Review on the development of marine floating photovoltaic systems

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Abstract: Global warming caused by the emission of fossil fuel consumption has become critical, leading to the inevitable trend of clean energy development. Of the power generation systems using solar energy, the floating photovoltaic (FPV) system is a new type, attracting wide attention because of its many merits. The latest progress in the research and applications of FPVs from multiple aspects is summarized in this paper. First, the development of FPVs is briefly described with a summary of typical installed FPV systems. Innovative photovoltaic design concepts and hybrid usage with other renewable energies are emphasized for offshore applications. Furthermore, critical structural design considerations are discussed, particularly emphasizing critical aspects such as load estimations, wave-structure interaction analysis, floating structure types, and mooring system design. Finally, several significant future challenges to the development and applications of marine FPV systems are identified, including survivability in the open sea, long-term reliability, and environmental impact. It aims to provide a broad overview of the development status, offering limited insights into the trends and challenges for marine FPV systems.

Highlights:

- Landmarks of floating photovoltaic (FPV) development are presented.
- Innovative PV design concepts for marine FPV systems are reviewed.
- Potential synergies of marine FPV systems are introduced.
- Critical structural design considerations of marine FPV systems are discussed.
- The main obstacles to developing FPV systems on the ocean are indicated.

KEYWORDS: Floating photovoltaic (FPV), Marine FPV systems, Types of FPV installation, FPV design factors, Hydrodynamic analysis

Abbreviations

PV	Photovoltaic	DTM	Direct time domain method
FPV	Floating Photovoltaic	FTTM	Frequency to time domain transformation method
FRP	Fiber-reinforced polymer	CFD	Computational fluid dynamics
HDPE	High-density polyethylene	ML	Mooring line
WEC	Wave energy converter	MRE	Marine renewable energy
DNV	Det Norske Veritas	PID	Potential-induced degradation

1 Introduction

With the increasing demand for electricity and rapid consumption of fossil fuels, the need to develop clean energy, including offshore wind energy and wave energy (Zeng et al., 2023; Zhang et al., 2022; Cheng et al., 2022; Zhou et al., 2022; Ren et al., 2023), has become urgent. As clean and renewable energy, solar energy is pollution-free, rich, widely distributed, and should be actively developed. The solar photovoltaic (PV) system is a typical system that can convert solar energy into electricity directly by using the photogenerated current effect of PV cells. It is widely used in on-grid and off-grid power systems. Typical PV modules can convert as much as 4-18% of incident solar energy into electrical energy (Dubey et al., 2013; Azmia et al., 2013).

Photovoltaic systems are mainly classified as ground-mounted, roof, and water-based PV systems (see Fig. 1). Ground-mounted PV systems require large land areas. In contrast, roof PV systems installed on the rooftops of buildings have a relatively small power generation capacity (Deo and Tiwari, 2014), which is approximately 5-20 kW for residential buildings and 100 kW for commercial buildings (Sahu et al., 2016). However, these onshore solar solutions cannot meet the electricity demand due to limited land resources. Therefore, water-based PV systems, including both fixed and floating PV (FPV) types, are gradually becoming a promising solution and contribute to fulfilling the energy demand. Wang and Lund (2022) briefly introduced the development state and faced challenges for offshore fixed pile-based and floating PV systems. Fixed PV systems (Zhang, 2017) are fastened to the seabed by pile foundations.

However, the financial benefit of such a bottom-fixed solution decreases with increasing water depth due to the largely increased piling cost. FPV systems float on water and are moored in position. The FPV system usually consists of floats or pontoons, PV modules, mooring systems and cables (Rosa-Clot and Tina, 2018; World Bank Group, 2019; Rosa-Clot et al., 2010b; Redon-Santafa et al., 2014; Sharma et al., 2015), as depicted in Fig. 2. PV on the water can increase the power generation efficiency, possibly due to the water-cooling effect (Tina et al. 2011) and higher wind speed (Refaai et al., 2022). Moreover, the large area of PV modules laid on the water surface can reduce evaporation (Helfer et al., 2012; Gozálvez et al., 2012). However, their impact on water quality and inhibition of aquatic life is complex and remains uncertain.

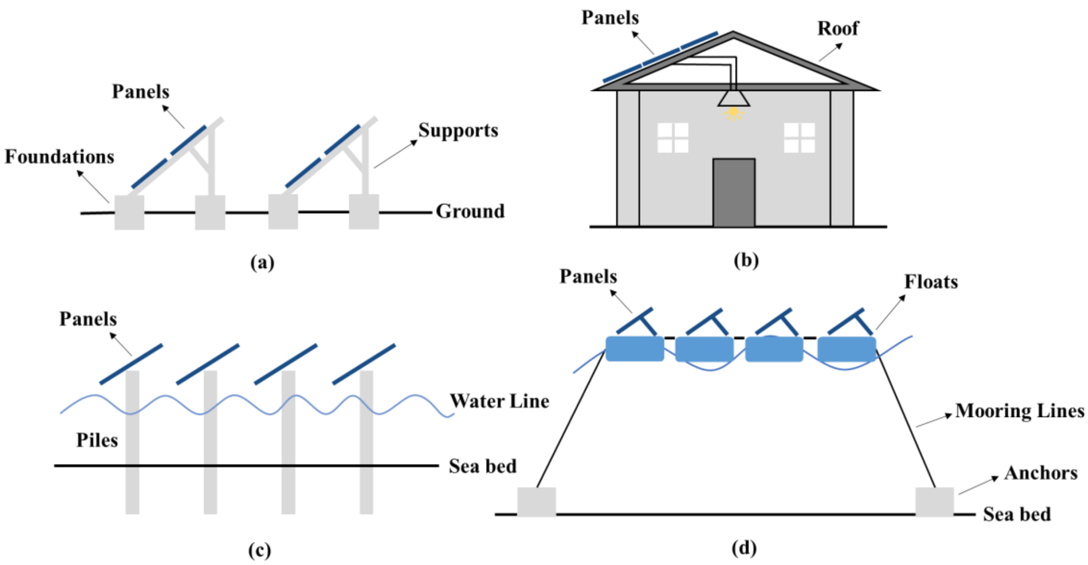


Fig. 1. Different types of PV systems: a) ground-mounted PV systems; b) roof PV systems; c) fixed PV systems in water; d) floating PV systems in water.

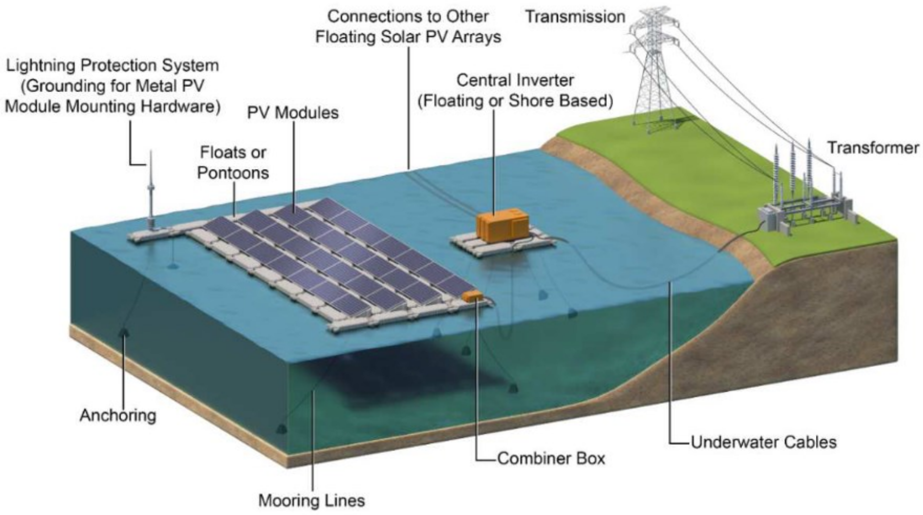


Fig. 2. Schematic of a typical FPV system and key components, reprinted with permission. (Lee et al., 2020)

In recent years, many countries have made great efforts to develop FPV technology. Global FPV installations are widely distributed in more than 60 countries, reaching a capacity of 3 GW by 2021, as shown in Fig. 3 (Kumar et al., 2021; DNV GL, 2022). The total capacity of FPVs is expected to increase to 10-30 GW by 2030. According to the statistics of SOLARPLAZA (2022), the largest 20 installed FPV projects in 2021 reached 1.2 GW, mostly located in Asia, with China in the lead. In the following five years, China may occupy the largest share of the FPV market, followed by India and Korea (Wood Mackenzie, 2022). SUNGROWPOWER (2022) and Ciel et Terre (2022) are the representative suppliers of FPV inverters and floaters, respectively.

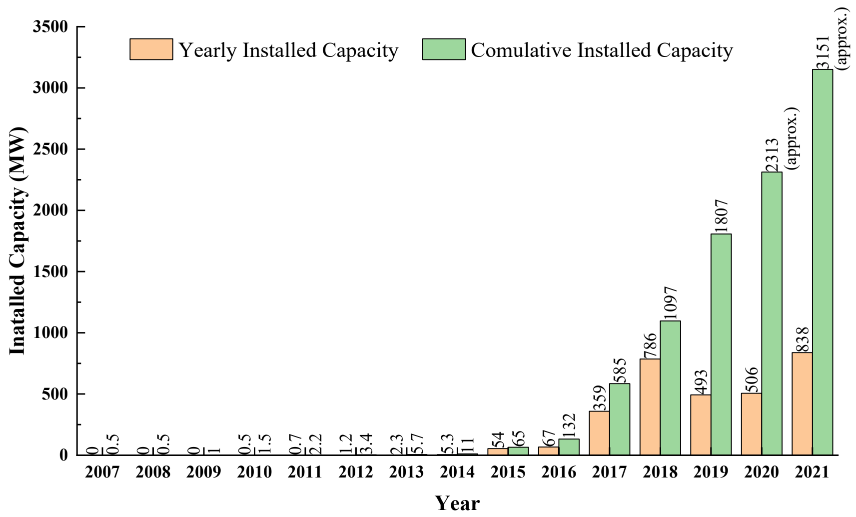


Fig. 3. Yearly and cumulative installed capacity of FPV systems (Kumar et al., 2021; DNV GL, 2022).

Structural safety and stability are essential for the operability of FPV systems throughout their life cycle. However, only a few books (Rosa-Clot and Tina, 2018; World Bank Group, 2019) and standards (DNV GL, 2021) are available for its design, and even fewer are available for marine FPVs due to insufficient technological maturity and exposure to harsher conditions. Oliveira-Pinto and Stokkermans (2020) reviewed the relevant applications and potentialities for FPVs in the marine environment. Claus and Lopez (2022) evaluated the compatibility of existing FPV structures with the marine environment, illustrating the general rules of designing marine FPV structures. Despite its current development, exploiting marine FPVs is still challenging (Kumar et al., 2021; Ranjbaran et al., 2019). Thorough and reliable assessments of the dynamic behavior of FPVs and their resistance to extreme and failure loads in harsh marine environments have become essential. As a milestone summary, promising applications, application trends, design considerations, and future challenges are addressed in this paper to provide a clear understanding of marine FPV technology.

This study aims to extensively summarize the typical existing FPV projects with a higher focus on the essential application trends, critical design considerations, and key challenges toward the marine environment, assisting the preliminary design of marine FPV structures. The paper is organized as follows. The landmarks of FPV development are summarized in Section 2. The important application trends of marine FPVs are presented in Section 3. Section 4 details the structural design considerations for marine FPV systems. Section 5 discusses the challenges that FPVs face in future development for ocean applications, including their survivability, long-term reliability, and environmental impact.

2 Landmarks of FPV development

FPV systems provide an excellent opportunity for many countries with limited land but abundant water resources. The first FPV project in the world was installed by the National Institute of Advanced Industrial Science and Technology research team in Aichi in 2007 to compare the power generation efficiency between water- and air-cooling conditions (Ueda et al., 2008). Then, the first on-grid FPV project was installed in 2008 by SPG Solar for Far Niente Winery (in the USA) to power the winery (Smyth et al., 2011). In 2012, Ciel et Terre (2022) installed the world's first-megawatt FPV project in Okegawa, Japan. Since then, FPV technology has developed rapidly with an increasing number of inland FPVs installed in lakes, canals, ponds, irrigation reservoirs, coal mining subsidence areas, etc. (SCINTEC, 2022; Ferrer-Gisbert et al., 2013; Santafé et al., 2014; Ferrer Ferrer et al., 2010). The most common FPV structure can be classified into three categories (DNV GL, 2021): (1) pure float refers to the direct installation of PV modules onto floats; (2) modular rafts mean fastening PV modules on a structural framework supported by floats; and (3) membranes are typified by PV modules attached to some form of reinforced membrane. The vital development history is illustrated in Fig. 4. Table 1 summarizes some of the world's latest and most representative FPV projects.

Table 1

Status of installed FPV systems worldwide (not exhaustive), grouped by FPV array categories.

FPV arrays categories	Name of plant/region	Operating from	Location	Capacity (kW)	Producer /Owner	Area covered (m^2)	Number of PV modules	Inland/ Offshore
Pure floats	Silbersee III lake (BayWa r.e., 2022)	2022	Haltern, Germany	3,000	BayWa r.e.	18,000	5,800	Inland
	Johor Strait (SUNSEAP, 2022)	2021	Woodlands, Singapore	5,000	Sunseap	111	30,000	Offshore
	Zhoushan (CHN ENERGY, 2022) (China's first offshore FPV project.)	2021	Zhejiang, China	2,695	CHN ENERGY	/	/	Offshore
	The Sirindhorn Dam (EGAT, 2022) (The biggest hybrid energy project in Thailand.)	2021	Sirindhorn, Thailand	58,500	EGAT	1,210,000	144,400	Inland
	Kasaoka Idachiike ECO Plant (Ichigo, 2022)	2021	Okayama, Japan	2,660	Ichigo lnc	47,017	5,928	Inland
	Dingzhuang reservoir (Ichigo, 2022) (The world's largest FPV system.)	2020	Dezhou, China	320,000	CHINA HUANENG	1,470,000	600,000	Inland
	O'MEGA1 (EURACTIV, 2023) (The largest Europe FPV plant.)	2019	Piolenc, France	17,000	Bouygues Energies & Services	200,000	47,000	Inland
	Amur region of the Far Eastern Federal (Solomin et al., 2021)	2019	Nizhne-Bureyskaya, Russia	1,200 (320 MW hydro)	Hevel Group and RusHydro	180,000	50,904	Inland
	Hyoshiga Ike (Ciel et Terre, 2022)	2019	Hyogo, Japan	2,703	Ciel et Terre	/	10,010	Inland
	CMCI (Ciel et Terre, 2022)	2019	Kampot, Camboida	2,835	Ciel et Terre	/	7,768	Inland
	Coal mining subsidence area of Huainan City (Ciel et Terre, 2022)	2019	Huainan, China	150,000	Ciel et Terre	4,000,000	1,034	Inland

Table 1 (Cont.)

Pure floats	Bahia Dam (Ciel et Terre, 2022)	2019	Bahia, Brazil	1,005 (175 MW hydro)	Ciel et Terre	474	140	Inland
	Yamakura solar power plant (Ciel et Terre, 2022) (The biggest Japanese FPV plant.)	2018	Chiba, Japan	13,700	Ciel et Terre	2,500	840	Inland
	Zon-op-Zee (Ciel et Terre, 2022) (The first offshore FPV project.)	2017	Dutch North Sea	50	Oceans of Energy, TNO, MARIN, et al.	18,000	5,800	Offshore
	AltoRabagão Dam (Ciel et Terre, 2022) (The first hybrid hydropower station.)	2016	Montalegre, Portugal	218 (68 MW hydro)	Ciel et Terre	50,000	13,312	Inland
Modular rafts	Yantai (CIMC RAFFLES, 2023)	2023	Shandong, China	400	CIMC	/	/	Offshore
	King Eider (SOLARDUCK, 2022)	2021	Gelderland, Netherlands	65	Solar Duck	33,333	/	Offshore
	KRISO's tank (The largest offshore FPV model test in Korea) (KHNP, 2021)	2021	South Korea	/	KHNP	/	/	Offshore
	Frøya in Norway (Moss Maritime, 2022)	2020	Trondheim, Norway	/	Moss Maritime, Equinor	/	/	Offshore
	MPVAQUA (Tractebel, 2023)	2019	North Sea, Belgian	/	Tractebel, et al	/	/	Offshore
	Heliofloat (Heliofloat, 2016)	2016	Australian	/	Heliofloat	/	/	Offshore
	Solarsea (Swimsol, 2014)	2014	Maldives	15	Swimsol	/	/	Offshore

Table 1 (Cont.)

Membranes	Shandong Peninsula (Ocean Sun, 2022) (The first deep-sea "wind + solar" project.)	2022	Shandong, China	500	Ocean Sun	4,412	1,540	Offshore
	Banja Dam (Ocean Sun, 2022)	2020	Banja, Albania	2,000 (73 MW hydro)	Ocean Sun	/	10,010	Inland

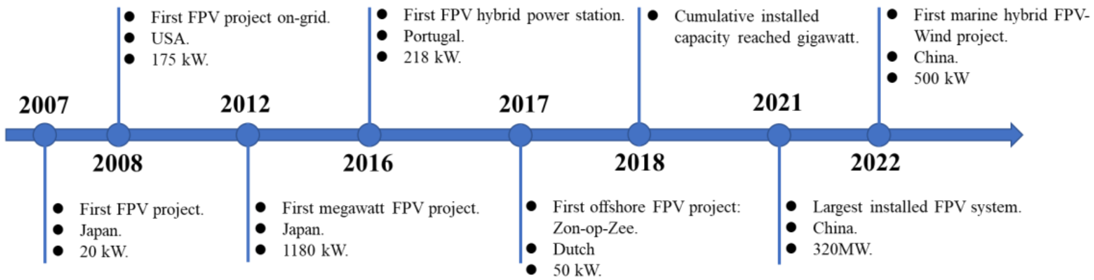


Fig. 4. Brief timeline of FPV development.

Hybrid power solutions involving FPVs have recently become increasingly recognized. In 2016, Ciel et Terre (2022) installed the world's first FPV hybrid power station on the AltoRabagão Dam in Montalegre, Portugal. The advantages of installing FPV systems on existing hydropower stations include collaborative compensation of electricity (Liu et al., 2018), additional energy storage opportunities (Liu et al., 2019; Aghahosseini et al., 2017), and improved transmission utilization (Rauf et al., 2019; Teixeira et al., 2015; Farfan and Breyer, 2018; Handleman, 2015). Despite several successful cases of installed hybrid FPV-hydropower systems worldwide, the actual operational benefit is unclear. Future research could focus on evaluating the levelized energy cost of the hybrid system with detailed data on actual operation benefits to help design the optimal FPV installation capacity. In addition, synergies between solar and wind energy are a popular research topic, especially in offshore areas with steadier and stronger wind conditions (Onea and Rusu, 2022). This will be reviewed in detail in Section 3.2.

In 2017, six Dutch institutions jointly developed the world's first offshore FPV project: Zon-op-Zee (see Fig. 5) (Oceans of Energy, 2022). It survived many sea storms throughout the operation stage, with wave heights up to 10 m, wind speeds up to 62 knots, and maximum currents of 4 knots. The successful demonstration of Zon-op-Zee has encouraged energy companies worldwide to investigate the potential of marine FPV systems. In 2021, Moss Maritime (2022) tested a 1:13 scale FPV model 4.5 km offshore from Trondheim. SOLARDUCK (2022) developed a modular marine FPV platform with a design lifespan of over 30 years. It can withstand wave heights up to 5 m and wind speeds up to 30 m/s. CHN ENERGY (2022) completed China's first marine FPV field test in Zhejiang, mainly composed of hydrodynamic and corrosion tests, to verify the reliability of offshore FPV systems. In 2022, SPIC (2022) installed the world's first marine hybrid FPV-Wind project in Shandong (China) to promote the commercial development of marine FPVs. The technological innovations of FPV systems continue, particularly for offshore applications being the frontier. However, the minimal maturity level of marine FPV technologies so far has yet dampened the development pace of offshore solar energy exploitation.

Fig. 5. Zon-op-Zee offshore FPV project, reprinted with permission (Ikhennicheu et al., 2021).

3 Potential for marine FPVs

Industrial and research institutions, with great enthusiasm, are committed to developing and improving various FPV solutions for marine environments with the aim of sufficient operating safety and acceptable cost-efficiency (Claus and Lopez, 2022). Attempts to co-locate marine FPVs with other marine renewable energy sources (MREs) are also worth special attention for better economic benefit (e.g., Zhou et al., 2010). In the following, Section 3.1 aims to discuss several proposed marine FPV concepts, while the synergies of marine FPVs will be emphasized in Section 3.2.

3.1 FPV design concepts for marine environments

3.1.1 Flexible FPVs

Flexible floating photovoltaics are potentially one applicable type toward marine environments with the capability to deform when suffering from dynamic wave loads, which yield wave motion rather than withstanding its forces (Trapani and Santafé, 2015). Generally, there are three main strategies for flexible FPV solutions, i.e., 1) using crystalline modules backed with flexible foam (Claus and Lopez, 2022); 2) using thin-film flexible modules; and 3) using hinged connectors for rigid modules.

Using crystalline modules backed with flexible foam may be cheaper than pontoon-based FPVs (Hayibo, 2021). Ocean Sun produced such concepts, which mainly consist of buoyancy rings, membranes, and PV modules (see Fig. 6(a)) (Ocean Sun, 2022). It was claimed that the system could resist 275 km/h wind and withstand huge mechanical stress and long-term sunlight. The flexible design reduces or even avoids using connectors between modules and, therefore, may improve the reliability of the FPV system in resistance to fatigue damage. Different shapes and sizes of flexible membranes can be selected according to application scenarios and installation capacity. Since 2016, Ocean Sun has conducted extensive research and experiments in prototype tests and projects in Norway, Singapore, China, etc. (Ocean Sun, 2022).

Thin-film flexible modules are designed to float with the aid of air pockets, which was proposed in the MIRARCO project (Fig. 6(b)) (Trapani et al., 2014). Field studies showed that the average power generation efficiency increased by approximately 5% due to water contact-induced cooling (Trapani and Millar, 2014). However, thin-film FPVs are unable to tilt the modules, and the alignment of the PV module will change as the system yields waves, causing an inevitable sacrifice of power generation efficiency compared to pontoon-based FPVs, which could optimally determine the inclination of PV panels (Kougias et al., 2016). In addition, even with long-term direct contact of thin-film PVs on the water surface, the water inflow caused no debonding of the laminate film, which did not affect the mechanical performance of the array (Trapani et al., 2014). However, the long-term performance of such structures needs to be deeply evaluated to determine the effect of water absorption on electrical performance. From an economic perspective, the thin-film FPV has less material usage, lighter structural weight, and fewer components, leading to a lower cost (Trapani and Millar, 2015). In addition, the consequences of collisions between flexible structures and ships are not as severe as other MREs, such as wind power. Thus, the corresponding insurance cost is also expected to be reduced (Trapani et al., 2013). By decreasing the loads subjected by the compliant structures, the load on the mooring system is also significantly reduced (this is a vital problem in the reliability of offshore floating structures) (Thies et al., 2009). Similarly, Det Norske Veritas (DNV) proposed the "SUNdy" concept (Fig. 6(c)) (Stainless Steel World, 2022), which is a hexagonal thin-film flexible FPV system floating on the sea inspired by a spider web structure. This can comply with waves but maintain its shape as firmly as possible (Trapani and Santafé, 2015). However, the hydrodynamic performance of DNV's FPV concept is expected to be fully studied in detail before any potential application.

Using connectors for stiff modules to form large arrays can be another solution for marine FPV systems. For this kind of multibody FPV, the design of the connectors is crucial. SolarDuck (2022) developed a triangular FPV module concept (Fig. 6(d)), flexibly connected and moving with the waves to be more compliant with wave loads. SolarDuck also raised the FPV modules to 3 m above the sea surface to avoid wave impacts. Similarly, CIMC RAFFLES (2023) launched China's first semi-submersible marine FPV project (Fig. 6(e)). The platform, consisting of four FPV modules, can survive in open seas with wave heights up to 6.5 m, tides up to 4.6 m, and 34 m/s wind. The connectors can transfer motions between modules in certain degrees of freedom (DOFs) while remaining robust and durable (Vegard et al., 2022). Knowledge of the relevant failure modes, mechanism of the connectors, and analysis method in the stage of FPV design can be crucial for designing reliable connectors. In the coupling analysis of multibody FPVs, connectors can be represented by introducing extra stiffness and damping matrices between the bodies. It is vital to decide reasonable stiffness values for the connectors to properly simulate the dynamics of FPV modules, especially with the increasing number of modules in an FPV system.

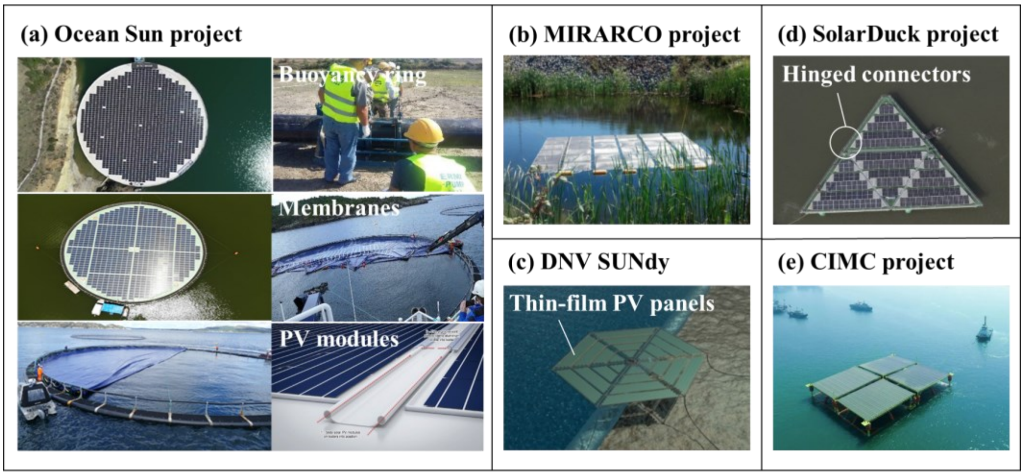


Fig. 6. Flexible floating FPV concepts: (a) Ocean Sun; (b) MIRARCO project; (c) DNV SUNdy; (d) SolarDuck project; (e) CIMC project. Reprinted with permission. (Sahu et al., 2016; SOLARDUCK, 2022; CIMC RAFFLES, 2023; Ocean Sun, 2022; Trapani and Millar, 2014)

3.1.2 Submerged FPVs

Unlike flexible FPVs compliant with waves, the submerged FPV structure is a rigid FPV concept for the marine environment, which is allowed to sink into the water to resist extreme conditions and survive in harsh marine environments by avoiding direct exposure to waves. The submerged FPV concept was first proposed by Stachiw approximately 30 years ago (Rosa-Clot et al., 2010b; Stachiw, 1979) to provide energy for submerged marine devices. In 2010, SCINTEC (Rosa-Clot et al., 2010a) filed a patent for a submerged FPV system named SP2 (see Fig. 7), designed to be submerged 2 m below the water surface by ballasting pontoons.

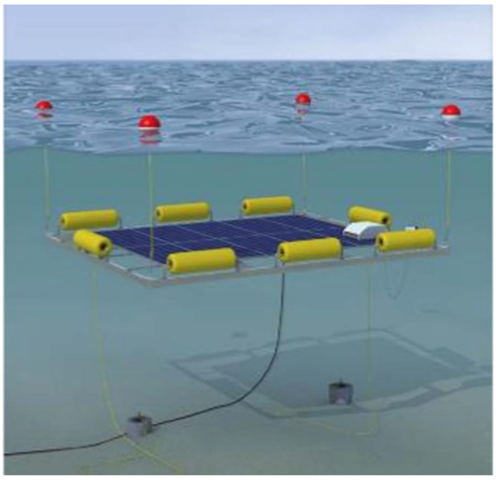


Fig. 7. Submerged photovoltaic design, reprinted with permission (Cazzaniga et al., 2018).

For submerged FPV systems, the underwater operational performance is a major concern of field researchers. Many factors affect the power generation efficiency of this FPV, such as the applied water depth, light intensity, light distribution, and other factors (Tina et al., 2019). Rosa-Clot et al. (2010c) compared the power generation efficiency of SP2 at different depths of 0-50 cm underwater. It was found that the optimal depth was 8-10 cm, where the power generation efficiency of SP2 increased by 10-20% compared to the non-submerged system. However, at the maximum depth of 50 cm, the power generation efficiency decreased by 10-20%, depending on the type of photovoltaic cell (Rosa-Clot et al., 2010c). As described, to maintain sufficient power generation efficiency, the depth of the submerged FPV is minimal, expectedly leading to limited effects on the reduction of wave-induced system dynamics. Similar conclusions were obtained later by different research methods (Tina et al., 2012) and objects (Enaganti et al., 2019). Furthermore, submerged PV can still work effectively even in seawater with a salinity of 3.5%, considering the corrosion of steel (Ajitha et al., 2019). Overall, submerged FPV performance is superior. However, marine growth is a critical issue for the operation of submerged FPVs (Oliveira-Pinto and Stokkermans, 2020).

3.2 Synergies of marine FPV systems

The commercialization of marine FPV systems depends on technological development and cost reduction. Synergy with other MREs may significantly save costs by sharing logistics, operation and maintenance, and power grid infrastructure (Pérez-Collazo et al., 2015).

Synergies of marine FPV systems with other MREs could be achieved in two ways: hybrid spatial layout and hybrid platform. Hybrid spatial layout refers to the rational use of space resources to integrate marine FPVs and other MREs, which can improve the power generation per unit of marine area (Golroodbari et al., 2021). The feasibility of combining solar and wind energy was evaluated through years of ERA5 data (Onea and Rusu, 2022; de Souza Nascimento et al., 2022). The power output can be optimized by the spatiotemporal complementarity of wind and solar (Zhou et al., 2010; Yang et al., 2007; Borowy and Salameh, 1996). Power generated by solar radiation can remain stable even under various high wind (speeds up to 60 km/h) and wave (heights up to 7.1 m) conditions (Bi and Law, 2023). However, it is critical to design the system configuration optimally with respect to the PV module number, PV panel inclination angle, wind turbine number, wind turbine installation height and total battery capacity (Yang et al., 2009). This combination can also replace gas turbines to provide electricity for oil and gas platforms (Oliveira-Pinto et al., 2020), aquaculture (Nookuea et al., 2016) and seawater desalination (Amin et al., 2020). The Ocean H2 project (Solomin et al., 2021) (see Fig. 8(a)) jointly integrates FPV, wind power, WEC (wave energy converter), and other technologies to build an energy island that can produce green hydrogen. It is expected to achieve a technological breakthrough in floating energy. A hybrid platform refers to directly integrating different MREs into a platform, taking full advantage of synergies, such as FPV+WIND (Hu et al., 2013), FPV+WEC (SINNPOWER, 2022), and FPV+WEC+WIND (SINNPOWER, 2022). The concept of the "ocean hybrid platform" proposed by SINN POWER (Fig. 8(b)) integrates wind, solar, and wave energy, which has been produced and tested. FPVs could also be integrated into the sheltering structures of ports, providing power and offering shelter (Claus and Lopez, 2022).

Fig. 8. (a) Offshore floating solar, wind, and green hydrogen (Solomin et al., 2021), (b) ocean hybrid platform of SINN POWER (source: SINN POWER (2022)).

For the combination of FPV systems and other energy sources, the available technology is still not sufficiently mature and lacks engineering experience (Bellini, 2022). A reasonable spatial layout for mooring system design is essential to avoid the collision of different systems. In addition, site selection is also a challenge. For example, a site may not simultaneously have the best wind and solar energy resources. Moreover, installing floating structures can be complex and expensive in the ocean environment because it involves large-scale hoisting and professional ships. To date, there is no corresponding specification for the logistics and offshore operation of FPV systems, and the lack of experience means an increase in insurance costs.

4 Structural design of marine FPVs

The structural design of a reliable FPV system to maintain its functionality, safety, and integrity is essential for its sustainable lifetime operation. Many aspects must be considered in designing FPV systems (Santafe et al., 2014). Ranjbaran et al. (2019)

summarized seven factors that may indicate whether or not FPV systems are optimally constructed, i.e., modular design, reliability, durability, protection, optimum support structure size, easy installation, and cost reduction. Compared with other large-scale offshore floating structures, such as ships, oil and gas platforms, and wind turbines, marine FPVs have less weight per wet surface, thus being more prone to resonance caused by high-frequency waves and more susceptible to fatigue damage. Furthermore, solar power generation requires a relatively large deck area for marine FPVs on the ocean surface. Consequently, the floating support structure may be subjected to larger wave loads. On the other hand, although the stability of marine FPVs may benefit from their low structural height, water on deck can become more severe. All of these factors make the design of marine FPVs significantly different from that of conventional large-scale offshore structures.

Although there are no specific standards for the design of marine FPV systems, the recommended practice for floating solar design published by DNV (2010) and experiences for mature marine engineering, e.g., from the offshore oil and gas industry, may be referenced. Claus and López (2022) provided a detailed summary of the widely used structural design standards worldwide. Some critical concerns for marine FPV structure design are summarized in this section to provide an overall understanding of load estimation and critical considerations.

4.1 Methods for environmental load estimation

FPV systems are exposed to (1) permanent loads, (2) operational loads, (3) environmental loads, (4) installation loads, and (5) accidental loads. Harsh environmental loads could be the dominator for the development of offshore FPVs. Environmental loads may be estimated analytically or numerically. Critical parameters involved in load estimation are usually obtained through experiments and engineering experience. The associated uncertainties for load estimation should be addressed by applying appropriate safety factors. The load and resistance factor design method (LRFD) (Galambos and Ravindra, 1981) is a widely applied engineering approach that uses several partial safety factors for structural design at ultimate and accidental limited states. It considers the load uncertainty in terms of load factors and the resistance uncertainty in terms of material factors. The partial safety factors depend on the considered limited state, working conditions, return period, the consequence of failure, etc. (DNV GL, 2016).

The typical exposed loads on FPV systems are shown in Fig. 9, including gravity, buoyancy, surface tension (only for flexible FPVs), mooring tension, etc. The external force acting on the system mainly comes from environmental actions such as wind, waves, and currents. In addition, it is worth mentioning that other environmental loads could also be critical to the design in some locations, such as tides, earthquakes, ice, and snow (Kolerski et al., 2021). Temperature also affects the mechanical properties of FPVs (Kjeldstad et al., 2021). The variation in the ambient and surface water temperatures can lead to periodic thermal expansion and contraction of PV modules, increasing the risk of system fatigue failure (George and Patel, 2019).

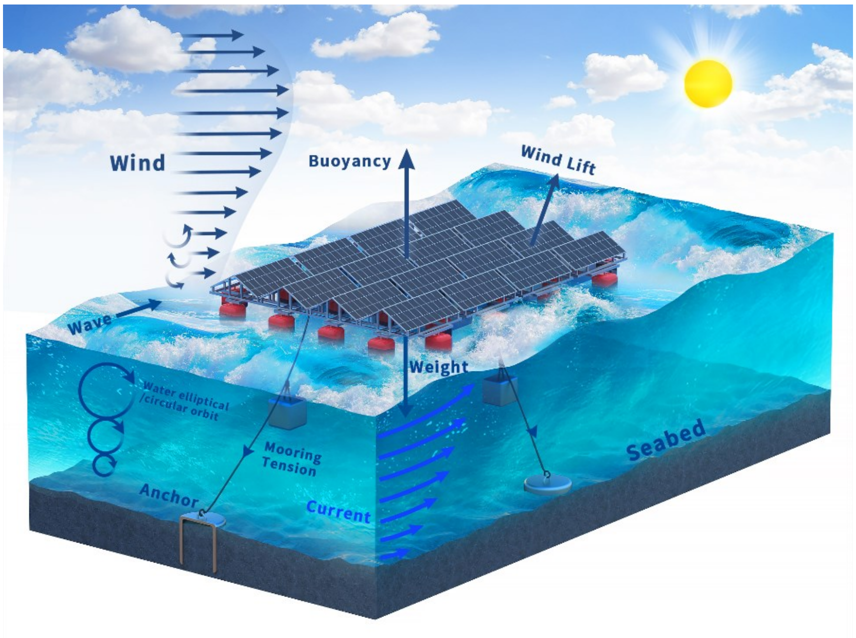


Fig. 9. Schematic loads on the FPV system.

4.1.1 Wind

Wind load is one of the essential environmental loads to be considered in the design of FPV systems. Extreme wind events can cause severe damage to FPV structures. For example, a large number of PV panels of the Dingzhuang (in China) FPV project were damaged by the instantaneous wind of Grade 12 in 2021. Wind creates dynamic loads on FPV systems and influences local wave conditions (Oliveira-Pinto and Stokkermans, 2020). During the initial design stage, the wind-induced loads on the structure (mainly considering the PV panels and pontoon freeboard) could be estimated according to the method proposed by DNVGL-RP-C205 (DNV GL, 2019). The wind loads on panels depend on the floating body geometry, its location in the array, wind direction, wind speed, wind intensity, etc. The shape of the floating body and the incidence angle of the wind are considered to determine the resistance coefficient. Shielding effects should also be considered when estimating the local wind load on the PV array. The value of the shielding coefficient is given by Jubayer and Hangan (2016). However, either wind tunnel tests or high-fidelity numerical simulations are always preferred to estimate the design-specific shielding coefficient considering floaters with different sections.

4.1.2 Currents

Currents may not be a significant issue for FPV systems installed in freshwater bodies; however, they are crucial for applications in the ocean (Chen and Basu, 2018), especially for the design of mooring and dynamic cable systems. Currents may be very complex, and there are various types of currents, including ocean currents, tidal currents, wind-generated currents and wave-induced currents, which require joint consideration (DNV GL, 2019). There are few publications related to the current loading on FPV structures. However, valuable experiences from the relevant and more mature offshore sectors could be referenced. The current loads on the structure can also be estimated by DNVGL-RP-C205. DNV recommends accounting for the velocity deficit behind a circular cylinder on a downstream cylinder. Hu et al. (2006) further modified the formula by considering the cross-sectional difference of the float cylinder. DNV GL (2019) indicates that offshore structural design involves currents that need to be addressed from the following aspects: (1) large steady excursions and slow drift motions of platforms; (2) resistance and lift on submerged structures; (3) vortex-induced oscillations of structures; (4) currents-wave interactions leading to waves changes; and (5) seabed scouring around anchors.

4.1.3 Waves

Wave generation is affected by incident wind characteristics, including wind speed, wind duration, and fetch length (Massel, 2013). Wave interaction with the FPV system generates dynamic loads on the structure. Wave loads are influenced by the wave height, period, incident direction, directional spreading, and relative position of the FPV systems (Ma et al., 2018; Nematbakhsh et al., 2015; Clément et al., 2022; Raed and Soares, 2018).

Wave-structure interactions can be simulated numerically in the frequency or time domain. For linear systems, solvers based on the frequency domain method have advantages in computational effectiveness. Commercial software such as WAMIT (Wamit, Inc., 2020) and Hydrostar (Bureau Veritas., 2016) is used for the frequency-domain hydrodynamic analysis. However, the floating module and mooring system of FPVs show more complex and nonlinear dynamic behavior due to the large geometrical dynamic response and coupling effect (Oliveira-Pinto and Stokkermans, 2020). Moreover, most components of FPV systems are made of polymers with short elastic response regions and orthotropic composite components, both of which require nonlinear solvers for estimating the structural responses (Friel et al., 2019).

The time domain method is more suitable for solving transient and nonlinear problems. Therefore, much work has investigated the wave-FPV interaction in the time domain. The time domain method can be further classified into two categories: the direct time domain method (DTM) and the frequency to time domain transformation method (FTTM) (Cong, 2015). The DTM is a full-time domain method that can account for the nonlinearities of the free surface boundary conditions, and instantaneous body surface boundary conditions are nonlinear (Cong, 2015). According to the level of nonlinearity, the DTM can be further divided into the linear time domain method, second-order time domain method, body nonlinear time-domain method, and fully nonlinear time domain method (Cong, 2015; Isaacson and Cheung, 1991; Isaacson and Cheung, 1992). For example, commercial software such as Wasim (Hess, 2000) for hydrodynamic analysis uses DTM for time domain analysis.

In the FTTM method proposed by Cummins et al. (1962), the wave loads on structures are obtained according to the Volterra series model rather than by solving the boundary value problem (Oortmerssen, 1979). At the same time, FTTM has lower computational complexity, better computational stability, and higher computational efficiency in comparison with DTM. Presently, FTTM has been applied in various fields of marine engineering. For example, commercial software (such as Sima (SINTEF, 2023), MOSES (Bentley, 2023), and Ansys Aqwa (ANSYS, 2018)) for hydrodynamic analysis and wave-structure interaction analyses of FPV (Wu, 2018; Song et al., 2022) both use FTTM for time domain analysis.

4.2 Critical design considerations

4.2.1 Floating structure types

The design of the support structure for FPV systems is crucial and should satisfy requirements with respect to stability, buoyancy, strength, and serviceability (Dai et al., 2020). Currently, the most commonly used floating structures for FPVs are made of high-density polyethylene (HDPE) (Boersma et al., 2019), including HDPE floating pipes, HDPE floating platforms and rafts, and HDPE floating pontoons (Kumar et al., 2021). Connectors are expected to be critical weak components, especially when FPV systems are installed in the ocean. The continuous action of waves may lead to fatigue of the connectors and even overturn the pontoons. Therefore, further improvements are required for applications in the ocean, such as adding wave protection and dissipation devices around the floating body.

Fiber-reinforced polymer (FRP) is also widely used in FPV systems. Compared to traditional structural materials, it has a lighter weight, with superior mechanical properties and corrosion resistance (Lee et al., 2014). Choi et al. (2010) and Yoon et al.

(2018) conducted tensile and shear tests to determine the mechanical properties of the FRP structure used in the design of FPV systems. Under different wave conditions, the critical structural stresses were also estimated to be less than the allowable stress (Lee et al., 2014). The FPV system made of FRP has been successfully designed, manufactured, and installed at Buksin Bay, Tongyeong-si, Gyeongsangnam-do, Korea (Lee et al., 2014).

Other widely used materials for floating structures are steel (Yu, 2018) and aluminum (Perera, 2020). The fundamental design and verification for these kinds of structures are to ensure that any structural responses are within the material and structural strength limits. Modal analysis, structural stress analysis, and deformation analysis of steel and aluminum FPV systems under different working conditions were carried out using finite element analysis software (Pan et al., 2017; Wang et al., 2018). Field consensus has been reached in long-term engineering experience that steel/aluminum-made materials are reliably used in FPV systems. For example, marine FPVs could be designed as semi-submersible (Zheng et al., 2020), which has been shown to have good hydrodynamic performance. The major concern of steel and aluminum in marine applications is corrosion; therefore, anti-fouling coatings are needed. In addition, the levelized cost of energy (LCOE) for such a solution could currently be too high (Hayibo, 2021).

Thin-film technology might be a promising solution for FPVs applied in marine environments. However, the relevant engineering experience is relatively limited, calling for thorough research to be conducted.

The cost-efficiency and integrity of marine FPV systems could be the most critical key components to consider for the design of floating supports and should always be carefully assessed and balanced. The relatively high LCOE of marine FPVs (PV Magazine, 2021; IRENA, 2021) is one of the largest barriers the real large-scale applications, thus requiring technological innovations of materials, key component design, manufacturing and operating processes (Dang et al., 2021; Vegard et al., 2022).

Jin et al. (2023) proposed a coupling hydrodynamic-structural-material model, which can realize the optimal design of FPV support structures considering the interactive influence among material properties, structural configuration, and wave conditions. This could help develop a more systematic approach for designing FPVs adapted to the demanding marine environment.

4.2.2 Wave-structure interaction analysis

Wave-structure interaction analysis is also crucial in structural design since waves play a critical role in the dynamics of lightweight FPVs in the ocean (Ikhennicheu et al., 2021). FTTM has been widely applied to investigate the hydrodynamic performance of designed FPV systems under different environmental conditions (Hu et al., 2013; Zheng et al., 2020; Friel et al., 2020). Friel et al. (2020) compared the hydrodynamic response of FPV systems against different pontoon diameters, drafts, and environmental parameters. It was found that increasing the diameter of the pontoons had little effect on the response, but increasing draft depths resulted in an increased heave response of the platform and reduced the surge response. Wu (2018) compared the influence of the pontoon shape, weight, and spacing of FPV systems on the hydrodynamic coefficient. The results indicated that the hydrodynamic coefficients of circular and square pontoons are similar under the same waterline area, while the rectangular pontoons differ significantly. Moreover, at high wave frequencies, the pontoon spacing significantly impacted the hydrodynamic response of the FPV systems. Abbasnia et al. (2022) used the fully nonlinear method to study the dynamics of FPVs with double tubular floaters under nonlinear wave actions. These studies provided a good reference for the economic optimization platform design of FPV systems.

Considering the large surface area needed for floating solar power systems to achieve an electricity generation scale, modularization could be a cost-effective choice for manufacturing, transportation, and installation instead of a huge single floating platform. Sree et al. (2022) proposed a method that combines numerical simulation and experimental verification to evaluate the motion and structural response of modular FPVs under wave action. In addition to the influence of environmental parameters on the platform's hydrodynamic response, the connector's rotational stiffness is also an essential factor influencing the performance of the multiconnected floating platform (Michailides et al., 2013). Lee et al. (2022) studied the dynamic response of multiconnected FPV systems under different sea conditions based on computational fluid dynamics (CFD) and model tests. Dynamic motions of FPV modules align with wave elevations under head sea conditions. However, for oblique sea conditions, due to the free rotation of the connector, different floating modules appeared in relative motion, leading to complex motion characteristics. Song et al. (2022) realized the simulation of articulation through ball joints, which can control the DOFs of connectors. The responses of the multiconnected FPV systems with varying types of connectors were predicted and compared. In the case of articulation, due to the additional moment generated by the vertical or rotary movement of the system at the connector, unexpected dynamic responses along the sway, roll and yaw directions occurred. In contrast, they disappeared while the connectors were fixed. Even if the same pretension was applied, the change in mooring tension under the articulated connection is greater than that of the fixed connection. Jiang et al. (2023) designed a marine FPV array to withstand wave heights above 10 m. The FPV array is composed of semi-submersible pontoon modules, soft-connected by ropes. The proposed concept exhibits excellent motion performance under both operating and extreme wave conditions, with no adjacent modules observed colliding with each other. However, significant surge motions were observed under extreme sea conditions. Ikhennicheu et al. (2022) studied the motion performance of a 3x3 FPV array under small waves (amplitude of < 1 m). Three modeling methods of the kinematics constraint chain between floats were considered, and their effects on the motion analysis results and calculation time were studied, providing insight into the dynamics of an FPV system with more modules.

For flexible thin-film FPV systems, because of their low bending stiffness, the motion of the film is generally not significantly different from that of the encountered waves (Trapani, 2014). Lower stiffness leads to more significant bending deflection and stronger hydroelastic interaction with waves (Schreier and Jacobi, 2020). Using CFD methods, Trapani and Millar (2016) analyzed the hydrodynamic interaction between thin-film FPV systems under regular waves. Compared with WECs of the same power, the mooring forces of thin-film FPVs were reduced by 80%, which can significantly reduce the mooring cost. However, the thin-film FPV systems could not adapt to high tidal currents and were submerged in water. Xu and Wellens (2022a) further investigated the analytic solutions of wave propagations on polymer floating structures based on Ocean Sun's thin-film FPV. In a subsequent study, the analytic solution was derived to the third order (Xu and Wellens, 2022b). An engineering example verified that the proposed approach is applicable to FPV structures at any water depth.

4.2.3 Mooring of FPV systems

The mooring system anchors the entire FPV array against environmental loads, ensuring its stability and safety (Jubayer and Hangan, 2016). DNV provides requirements and recommendations for designing FPV mooring systems in freshwater (DNV GL, 2021). In 2019, a typhoon in Japan caused a mooring line failure at a 13.7 MW FPV project, leading to approximately 70% of the PV panels being damaged (Kaneko and Kato, 2022). Due to insufficient insight into the dynamics of marine FPVs and the lack of relevant standards and engineering experience, the design of mooring systems for marine FPV structures remains a challenge (Friel et al., 2019). On the one hand, the drifting of lightweight marine FPVs may be more severe than that of heavy offshore platforms under the same sea conditions without mooring. Therefore, a relatively stiff mooring system design is usually considered for marine FPVs. On the other hand, the stiffness of the mooring system significantly affects the natural periods of surge, sway, and yaw of FPVs. It could be important to design a relatively soft mooring to keep the natural periods of FPV horizontal motions away from typical wave periods (5-25 seconds). This contradiction makes mooring design challenging for marine FPV systems. For modular FPV arrays, it is also necessary to consider how to reduce or eliminate the motion differences between floats. In addition, designing the strength of the connectors between mooring lines and floats poses many challenges to mooring design. Fortunately, relevant, valuable mooring design experience from other MREs could be referenced as a good starting point for investigating FPV moorings. The mooring system accounts for nearly 10% of the total cost for WEC projects and even more for oil and gas platforms or offshore wind turbines (OES, 2015). For marine FPV systems, the cost of the mooring system is also expected to be significant (Myhr et al., 2014). The relatively low power generation efficiency of FPVs and the less critical consequences of mooring system failure indicate that designing low-cost mooring systems for marine FPVs is important from an economic aspect. Table 2 summarizes the common FPV mooring configurations with their applicable characteristics and economic performance.

The configuration of the mooring system can be classified into catenary, compliant, and taut mooring. Catenary mooring provides a restoring force through the weight of mooring lines (MLs). Determination of pretension for MLs could be critical to limit the platform motion envelope (Sound and Sea Technologies, 2009). Compliant mooring can reduce the mooring radius by connecting the MLs with the buoy (submerged or surface) and sinker (Sound and Sea Technologies, 2009). Taut mooring can provide a more significant restoring force than catenary mooring, requiring shorter MLs under the same water depth. However, the installation and maintenance of taut moorings are complex. Taut mooring becomes more cost-efficient for deep and ultradeep water compared with excessively heavy catenary MLs.

Generally, MLs are made of chains, wire rope, and synthetic rope (with increased costs) (Harris et al., 2004). A chain ML is suitable for catenary mooring because its weight helps the MLs remain in contact with the seabed. In addition, the wire rope is usually selected according to bending resistance and fatigue, which is particularly important for marine applications due to continuous loading from the ocean. Synthetic ropes show more complex nonlinear effects than chain and wire ropes (Sound and Sea Technologies, 2009).

The design of MLs needs to consider the working environment and level of technological maturity, in addition to the material cost. For instance, at intermediate water depths (e.g., 50-80 m) (Xu et al., 2021), the advantage of less effective weight using synthetic rope may be insufficient to overcome its disadvantage in terms of cost. The primary technical consideration of MLs is their performance in terms of reliability. Chain and wire ropes require a lower safety factor, while synthetic ropes require a higher safety factor due to the different maturity levels (DNV GL, 2001). A combination of two or three ML types can be used to meet operational and financial requirements. For example, catenary moorings that typically use wire instead of chains in the middle of MLs can reduce the weight and cost of the mooring system 0.

It is necessary to reasonably select the anchor based on the characteristics of different mooring configurations. Standard anchors used in freshwater FPVs are dead-weight and pile anchors (World Bank Group, 2019). Currently, preferable anchors have not been fully investigated for marine FPVs. Generally, dead-weight anchors are less efficient (evaluated by the holding capacity ratio to weight) than other anchors. For pile anchors, ideally, MLs are connected at a penetration depth of 1/2 to 1/3 of the pile (Sound and Sea Technologies, 2009). The penetration depth of drag anchors depends on the load, anchor configuration, and seabed characteristics. Under the condition of a hard seabed where the drag anchors are invalid, plate anchors may be effective (Sound and Sea Technologies, 2009).

Table 2

Mooring configuration in water.

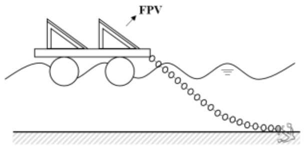
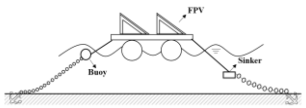
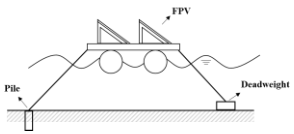
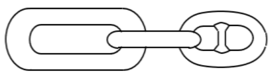
Mooring configuration	Types	Figures	Description	Costs	Advantages	Disadvantages
Mooring types (Harris et al., 2004)	Catenary		Part of the MLs is laid horizontally on the seabed. The restoring force is mainly generated by the weight of the MLs.	Up to configuration	• Easy installation. • Applicable to all anchors. • Superior abrasiveness.	• Hard to maintain the pretension. • Varied mooring stiffness during the life cycle.
	Compliant		The catenary mooring line contains sinkers or buoys. The horizontal restoring force comes from the weight of MLs or sinkers.		• Requiring less mooring scope. • Buoys limiting the vertical loads of the FPVs.	• Suitable for deep water to submerge the buoy. • Complex installation and maintenance.
	Taut		MLs are nearly straight with a constant laying angle. The restoring force is mainly generated by the tension of the mooring line.		• Economical in deep water.	• Unsuitable for shallow water with large tides and waves. • Unsuitable for drag anchors. • High costs of installation and maintenance.
Mooring lines	Chain		A long length with high strength is needed.	Medium	• Rich use experience. • Superior abrasiveness.	• Unsuitable for a water depth of more than 450 m.

Table 2 (cont.)

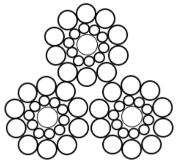
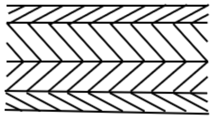
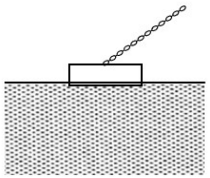
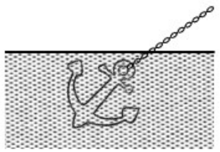
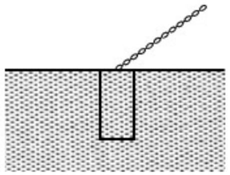
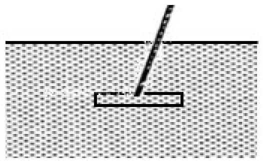
Mooring lines	Wire rope		Spiral wire bundles twist together with steel wires to obtain the required mechanical properties.	Low	• Rich use experience. • Superior abrasiveness.	• Unsuitable for a water depth of more than 900 m. • Avoiding extreme bending.
	Synthetic rope		Composed of synthetic polymer compounds with high strength and good elasticity but with more complex nonlinear effects.	High	• Low weight. • High strength-to-mass ratio. • High elasticity.	• Complex nonlinear characteristics. • Avoiding axial compression and hysteretic heating in extreme conditions.
Anchors	Dead-weight		Bearing horizontal mooring load, self-weight, and friction with the seabed.	Medium	• Resisting uplift. • Easy construction. • Easy inspection and maintenance.	• Limited applicable water depth. • Low lateral carrying capacity. • Requiring large handling equipment.
	Drag		The anchor embedded in the seafloor, and the mooring load paralleling to the seabed.	Medium	• Recyclable. • Excellent capacity.	• Unable to resist vertical loads. • Unsuitable for the hard seabed. • Instable behavior in the layered seabed.

Table 2 (cont.)

Anchors	Pile		Capacity generated by the action of pile and soil.	High	• Shorter MLs are needed. • High capacity. • Resist uplift.	• Requiring specialized installation equipment. • Rapidly increasing costs.
	Plate		Capacity generated by the action of MLs and the overburdened soil.	High	• High capacity. • Easy construction. • Resisting uplift. • Minor environmental impact.	• Unrestored. • Noticing wear and fatigue.

5 Future challenges and discussions

Although the momentum of marine FPV development can be observed, the technology readiness level (TRL) of marine FPVs is still relatively low. It has yet to form a large-scale commercial application. The design of marine FPV systems is a complex process that needs to ensure their safe operation throughout their lifecycle in harsh marine environments. In addition, a cost-competitive concept for the floating structure needs to be developed. It is currently conceivable that the main challenges for the design of marine FPVs include ensuring sufficient survivability and long-term reliability and clarification of relevant environmental impacts.

5.1 Survivability in the open sea

The survivability of marine FPV systems involves maintaining structural integrity and functionality in extreme ocean environments, which is one of the major structural design challenges. In the offshore oil and gas and wind sectors, typical floating structures require high manufacturing costs, consuming tremendous amounts of metallic materials to withstand demanding open sea loads. However, the cost is affordable in those sectors due to their high return rate (Wang et al., 2023). However, economic feasibility has yet to be proven for offshore solar sectors. For instance, the weight of the OC4 wind platform is 13,473 tons for a 5 MW wind turbine (Roddier et al., 2017). If used for PVs, its deck area (900 m^2) will only accommodate solar panels with a maximum capacity of 130 kW. Consequently, the increasing deck area requires more materials to improve the installed capacity of power generation in comparison with the oil and gas industry. The above economic and technical challenges still hinder the development of offshore PV sectors.

Operating an offshore PV farm is fundamentally different from traditional offshore projects (e.g., oil and gas). It requires a large ocean surface area without supporting heavy substructures. Therefore, a step change in the design of the floating system needs to be proposed, which can be used to support solar panels safely and economically. An inexpensive, lightweight, and durable structure could be ideal for fabricating substructures to support panels. The biggest challenge for operating such a lightweight facility floating in the open sea is to ensure its survivability under harsh environmental conditions, particularly from large wave impacts. Recently, the ocean space utilization community has focused on a modular design in which the units are connected by mechanical joints/hinges (Flikkema and Waals, 2019). This interconnected multibody can be regarded as a flexible solution, partly converting the wave energy into the kinetic energy of each module's motion. Another example to improve survivability is through flexible thin-film design (Trapani and Millar, 2014), which can deform with the waves to absorb the wave energy, thereby enhancing the reliability of the structure in ocean environments (more details are provided in Section 3.1.1). However, more studies are needed to verify its survivability under extreme wave conditions.

5.2 Long-term reliability

Being exposed to onerous and harsh ocean environments in the long term, material degradation and cumulative structural fatigue (Sahu et al., 2016) are critical concerns for FPV systems during operation. However, such a long-term reliability assessment for FPV systems has yet to be established (PVQAT, 2019). Temperature, humidity and UV radiation, which are more intense in the marine environment, significantly influence the degradation of FPV modules (Ndiaye et al., 2013). Increasing the mechanical properties (such as panel stiffness) of the modules may reduce the impact of fatigue, thereby increasing reliability (Claus and Lopez, 2022). At the same time, the inclination angle of PV panels is the critical factor affecting the wind load on modules. Smaller inclinations of the PV panels will undoubtedly positively impact structural safety due to smaller wind loads at the cost of solar radiation efficiency. Therefore, balancing the long-term reliability and power generation efficiency of PV modules in the ocean environment should be studied in the future.

Connectors between floating modules are also key components prone to fatigue damage. Selection of the type (e.g., rigid, semi-rigid, and flexible) and material is vital for the design of connectors to meet project requirements and optimize production costs.

Jiang et al. (2021) detailed their advantages and disadvantages when applied to large floating structures, which could be referenced by marine FPVs. The fracture of rigid connectors is more likely due to the transferred huge force from modules, while semi-rigid and flexible connectors are more prone to fatigue and wear damage. The selection of materials needs to be evaluated in combination with their mechanical properties. Their material properties may be well-known for metallic materials, but for polymers or composite materials, their complex constitutive models may pose more design uncertainties (Oliveira-Pinto and Stokkermans, 2020). The issue of connectors remains a long-standing challenge in the design of marine FPVs.

The flexible thin-film FPV design is expected to minimize the loads on structures (Trapani and Millar, 2014). However, its long-term reliability when exposed to the ocean environment needs to be further explored since this application has only emerged in recent years. Similarly, in-situ trials and applications are required for submerged PV systems to verify the service-life safety and reliability.

The long-term work of FPV systems in the ocean environment also needs to consider the impact of marine growth (El-Reedy, 2019). When tiny aquatic organisms and algae attach to and gather on the FPV systems (especially for submerged PVs), the dead-weight load of the structure will be increased, as well as the environmental loads (El-Reedy, 2019). Moreover, FPV systems may also attract birds as habitats. Bird droppings negatively affect power generation efficiency, increasing the difficulty and cost of maintenance and cleaning.

Salt mist is another critical factor that needs to be considered for marine FPV systems. Salt mist causes corrosion of the PV frames and metal wire boxes and consequently reduces the bonding strength of the encapsulant (Yadav and Chandel, 2013; Kugler et al., 2011). Additionally, exposure to salt mist in the long term may accelerate potential-induced degradation (PID) (Suzuki et al., 2015), which further degrades the power generation performance of PV modules (Felix et al., 2019; Liu et al., 2020). However, the mechanism of PID acceleration has yet to be fully clarified. It is assumed that sodium ions penetrate into the PV modules from the surrounding environment (Suzuki et al., 2015). It is necessary to further investigate how to prevent or control PID in marine FPVs in the future.

Reasonable and smart maintenance strategies would help improve the long-term reliability of the system. Maintenance aims to maximize economic benefits, extend component life, reduce emergency repairs, and avoid unpredictable equipment failures (Ren et al., 2021). The maintenance scope can be determined by field analysis conducted by qualified structural engineers who are familiar with mature structural assessment (El-Reedy, 2019). There are currently no standards related to the maintenance of marine FPVs, but the standards for freshwater FPVs (DNV GL, 2021) and ground-mounted FPVs (IEC 62446-2, 2020) provide maintenance precautions for each component of the photovoltaic system that can be used as a reference. It should be noted that during the maintenance period, it is necessary to ensure the safety of maintenance personnel. Research experience of occupational safety hazards (OSH) from mature marine engineering (e.g., oil and gas) can be referenced (Al Nabhani and Khan, 2020).

5.3 Environmental impact of FPV systems

In addition to the structural aspects, the environmental impact of FPV applications should also be considered (Liu et al., 2020). For freshwater applications, relevant studies have shown that FPV systems have no significant negative impact on animals (BayWa r.e., 2022). However, a study showed that the aquatic plant biomass under freshwater FPV systems decreased by one-third (Baradei and Sadeq, 2020). For water quality (e.g., total nitrogen, total phosphorus, chlorophyll-a, and cyanobacterial chlorophyll), there is no consensus on the shading impact of FPV systems on water quality. The complex impact may also be related to the installed water environment and local climate environment, and more long-term observation data need to be combined for evaluation. (AI-Widman et al., 2021, Lee et al., 2017, Yang et al., 2022, Ziar et al., 2021). In contrast to freshwater FPVs, marine FPVs are not anticipated to decrease aquatic plant biomass, preventing the death of undersea fish due to low oxygen concentrations and eutrophication of the water body (Rao et al., 2014).

During the design stage, the construction site should preferably be located in areas without protected species of marine life and environmental restrictions to minimize the environmental impact of marine FPV systems (Choi, 2014). Moreover, proper design of the installation process and efficient marine operations to reduce the total construction period could help minimize the effect on the marine environment. Suspended sediments from construction and possible leakage of oily wastewater can also cause marine pollution.

During the operation, the visual impact should be considered. It may not be conducive to the beauty of the coastal landscape and may contribute to light pollution due to reflection. FPV systems should minimize the release of toxic substances (e.g., cadmium and arsenic) into the water to avoid affecting aquatic ecology and coastal biological habitat ecology (Gorjian et al., 2021). Currently, most FPV support structures are made of HDPE. Despite its corrosion resistance, it still requires a protective coating due to long-term immersion in water. Other materials, such as steel or aluminum, also require protective coatings. There could be minor amounts of these coating materials dissolved in water, which could be sources of pollution. Even the parts that are not in direct contact with water may have a small amount of release under long-term wave action (Cazzaniga, 2020). On the other hand, PV modules need to be cleaned periodically with water and other chemicals, which are bound to have an environmental impact and even cause the death of marine organisms (Lovich and Ennen, 2011). Therefore, it is necessary to change cleaning procedures by switching to nonpolluting cleaning materials. Plastics are a key issue in marine pollution, and HDPE has been noted as a potential source of plastics (Claus and Lopez, 2022). Hence, environmentally friendly structural materials and harmless protective coatings need to be further developed. For marine organisms, FPV systems provide bird habitats and fish shelter. At the same time, marine FPV development areas restrict vessel traffic or fishing in general, creating a refuge for fish. However, construction and operation noise may cause hearing damage to marine organisms, as the noise generated during the operation may disorient marine organisms' communication or sense of direction. Therefore, the complex effects of marine FPV systems on marine organisms require further research in combination with long-term observation data.

During the maintenance stage, there is a risk of water pollution caused by fuel and lubricants from the operation and maintenance equipment. At the same time, it is also necessary to give attention to the disposal of waste materials, such as replaced PV panels. (Aman et al., 2015).

6 Conclusions

The FPV system, developed as a substitute for conventional fossil fuels for electricity generation, is expected to be widely applied due to its many advantages, such as less land occupation, reduced water evaporation, and higher power generation efficiency. This paper provides landmarks of FPV development and introduces the important application trends of FPV toward the marine environment. Critical concerns regarding the structural design of marine FPV systems and the relevant challenges are discussed. The main conclusions are as follows:

(1) FPVs are believed to have broad market prospects and development potential. The number of sizeable MW-level FPV projects is increasing. The capitalization of marine FPVs is a significant trend. Toward ocean applications, cost-efficient designs are desired.

(2) Thin-film and submerged FPV technology might be a promising solution toward marine applications. The effects of water-cooling, self-cleaning, and high wind speed help improve the power generation efficiency, while horizontally placed PV panels could negatively influence the generation efficiency. To maintain sufficient power generation efficiency, the depth of the submerged FPV is minimal, leading to a limited reduction in wave-induced system dynamics.

(3) Synergies of marine FPV systems could be achieved by hybrid spatial layouts

and platforms, which may bring better opportunities for exploiting marine FPVs.

(4) Critical structural design considerations were discussed. Environmental loads are the primary loads on marine FPV systems, for which estimations and design methods may refer to the standards for relatively mature marine engineering, such as those of the oil and gas industry. The robust design of connectors can be important for the reliability of modular FPV platforms. Wind loads are the crucial factor affecting the motion response of freshwater FPVs, while wave loads are increasingly critical for marine FPVs.

(5) Designing marine FPVs in terms of survivability and long-term reliability is challenging. Improving of scalability cost-effectively and overcoming the fatigue issue in marine environments are the keys to marine FPV design in the future.

(6) In contrast to the aquatic' plant biomass under freshwater FPV systems decreasing by one-third, marine FPVs are not anticipated to decrease aquatic' plant biomass. For water quality, there is no consensus on the shading impact of FPV systems on water quality, and the complex impact may be related to the installed water environment and local climate environment. The environmental impact of marine FPV systems needs to be assessed at various stages, from site selection, construction, and operation, to maintenance. The complex impacts require further research combined with long-term observational data.

Further research on risk assessment and operational personnel safety of marine FPVs could be conducted. In addition, with more installed industry projects and more operation data collected, precise quantitative analysis will help scholars and engineers better understand the development status and potential of marine FPVs.

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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