact of wind and wave currents even under harsh sea conditions. However, the platform structure is complex and costly. Moreover, with the trend towards scaling up offshore FPV arrays, connecting multiple platforms can significantly reduce the stability of the system, especially vulnerable to damage at connection points during severe weather conditions [32,35,73,76]. It has been demonstrated that the utilization of flexible connections at rigid platform joints can serve to diminish external loads and mitigate fatigue damage to some extent, thereby enhancing the stability of the FPV system [75,93,94]. Designing reliable platform joints and ensuring the stability of rigid floating structures in large-scale FPV systems will be a major challenge in the future [94].

Flexible floating structures offer a cost-effective and stable solution for large-scale FPV systems in harsh sea conditions compared to rigid floating structures [26,35,43,79]. For example, SUNdy's design, with its flexible floating structure, is more lightweight and structurally simple. This design minimizes the need for anchor chains, enhances its ability to adapt to wave motion, and improves its ability to withstand external loads [76]. Nevertheless, the practical applications of this system remain constrained, as the majority of research is currently confined to laboratory settings. Relevant studies indicate that the flexible FPV system, which comprises a flexible floating body structure and a thin film photovoltaic module, holds significant promise for applications in marine environments. However, analyzing the forces and stability of such FPV systems under varying sea conditions presents considerable challenges. Ensuring the accuracy of these analyses is particularly difficult, especially in the context of fluid–structure coupling.

On the other hand, the optimization of the anchoring device, the reasonable arrangement of inverters and power lines, and the development and use of corrosion-resistant materials will also be important challenges for the stability of FPV systems [18,68,95]. These elements are crucial for maintaining the operational efficiency and longevity of FPV systems in diverse marine environmental conditions. The optimized placement of moorings mitigates the risk of damage to FPV systems by preventing steering or drifting, while the suitable arrangement of inverters and power cables minimizes potential malfunctions and enhances energy output. Furthermore, the use of corrosion-resistant materials contributes to the long-term durability of FPV systems and reduces the risk of pollution in the marine environment. Addressing these challenges concurrently is essential for the successful implementation and sustainability of offshore FPV systems.

The potential impact of FPV systems on marine ecosystems raises significant concerns. It is crucial to minimize the effects of FPV systems on the growth of aquatic organisms throughout their design, operation, and maintenance phases. During the design stage, the selection of appropriate installation locations and procedures can effectively mitigate the impact of FPV systems on marine organisms [35]. In the operational phase, the effects of material degradation of floating structures and the electromagnetic emissions from FPV systems on the marine ecosystem should be minimized [71,72]. Furthermore, during maintenance and repair, it is of significant importance to prevent pollution of the marine environment from waste materials.

5.2. Economic Performance of FPV Systems

The economic performance of offshore FPV systems is a significant challenge. Factors that affect economic performance include the costs of constructing, operating, and maintaining offshore FPV systems, as well as the power generation efficiency [14]. In rigid floating structures offshore FPV systems, to reduce construction and operation costs and improve economic performance, the float material is primarily made of corrosion-resistant HDEP [35], and sometimes the partly intermediate float of the FPV system is made of the more affordable medium-density polyethylene (MDPE) [96]. These floats are equipped with small amounts of metal to support the PV modules. Recently, research has concentrated on reducing the quantity of metal used in the support structure. The challenge is to develop less expensive float materials with high fatigue strength and corrosion resistance. Additionally, the float structure should be modular to reduce the cost of installing and maintaining FPV systems [97,98].

Flexible floating structures photovoltaic systems, when combined with amorphous silicon (a-Si) thin film PV modules, offer advantages such as simplicity, high-efficiency, and suitability for rough sea conditions [17,43,79,99]. These thin film PV modules are structurally simple, lightweight, and economically efficient compared to traditional crystalline silicon PV modules, reducing the need for complex floating structures and anchoring devices. Moreover, the direct contact of thin film PV modules with water enhances cooling efficiency, leading to improved power generation and economic performance of the FPV system [43,79,100]. The combination of "flexible floating structures + thin film PV modules" not only improves stability but also increases economic efficiency, making it a competitive option for future offshore FPV systems.

Ravichandra established a numerical model of the PV system using Helioscope software (https://helioscope.aurorasolar.com/) and compared the power generation performance of the offshore FPV system (OFPV) with that of the inland lake FPV system (FPV) and the ground-mounted PV system (GM-PV) [17]. The results indicated that the power generation efficiency of the OFPV system was significantly higher than that of the FPV system and the GM-PV system. The annual power generation of the OFPV system increased by 13% and 14% compared to the FPV system and GM-PV system, respectively. Furthermore, the carbon emission of the OFPV system was reduced by 14% compared to the other systems, leading to improved environmental benefits.

In addition, the co-location of wind and photovoltaic power generation can effectively utilize electrical equipment such as inverters and cables, while optimizing the use of ocean space and reducing overall system costs as well as operations and maintenance fees. By taking advantage of stronger winds during winter and at night, as well as more sunshine during summer and daytime, the co-located power generation can effectively utilize wind and solar energy at different times to ensure stable and continuous power output. This approach not only enhances economic performance but also promotes the large-scale commercialization process of offshore FPV systems [101–105]. In the future, the main challenge for systems that combine offshore floating photovoltaic and wind power generation is the optimal placement of FPV equipment between wind turbines to minimize interactions and maximize power generation.

6. Conclusions

FPV systems present a number of advantages compared to land-based PV systems, such as saving land resources, reducing water evaporation, and improving water quality. In recent years, FPV systems have experienced rapid growth and are increasingly being applied in inland lakes and reservoirs. Due to abundant solar energy resources available at sea, offshore FPV systems hold significant market potential. However, the practical implementation is limited by the corrosive nature of seawater and severe sea conditions influenced by wind, waves, and currents. Achieving large-scale commercial applications of offshore FPV systems at this stage proves to be challenging.

Offshore FPV systems can be classified into two types based on their float composition: rigid float structures and flexible float structures. Rigid floating structures FPV systems can be applied to the marine environment, and at this stage, some marine energy enterprises have already designed and installed such offshore FPV systems, but with the increase of FPV arrays, the manufacturing cost of the rigid floating structures FPV systems will be greatly increased. On the other hand, flexible floating structures FPV systems are better suited for marine environments with challenging sea conditions, however, research in this area is still in the initial stages, and the practical application at sea is relatively limited.

Enhancing the stability and the economic performance of FPV systems pose significant challenges in offshore FPV systems. Ensuring stability for large-scale rigid floating structures in FPV systems is a complex task, but incorporating flexible connections at the rigid platform junctions can enhance float stability to a certain degree. Flexible floating structures FPV systems are simple in structure and high in stability. Additionally, thin-film photovoltaic modules are advantageous due to their cost-effectiveness, lightweight nature, and high power generation efficiency. Therefore, the potential application of "flexible floating structures + thin film photovoltaic modules" FPV systems appears promising and holds a wide range of opportunities.

The research and development of corrosion-resistant materials for deployment in high salinity environments and the optimization of floating structures and mooring arrangements represent crucial areas of focus for future research on offshore FPV systems. Concurrently, the advancement of large-scale offshore FPV systems can be effectively facilitated by the establishment of pertinent policy incentives and design specifications for offshore FPV systems.

Wind power and photovoltaic co-located power generation can effectively utilize electrical equipment such as inverters and cable lines, thereby reducing system operation and maintenance costs. This approach also optimizes the use of wind and solar energy, leading to more stable and continuous power generation. It represents a crucial avenue for the future advancement of large-scale offshore FPV.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Meaning
PV	Photovoltaic
FPV	Floating photovoltaic
HDEP	High-density polyethylene
LCOE	Levelized cost of electricity
FRP	Fiberglass-reinforced plastic
PFRP	Pultruded fiberglass-reinforced plastic
ETFE	Ethylene tetrafluoroethylene
DNV	Det Norske Veritas
TNO	The Netherlands Organization for Applied Scientific Research
CIGS	Copper–Indium–Gallium–Selenide
MDPE	Medium-density polyethylene
GM-PV	Ground-mounted photovoltaic

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