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Developing reliable floating solar systems on seas: A review

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ABSTRACT

Solar PhotoVoltaic (PV), as a clean and affordable energy solution, has become ubiquitous around the world. In order to install enough PV coverage to meet the demand of global climate action, there has been a growing research interest in deploying solar panels on abundant sea space. However, the harsh marine environment is holding stakeholders back with safety concerns. There is a necessity to ensure the reliability of FPV on seas. To facilitate research in this area, the present review scans all Floating PV (FPV) literature related to the ocean, with a focus on reliability and risk mitigation. It starts by presenting contemporary and potentially future FPV designs for seas, inventorying both mechanical and electrical components. Accordingly, possible risks in the system are discussed with the associate mitigations suggested. Subsequently, a series of protective approaches to assess offshore wind and wave loads on FPV are introduced. This is followed by a structural integrity review for the system's fatigue and ultimate strength, accompanied by anti-corrosion, anti-biofouling, and robust mooring concerns. Finally, essential research gaps are identified, including the modelling of numerous floating bodies on seas, mooring methodology for enormous FPV coverage, the interactions between FPV and the surrounding sea environments, and remote sensing and digital twins of the system for optimal energy efficiency and structural health. Overall, this work provides comprehensive insights into essential considerations of FPV on seas, supporting sustainable developments and long-term cost reductions in this sector.

Contents

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1. Introduction

Solar panels have become one of the most important energy approaches globally, promoted primarily by the goal of developing clean and affordable energy. Compared to other renewable energy choices such as wind energy, solar energy offers superior flexibility and cost savings (Irena, 2021). Solar panels are a fully scalable energy approach as the number of solar panels used can be tuned to meet the energy demands at different scales. This enables a solar farm to adapt to various locations, sizes, shapes, and scenarios. Benefiting from modularised components, the installation, maintenance and operational costs of a solar farm are advantageous (Majdi et al., 2021). The International Energy Agency (IEA) has predicted that solar will soon stand out as the most popular energy approach globally and could have twice the installed capacity as wind by 2050 (IEA, 2022).

A strong interest in the topic of Floating PhotoVoltaics (FPV) has unfolded over recent years. The design of a modularised FPV unit can include a floater to provide buoyancy for a selected commercial solar panel, followed by the design of another type of floater to connect multiple panels to form an array (Wei et al., 2024d), as illustrated in Fig. 1. Considering various power requirements, standard matching packages electrical components, outer structural frames and mooring can be added. Compared to land-based solar, FPV can have approximately 5% more overall energy yield due to the water-cooling effect (Kjeldstad et al., 2021; Dörenkämper et al., 2021). Whilst FPV have widespread initial installations on lakes and reservoirs, this comes hand-in-hand with the dilemma of occupying those scarce and environmentally sensitive waters. In this context, there has been a trend of installing FPV on seas instead of calm waters, taking advantage of abundant ocean space for mitigated conflicts (Zhang et al., 2024a; Esparza et al., 2024).

Operating FPV on seas faces significant challenges due to harsh marine environments, undertaking physical, chemical and biological effects. As illustrated in Fig. 2 (Shi et al., 2023), whilst the wind condition offshore can be much larger than onshore, significant wave

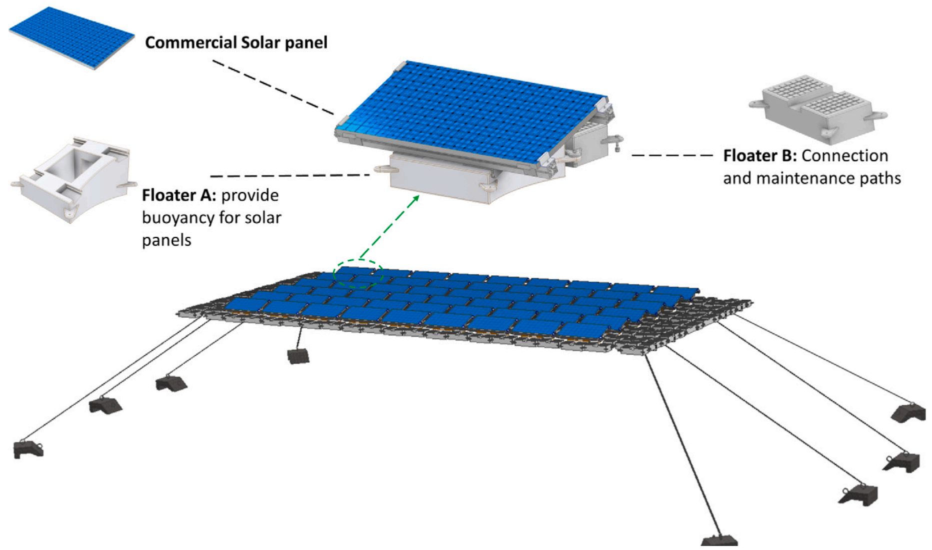


Fig. 1. Illustration of a modularised FPV system.

loading has become one of the most concerning factors of ocean-based FPV projects (Shi et al., 2023; Jifaturrohman et al., 2024). It is necessary to reduce the loads and associated motions of the floating structure, which is further instigated by a suboptimal energy yield due to a varying tilt angle based on wave-induced motions (Huang et al., 2024). This potentially induces high costs of FPV systems on the ocean due to structural mitigation required, such as advanced floaters, structural frames and mooring systems (Yang et al., 2024d; Wei et al., 2024b). Marine corrosion and biofouling can cause the structures to have deviated properties from the designed conditions, which induces more sensitive fatigue and the ultimate strength required (Igwemezie et al., 2018, 2019). Maintenance costs at seas are high and therefore require highly reliable solutions, leading to the need for new design and prediction approaches. These challenges motivated this review to address FPV on seas, instead of calm waters. The present review differs from previous FPV reviews such as Wei et al. (2025) covering calm water and the interdisciplinary matters of environment, economics and power generation. The present work focuses on the reliability of FPV in harsh marine environments, where ocean waves dominate. This work presents ocean-based mechanical and electrical designs and their associated mooring and fatigue aspects, aiming to motivate future ocean-compliant designs, mitigate risks, informing maintenance plans and reducing the Levelised Cost of Energy (LCOE).

The first step of this review is to collect relevant research publications available in the public domain. The literature scan was performed using the Web of Science, searching for two criteria appearing together in the same article (a) "floating solar", or "floating photovoltaic", or "floating PV", or "FPV" in any paper's title or abstract, (b) "ocean", or "wave", or "sea", or "offshore" in any paper's title or abstract. 547 publications have been found as of November 2024, and their distribution is given in Fig. 3. It can be seen that FPV on seas has been a rapidly growing topic for the past five years. The affiliations on these papers are distributed mostly in China and the United States, indicating strong regional interests. England publishes most of the papers in Europe, accompanied by high volumes from Spain, Italy, Germany, Norway, France etc. It is worth noting that there has been a notable contribution from Asian countries such as India, Singapore, and South Korea.

Upon collecting the literature, this review is grouped into the following Sections. Sections 2 and 3 provide an overview of ocean-based FPV mechanical and electrical components. Section 4 introduces the risks and failures that FPV can possibly occur offshore. Sections 5 and 6 review wind loads and wave loads of FPV at seas, respectively, which is accompanied by their contemporary assessing approaches and future research directions. Section 7 introduces the methods to assess the fatigue and ultimate performance of FPV, alongside the prevention of corrosion and biofouling. Section 8 identifies research gaps and future work, and summarises the key accomplishments of this review.

2. Floating solar structural designs

For floating solar installations, there are three main deployment categories: onshore, nearshore, and offshore. Onshore floating solar installations are primarily designed for lakes and reservoirs, where the technology is well-established, with fully commercial power plants already operational (Vidović et al., 2023). Nearshore installations are located in marine environments but are relatively sheltered from extreme waves and winds; this type is becoming more popular, with several new projects, such as the 440 MWp Changbin floating solar project in Taiwan. Finally, offshore floating solar installations are fully exposed to waves, currents, and winds in the open sea or ocean, which is the focus of this paper. Offshore floating solar has yet to achieve fully commercial-scale plants and is still in the prototype and small-scale phases (Oliveira-Pinto and Stokkermans, 2020).

In terms of structure type, Claus and López (2022) proposed a classification with two main design classes: the pontoon type and the superficial type, as illustrated in Fig. 4. Both classes have been installed and tested for offshore floating solar, each with its own advantages and disadvantages. In the next section, each class will be presented and reviewed.

2.1. Current designs

The mechanical components and materials of the two main classes are reviewed in this section.

2.1.1. Pontoon type

The pontoon-type floating solar system is a design that elevates the solar panels from the water surface and is divided into three classes.

Class 1 pontoon-type FPV systems are made up of rafts with buoyant trusses that support a structure housing multiple PV panels. This design was the first used commercially, with an installation of 175 kWp at the Far Niente vineyard in California (Amanda, 2020).

In Class 2 pontoon-type FPV systems, each PV panel is supported individually by a single float with integrated rails. These floats are connected by pins, forming a linked structure. This design was first introduced by the French company Ciel et Terre in Sainghin-en-Mélantois

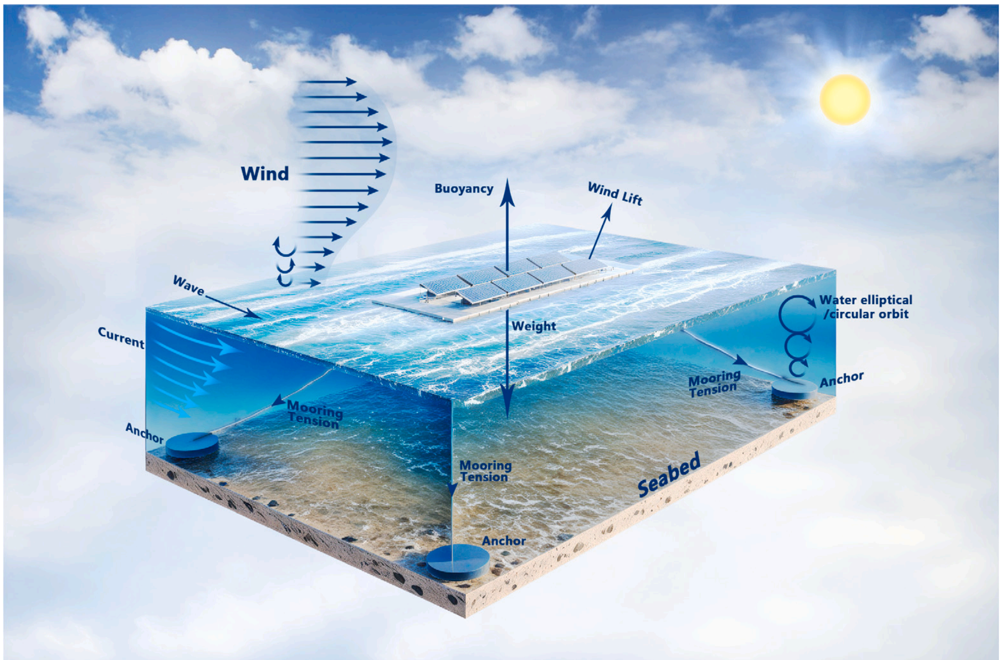


Fig. 2. Illustration of a FPV system on seas.

in 2011, using their patented Hydrelio floating system (Delacroix et al., 2023).

Class 3 pontoon-type FPV systems use floats assembled to create a large floating platform, on which PV modules and electrical components are mounted separately. These platforms can be connected to form larger solar power installations. It is also known as an elevated truss design. This design has been the most commonly used in offshore applications, as the structure is robust enough to withstand environmental forces.

In addition to conventional pontoon-type FPV systems, the newly patented ball-net reflector for bifacial floating photovoltaic systems (Ziar et al., 2024) introduces an innovative floating reflector designed to enhance the efficiency of bifacial solar panels in floating photovoltaic installations. By incorporating a net embedded with floating balls, this system increases the light reflected onto the panels, thereby boosting energy generation. It provides new insights into environmentally considerate solutions and is adaptable to varying water and weather conditions, making it a practical approach for improving renewable energy efficiency on water surfaces.

Various studies, using either experimental or analytical approaches, have been conducted to estimate the forces on different FPV system classes, as in Delacroix et al. (2023), Lee et al. (2022), Ikhennicheu et al. (2021a, 2022), additionally, Kaymak and Şahin (2021a,b) proposed an enhanced design focused on the performance of FPV systems under natural conditions. Although these studies have proven very useful for understanding performance under different environmental conditions, they have all been conducted on small-scale experimental models suitable for wave tanks or small-scale numerical studies using Computational Fluid Dynamics (CFD) or semi-empirical equations, such as the Morison equation. This limitation arises from the restricted size of wave tanks, which cannot accommodate commercial-scale farms with several megawatts, and the lack of numerical tools capable of simulating an entire FPV plant.

While Class 1 and 2 systems could potentially be economically viable solutions (Ramasamy and Margolis, 2021), their structures are generally too weak to withstand harsh environmental forces and are often limited to a maximum wave height of 2 m, as reported by various manufacturers. On the other hand, class 3 systems are capable of withstanding higher forces, but achieving economic viability with these structures is uncertain due to their high costs. The superficial FPV represents another class aiming to achieve both technical and economic viability, as discussed in the following section.

2.1.2. Superficial

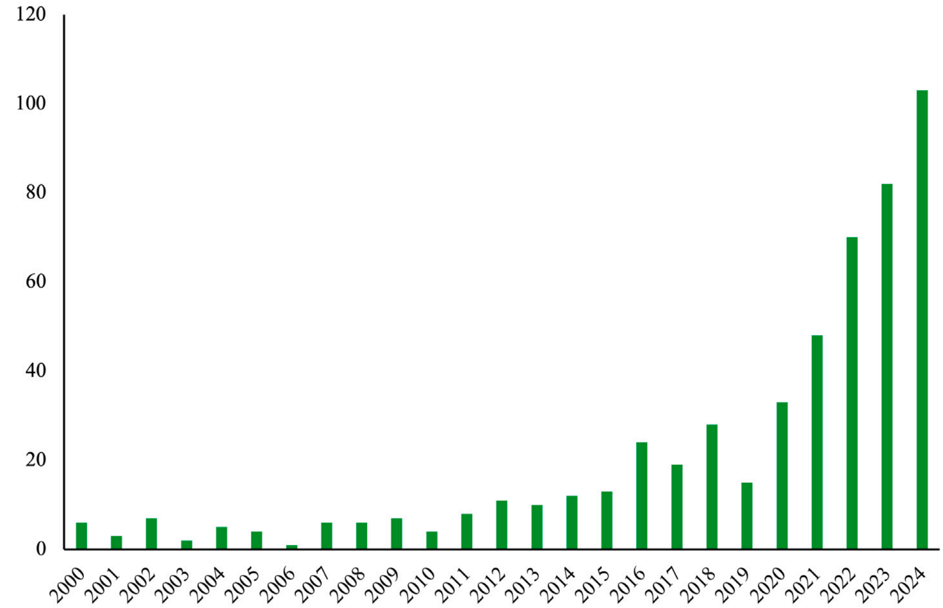
In contrast to the pontoon type, the superficial class relies on having the PV panels floating on the water's surface, whether rigid or flexible. The concept is to ensure that the panels follow the shape of the free surface, reducing structural costs while moving with the waves to minimise environmental forces. However, with the panels positioned closer to the water, additional challenges arise, such as splashing of salty water, marine growth, and the need for modular maintenance solutions. Studies on this class are limited, with Trapan et al. addressing the circular flexible FPV (Trapani and Millar, 2014), Sujay studying flexible thin-film PV modules and flexible floaters (Patil Desai Sujay et al., 2017) and Zhang et al. analysed the hydroelastic responses of membrane-based FPV platforms (Zhang et al., 2024b). Further publications and research are needed on this class of floaters. Various designs have been proposed and tested, which will be discussed in the following section.

2.2. Prototypes and materials

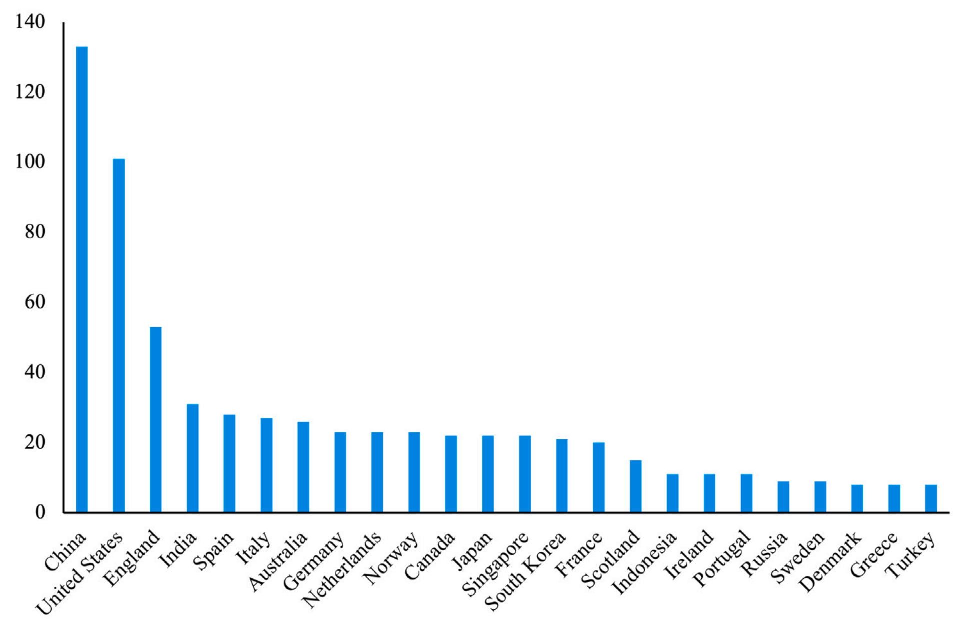
This section presents selected prototypes, highlighting notable installations rather than providing a comprehensive overview. Gang and colleagues provide a review covering various installations in seas and oceans (Liu et al., 2024).

2.2.1. SolarDuck

The Dutch-Norwegian company SolarDuck has developed a 0.52 MW pilot project shown in Fig. 5, known as the Merganser Project, with a prototype certified by Bureau Veritas in 2024. This certification confirms the structure's resilience against wave heights up to 11.6 m (Artificulated Floating Structure, 2020), with a directional 10-year return period, at a water depth of 21.5 m, specifically at the North Sea Farmers test site. The pilot will be deployed off the coast of The Hague, Netherlands, providing a real-world setting to assess its performance and durability in the challenging conditions of the North Sea (Artificulated Floating Structure, 2020).



(a) Publication numbers by year



(b) Publication numbers by affiliation country

Fig. 3. The distribution of literature related to FPV on seas. Data accessed from Web of Science in November 2024.

The design is classified as a pontoon-type Class 3 structure, featuring a fixed triangular platform supported by an elevated metallic truss. This configuration facilitates controlled rotational and translational movements. Equipped with motion limiters, including telescopic cylinders, the structure limits excessive motion and reduces collision risk. This design enhances the platform's adaptability to fluctuations in the water surface, ensuring stability amid variable wave conditions (SolarDuck, 2020).

2.2.2. *Moss maritime*

Italy-based engineering service provider Saipem has introduced the first full-scale prototype of XolarSurf as shown in Fig. 6, a modular offshore floating solar solution designed for harsh environments, now undergoing testing in Norway. Developed by Moss Maritime, the prototype will be evaluated over the course of one year. It features a pontoon-type class 3 structure with an octagonal metallic frame supported by buoys, connected to a metallic truss that holds the solar panels (Moss Maritime, 2024).

2.2.3. *CIMC raffles*

CIMC is at the forefront of Chinese innovations with the country's first semi-submersible offshore floating photovoltaic power generation platform. They have developed a booster station for the CGN Yantai Zhaoyuan 400 MW offshore floating solar project as shown in Fig. 7, one of the largest offshore installations to date (Sunergy, 2024). This structure is a pontoon-type, class 3 design featuring an elevated truss. CIMC has incorporated a bamboo-based composite material (CIMC, 2024), which they claim offers several benefits over traditional steel structures: reduced weight, lower cost, resistance to seawater corrosion, extended service life, and enhanced environmental sustainability.

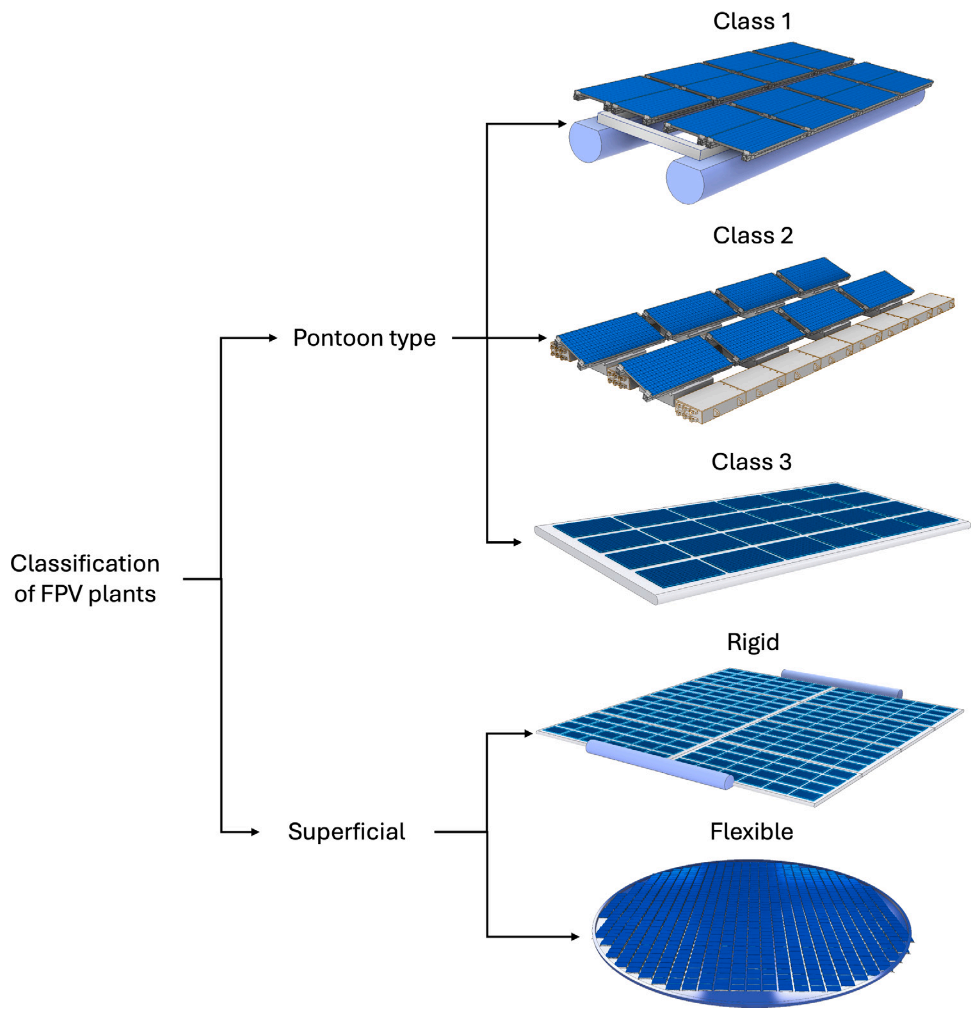


Fig. 4. Classification of FPV systems.

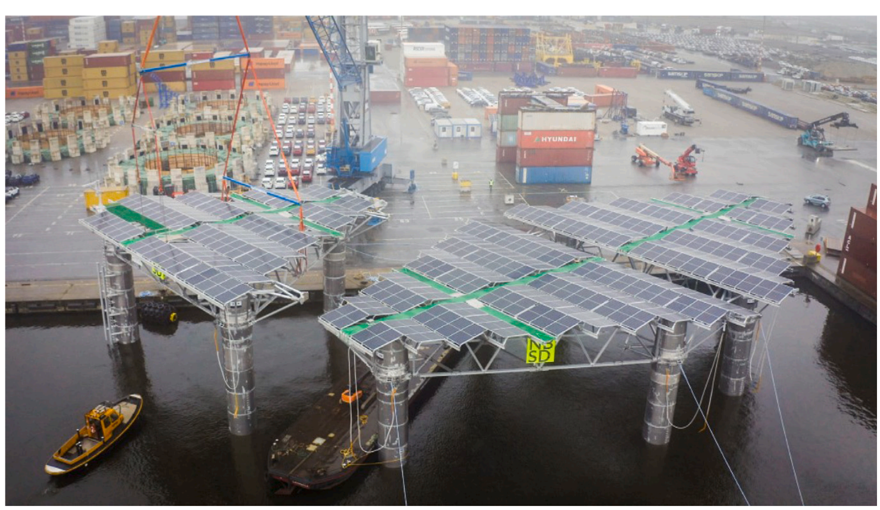


Fig. 5. The prototype of SolarDuck in the Merganser Project (Artificulated Floating Structure, 2020).

2.2.4. Oceans of energy

The Belgian company Oceans of Energy is a pioneer in superficial floating solar design, demonstrated through its three pilot projects—North Sea 1, 2, and 3. These projects began with systems generating a few kilowatts and have scaled up to 3 MW over five years of testing. The system has been tested in extreme conditions, enduring waves up to 13 meters high, heavy storms with wave heights of 9-10 m, wind speeds reaching 62 knots, and tidal currents of up to 4 knots, surviving

Fig. 6. Upper image: the prototype of Moss Maritime in the XolarSurf Project after being deployed in the water. Lower image: the prototype during installation (Moss Maritime, 2024).

multiple severe storms (Oceans of energy, 2024). The design consists of groups of solar panels mounted on flat, rigid floating platforms interconnected to form an array as shown in Fig. 8. Since the solar panels are positioned close to the water's surface, the system qualifies as a rigid, superficial FPV design.

2.2.5. Fred. Olsen 1848

Fred. Olsen 1848 (FO) installed a 124 kW floating solar system featuring a distinctive design shown in Fig. 9. It uses a pre-tensioned rope mesh as a skeleton to support individually anchored floating solar modules. The ropes are mounted on polyethene (PE) pipes, which serve as the connection between the mooring system and the rope mesh. These PE pipes offer essential buoyancy, rigidity, and flexibility, while also acting as a protective barrier against short, steep waves (Fred Olsen 1848, 2024). This design is yet to be proven for harsh environments. Due to the panels' close proximity to the water, this system is classified as a flexible superficial design.

2.2.6. Ocean sun

The Norwegian company Ocean Sun has deployed one of the earliest designs of floating solar using circular, flexible film-type solar panels. In addition to several onshore solar farms, Ocean Sun is also working on a 0.5 MW offshore project. This project includes sea trials of Ocean Sun's technology in exposed waters with 10-meter waves in the Yellow Sea as shown in Fig. 10. The first round of sea trials began in October 2022 and concluded in May 2023. Based on insights from the initial trials, design improvements have been made to the offshore version of Ocean Sun's technology (Ocean Sun, 2024).

2.3. New designs

As reviewed, contemporary FPV structures for seas are mainly two types (a) not robust enough to handle harsh wave environments, and (b) using giant floating structures to place solar panels. The latter renders the costs being prohibitive compared to calm-water FPV projects, as the floating structures can become much more expensive than the solar panels themselves.

A potential solution, as mentioned by Yang et al. (2024d), could be applying a breakwater surrounding the edges of the FPV. The breakwater aims to interact with incoming waves and significantly dissipate them (Lyu et al., 2024), so that the solar panel part can have minimal interaction with waves. The idea could help FPV on seas to retain their floating support used on calm water, lowering the additional costs. Noting that the breakwater is only required at edges, the costs will not increase proportionally with solar coverage area like other

Fig. 7. Upper image: the 400 MW booster station of CIMC Raffles. Lower image: the plant during assembly and installation (Sunergy, 2024).

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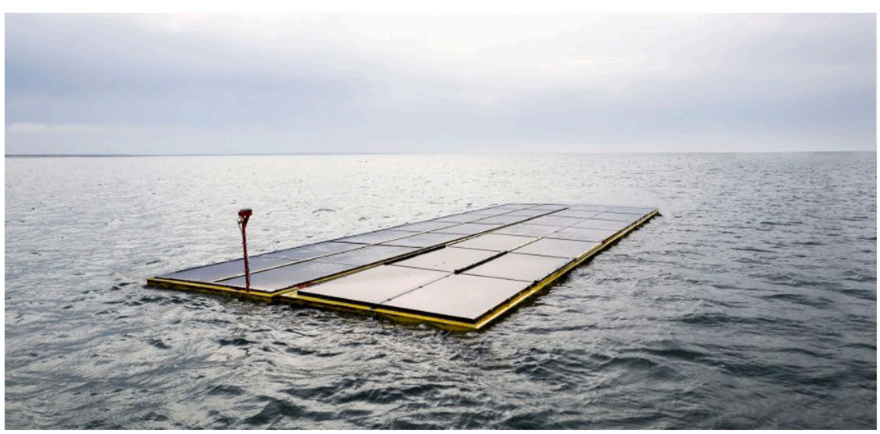


Fig. 8. North Sea 1 project of Oceans of Energy (17 kW) (Oceans of energy, 2024).

designs, which makes breakwater-FPV averagely cheaper for large-scale projects.

Another iteration of the breakwater idea could be Wave Energy Converters (WECs). WECs have been widely combined with breakwaters due to their harmonic purposes (Zhou et al., 2022; Wei et al., 2024c). The WECs transform the surrounding ocean wave movement into useful electricity generated. This absorbs the wave action and thus protects the platform from the destructive loading of waves. The extra electricity is therefore an additional benefit. However, the cost-effectiveness of converting breakwaters to WECs needs to be assessed, balancing the additional electricity gain against system upgrade costs. One idea could be integrating Oscillating Water Column (OWC) (Zhang et al., 2020b,a; Chen et al., 2024) with a breakwater attached to FPV, as illustrated in Fig. 11.

2.4. Mooring system

The mooring system is what keeps the floating platform in place in the sea with reasonable and calculated offsets. In addition, it allows movement with the tide. There are different types of mooring systems, and the most common type used for floating PV platforms is the spread mooring system which has multiple mooring lines on the circumference of the platform connecting it to the seabed (Ma et al., 2019). Furthermore, a mooring line profile could be either categorised into catenary

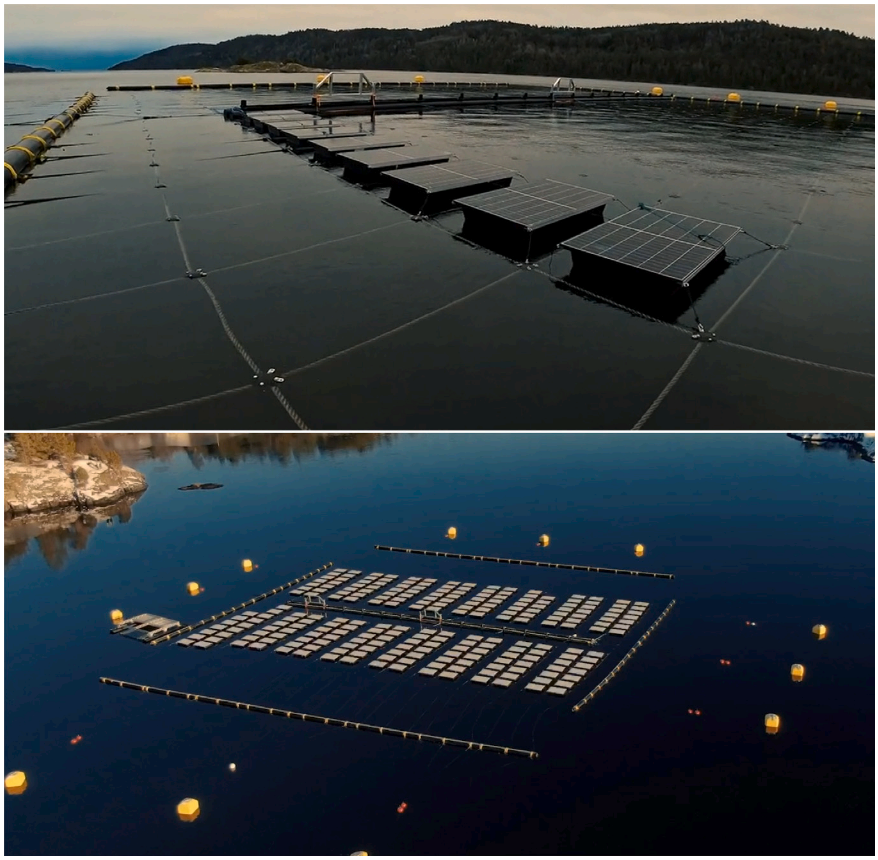


Fig. 9. Upper image: the FO system during installation, showing the ropes, pipes, and floaters supporting the panels. Lower image: the 124 kW FO prototype (Fred Olsen 1848, 2024).

Fig. 10. Ocean Sun's 0.5 MW sea trial in Haiyang, China (Ocean Sun, 2024).

or taut leg, see Fig. 12. A catenary line profile would have part of the line lying on the seabed and the weight of the line would provides needed flexibility to accommodate both static offsets and dynamic motions. The catenary type is the most used especially in shallow water less than 500 m deep. On the other hand, for a taut leg system, no part of the mooring line lies on the seabed in the static equilibrium position; instead, the lines remain taut between the seabed anchor and the floater's fairlead. This setup requires less line material compared to catenary mooring. However, because the lines are taut, flexibility for the floater's offset and movement is mainly achieved through the tensile stretching of the lines. In shallow water, this system can be too rigid, potentially leading to excessive line tension. Therefore, taut leg systems are more suitable for deep and ultra-deep water applications.

The configuration of the mooring lines also determines their composition, which could be an all-chain setup, a chain-wire-chain combination, or a chain-rope-chain configuration, among others. The choice of configuration — and thus the line composition — depends largely on water depth. For instance, in depths of less than 500 m, a catenary profile is typically the most cost-effective option, with both all-chain and chain-wire-chain setups being viable. However, for depths exceeding

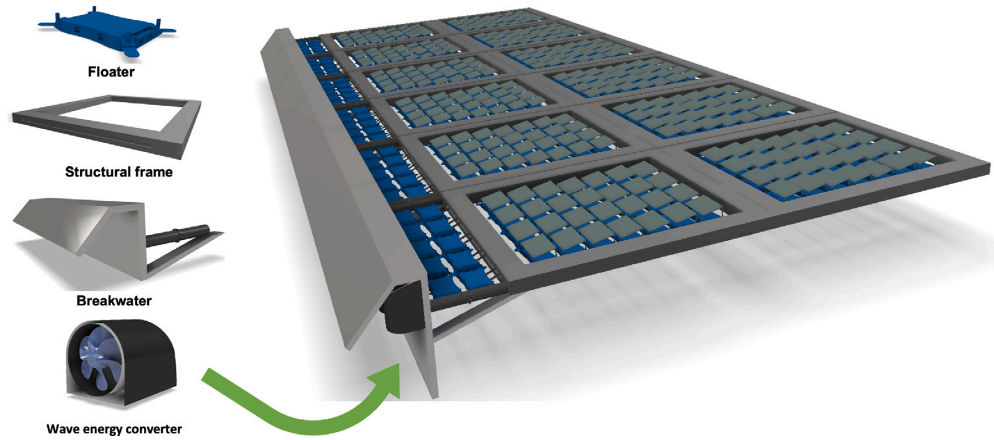


Fig. 11. Illustration of a combined OWC-WEC breakwater and FPV system.

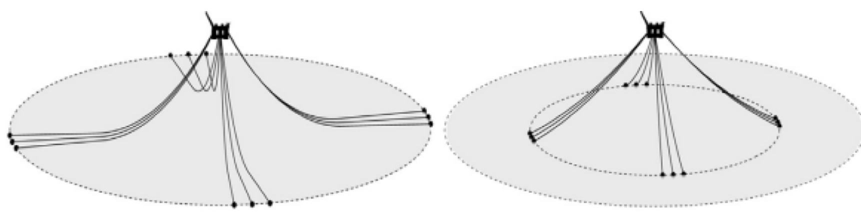


Fig. 12. Catenary (left) versus Taut Leg (right) (Ma et al., 2019).

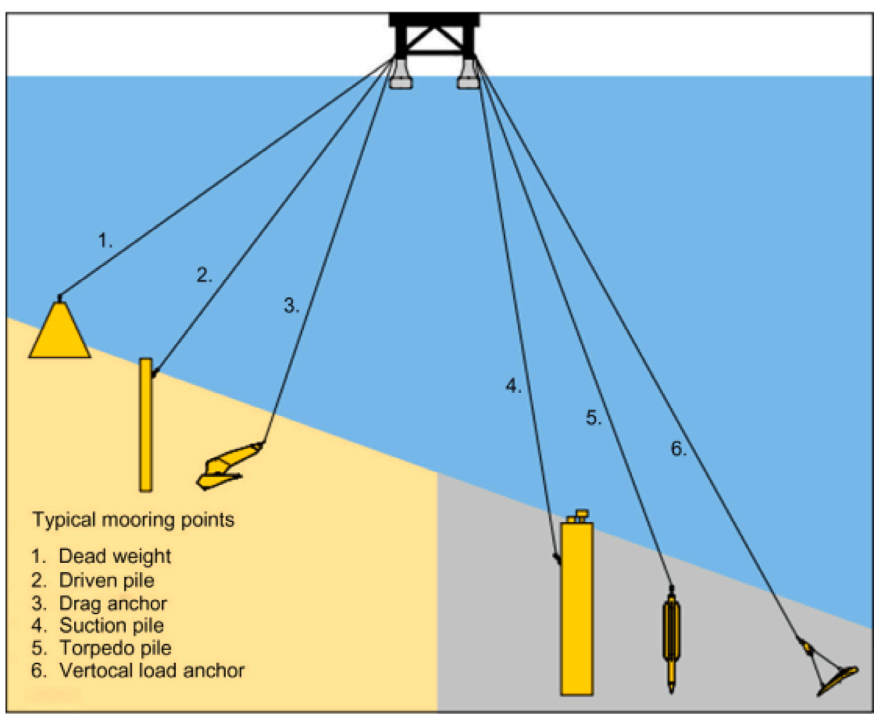
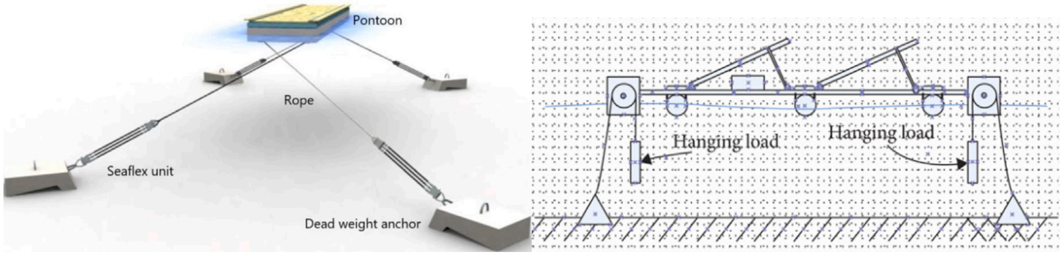


Fig. 13. Anchor types according the water depth (Ma et al., 2019).

300 m, the chain-wire-chain setup may offer greater cost efficiency (Ma et al., 2019).

The mooring system in offshore environments is always associated with an anchoring system. There are several types of anchors such as dead weight. driven pile, drag embedment anchor (DEA), suction pile, gravity installed, and vertically loaded anchor (VLA). See Fig. 13. For more details on the types and the choice criteria of anchors the reader is invited to check Chapter 8 of Ma et al. (2019).

Finally, a comprehensive and complete mooring design is needed to achieve two main objectives: (a) To maintain the floating structure on the station within specified offsets, and (b) to provide a mooring system with sufficient strength and fatigue life. Some of the available mooring design software available in the market among others are OrcaFlex by Orcina (Orcina, 0000), Moses by Bentley Systems (Bentley Systems, 2024), and AQWA by Ansys Inc. Ansys Inc. (2024). It is believed that mooring systems have plenty of room for development



(a) Innovation in mooring components. (b) Innovation in mooring system design for FPV.

Fig. 14. Mooring innovation examples (Seaflex, 2024; Elshafei et al., 2021).

and innovation. There are a few innovations in the mooring systems design or components that are seen for instance in Fig. 14.

3. Floating solar electrical design

3.1. System layout and integration

Solar power systems can be categorised into three main types: grid-tied, off-grid, and hybrid. In general, the structure of a PV system can be derived from the nominal power of the system looking at the highest efficiency with the lowest costs (Romero-Cadaval et al., 2013). The optimal system configuration depends on factors such as location, grid infrastructure, and energy requirements. Land-based systems are typically divided into large-scale utility-scale plants, residential and commercial installations, and small-scale systems (Mariusz Malinowski, 2017). Offshore floating solar systems, due to their unique installation challenges, are primarily prospected to be designed as large-scale power plants. On such basis, the system layout and the items to be integrated into the floating structure shall be defined.

3.2. Essential electrical components

The selection of electrical components is crucial for the efficient operation and maintenance of the FPV system. The system layout, as described in the previous section, influences the placement of these components. To optimise the system's performance and accessibility, we can categorise the components into two groups: essential and preferred. For a visual representation of some of the components of the FPV system, refer to Fig. 15, as an example of a floating system and its related components, the core components of a floating solar system include PV modules, floating structures, and the necessary electrical components. Key electrical components such as cables and combiner boxes are essential for system functionality and safety. Depending on the specific system design and scale, additional components may be required. Hence, the Essential Electrical Components on the floating Structures PV modules, DC secondary cables, earthing and lighting systems, emergency shutdown systems, combiner boxes, and DC main power cables shall considered as the Essential Components. Solar panels convert sunlight into direct current (DC) electricity, which is then transmitted through DC cables to combiner boxes. These boxes consolidate the power output from multiple panels, reducing the number of cables required. The combined DC power is further transmitted via DC main power cables to the central inverter, especially in large-scale systems. To ensure safety and efficient operation, earthing and lighting systems are essential, along with emergency shutdown systems that automatically deactivate the system in hazardous conditions.

3.2.1. Cables management system

Effective cable management is crucial for the reliability and safety of floating solar systems. The system typically involves three key areas: (1) On Platform Cable Management: cables are routed through cable trays and secured using clamps and glands to prevent damage and water ingress. (2) Submarine Cable Connection: strong submarine cables connect the floating platform to the onshore grid, often requiring specialised installation techniques and protective measures. The mentioned cable could be known as "array cables". The array cables are widely used to transfer power from the offshore wind turbines to the offshore substation. Hellenic Cables, JDR Cable Systems, LS Cable and System, Nexans, NKT, Prysmian, Sumitomo Electric and TKF supply such cables. Other cable manufacturers based in China and Japan have yet to be used widely for UK projects (guidetofloatingoffshorewind, 0000). (3) Onshore Cable Management: the onshore cable system ensures a seamless connection between the submarine cable and the grid, often involving underground or overhead cable routes whereas local standards and practices for such installation shall be applied. By carefully designing and implementing these cable management systems, engineers can optimise the performance and durability of floating solar power plants.

3.2.2. Earthing system

One of the most challenging components is the Earthing system, and how it could be implemented on the floating platform. Speaking of the Earthing Rod instalment presents unique challenges compared to a land-based PV system, primarily due to the complexities of underwater installation. In such cases, underwater grounding techniques are employed to control costs; however, estimating grounding resistance becomes a challenging task. To overcome this burden, water temperature measurements are taken at different depths to look forward to resistivity levels. Grounding resistance is then computed based on the position of the electrode within the water as shown in Fig. 16 (Bhang et al., 2018; Ko et al., 2017). The mentioned procedure ensures electrical safety and offers protection against environmental factors for the floating PV system. For further insights into the modelling parameters used to calculate the resistance for the Earthing Rod, refer to Safety Analysis of Grounding Resistance with Depth of Water for Floating PVs (Ko et al., 2017).

3.2.3. Emergency shutdown system

An important safety component that might be included in the floating PV system is the Emergency Shutdown System. Commercially, it goes by the name of the Rapid Shutdown System, and it is considered a vital component for ensuring safety on floating structures. The system can be equipped with a disconnect button or operate without one. Additionally, it can serve as a fire detection mechanism. For example, if the system's temperature surpasses 70 °C, it will trigger an immediate shutdown. The Rapid Shutdown System can accommodate multiple strings, although this varies by manufacturer, as shown in Fig. 17 (RPOJOY Electric, 2024; SMA, 2017).

3.3. Desirable electrical components

Other key components can enhance the system's efficiency and operation. These desirable components that can be situated on the floating structures are the inverter, transformer, and switchgear. Integrating

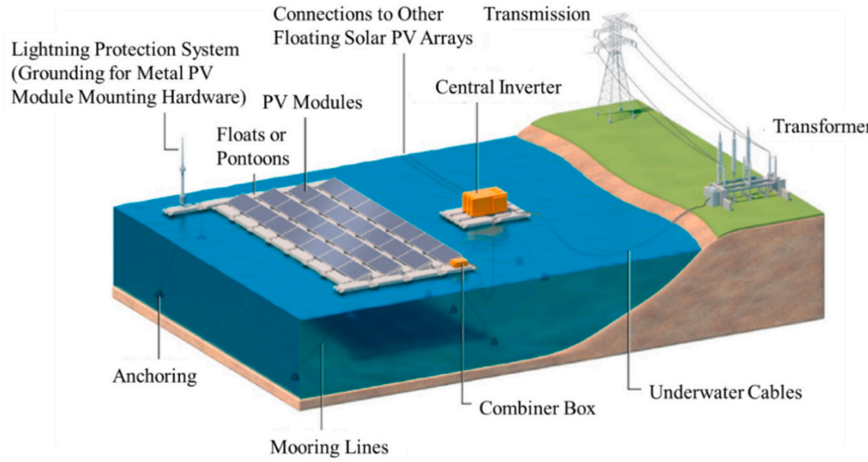


Fig. 15. FPV electrical system illustration (Liu et al., 2024).

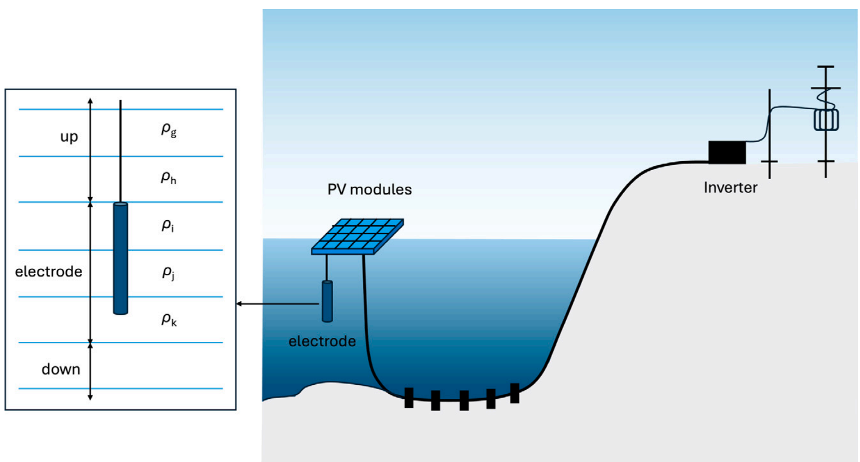


Fig. 16. Illustration of an underwater grounding system for FPV.

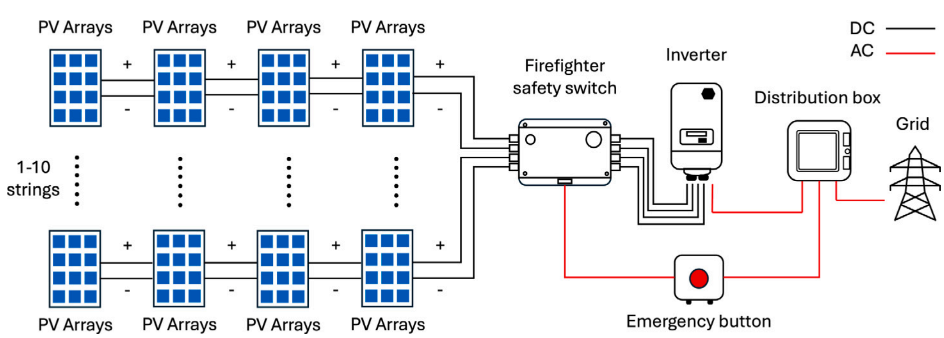


Fig. 17. Diagram of emergency shutdown system.

inverters directly onto the floating platform offers several advantages. A dedicated section of the platform could house the inverters and the other mentioned components instead of additional PV modules. This approach not only reduces energy losses in transmission but also streamlines the system by requiring a single cable to exit the platform. As mentioned in the previous section and speaking of the perspective of large-scale power plants, not only the solar string inverters can be incorporated but also an all-in-one unit (inverter, transformer, and switchgear). This pre-assembled unit is ideal for larger systems generating significant power or connecting to high/medium voltage grids. The mentioned unit is possible to find by many manufacturers such as Ingteam and is similar to a fully equipped power station, the “Full Skid” solution combines solar PV inverters, a step-up transformer, switchgear, and auxiliary components (INGETEAM, 0000).

4. Risks and failures on seas

Offshore FPV platforms face numerous risks and potential failures, both mechanical and electrical, due to the unique environmental stresses of marine conditions. These risks are driven by factors such as wave action, saltwater corrosion, extreme weather, and complex maintenance challenges.

Table 1
Basis for characteristic load in design condition.

Load category	Limit states - Operating design conditions				
	ULS	FLS	ALS		SLS
			Intact structure	Damaged structure	
Permanent			Expected value		
Variable			Specified value		
Environmental	50-year return period	Expected load history	500-year return	1-year return	Specified value
Accidental			Specified value		
Deformation			Expected extreme value		
Prestressing			Specified value		

4.1. Mechanical risks and mitigations

In this section, the most common risks that lead to mechanical failures are discussed. Below is a list of the potential risks and failures.

4.1.1. Structural integrity of the floating platform

Offshore FPV systems must withstand high wave loads, strong tidal currents, and wind pressures that can lead to structural fatigue, bending, or even breakage of the floaters and support frames. A comprehensive guide on the design considerations is given by the recommended practice DNVGL-RP-0584 (Veritas, 2021), Chapters 4 and 5. The general mitigation action is to have the FPV system and its components designed with a defined design life, representing the operational period during which the floating structure and station-keeping system are expected to maintain an acceptable minimum level of safety. Once the design life is established, a limit state design approach is recommended. A limit state is a condition at which a structure or structural component no longer meets the intended design requirements. The following limit states are considered: (a) Ultimate Limit States (ULS) which correspond to the maximum load-carrying capacity of the system, (b) Accidental Limit States (ALS) that relate to survival of the structure under damaged conditions, (c) Fatigue Limit States (FLS) which address failures resulting from cumulative damage under cyclic loading, and (d) Serviceability Limit States (SLS) that are based on project-specific criteria governing the intended use of the structure.

For each of the limit states, a combination of the following load categories is considered: (a) permanent, (b) variable functional, (c) environmental, (d) accidental, (e) deformation, and (f) prestressing loads. The basis for characteristic load in design condition is shown in Table 1.

On the other hand, the structure resistance is evaluated. The effects of corrosion and degradation, which reduce structural durability and impact the properties and geometry of components, should be considered across all limit states. Specifically: (a) ULS, ALS, and SLS conditions should account for the maximum anticipated corrosion and degradation over the system's lifespan, as well as scenarios with minimal degradation if such conditions could impose greater loads on specific components. (b) For FLS conditions, mean corrosion and degradation levels may be used when evaluating material properties and thickness.

A general rule of thumb is to make sure the design load effect S_d does not exceed the design resistance R_d

$$S_d \leq R_d \tag{1}$$

The design load effect and design resistance are obtained after adding the following safety factors: (a) load factor γ_s that multiplies the characteristic load effect S_c, and (b) material factor γ_R that divides the characteristic resistance R_c.

$$S_d = S_c \gamma_s \tag{2}$$

$$R_d = \frac{R_c}{\gamma_R} \tag{3}$$

Example of load factors used for floating platform is shown in Table 2.

Guidance on material factors for the ULS and FLS of metallic and composite materials can be found in various international and local standards. These material factors can also be derived through physical testing. For further details, refer to EN1990-2002 Annex A1, DNVGL-OS-C101 Chapter 2 for steel materials, and DNVGL-ST-C501 Appendix E for composite materials. Material factors for aluminum are available in EN 1999-1-1. An example of the material factor for steel structures is shown in Table 3 for the different limit states.

4.1.2. Mooring and anchoring failures

Mooring and anchoring systems in offshore floating PV platforms are subject to complex environmental forces, and an uneven distribution of these forces can lead to critical peak loads. When peak loads occur, they can overload individual anchors, causing excessive strain that may lead to failure. This can result in snapped mooring lines or even detachment of floats from their attachment points, creating a domino effect where failure in one area increases stress on adjacent lines and anchors. To prevent such failures, redundancy in mooring lines is crucial. This ensures stability under varying environmental conditions, such as waves and winds from different directions, by distributing forces more evenly and allowing the system to maintain integrity even if one line or anchor fails.

As described in Section 4.1.1 for the structural integrity of the floating platform components, a similar technical analysis for the load effects considering the different limit states and safety factors is needed to ensure the durability and safety of the mooring and anchoring system throughout the design life of the project. A comprehensive guide is given by DNVGL-RP-0584 (Veritas, 2021), Chapter 6.

4.1.3. Marine growth - under water

The marine growth on the floating structure and the mooring lines can hinder the buoyancy and hydrodynamics of the installed platforms. In simple words: (a) The marine growth adds more weight to the floating structure. (b) It changes the geometry of the platform and mooring and hence it changes the expected drag forces acting upon them. and (c) It changes the mooring line weight properties thus it changes the mooring line response to loads. Therefore, marine growth has to be considered in the design and the technical analysis of the project. Fig. 18 shows an example from offshore renewable energy projects. Furthermore, removal of excessive marine growth has to be incorporated in operation and maintenance procedures.

4.2. Electrical risks and mitigations

The marine environment poses a challenge for PV installations offshore. Below is a list of the potential electrical risks and failures.

4.2.1. Corrosion of PV panels and fittings

Offshore PV systems face issues with electrochemical corrosion at frame-bolt connection points. This can be mitigated through the following approaches: (a) Ensure that the oxide film on PV module frames is at least 15 μm thick (Trina Solar, 2024), increase the thickness of the galvanised layer on PV brackets, and apply a specialised insulating coating to mounting bolts. This prevents galvanic corrosion by

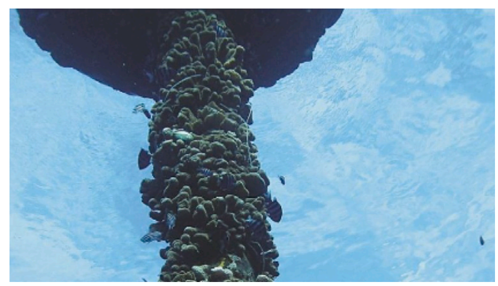
Table 2
Load factor γ_s for each load category for different limit states.

Load category	Limit states - Load factors γ_s				
	ULS	FLS	ALS		SLS
			Intact structure	Damaged structure	
Permanent	1	1	1	1	1
Variable	1	1	1	1	1
Environmental	1.55	1	1.15	1.15	1
Accidental	1	1	1	1	1
Deformation	1	1	1	1	1
Prestressing	1.1	1	1.1	1.1	1

Table 3
Material factor γ_R for steel for different limit states.

Limit states - Example of material factor γ_R often used for steel				
ULS	FLS	ALS		SLS
		Intact structure	Damaged structure	
1.15	1	1	1	1

(a) Marine growth on individual floaters [62].



(b) Marine growth on mooring lines [63].

Fig. 18. Marine growth examples.

inhibiting the migration of metal ions in seawater. (b) Once installation is complete, protect connection points by applying a protective coating, such as a corrosion-resistant paint, to shield these areas from seawater exposure.

4.2.2. Insulation breakdown

In offshore floating PV platforms, MC4 connections are particularly vulnerable to insulation breakdown due to harsh marine conditions. The constant exposure to salt spray, high humidity, and UV radiation accelerates the degradation of insulation materials, compromising their ability to prevent electrical leakage. Over time, saltwater intrusion can penetrate the insulation, leading to corrosion within the connectors and increasing the risk of short circuits and electrical faults, see Fig. 19. This not only threatens the operational efficiency of the PV system but also poses safety hazards. To mitigate these issues, it is essential to use marine-grade MC4 connectors with enhanced UV and saltwater resistance and to apply regular maintenance checks to detect and replace degraded connections before they fail.

4.2.3. Inverter and transformer failures

Inverters and transformers are vulnerable to various environmental factors, including salt spray, humidity, temperature extremes, and dust accumulation, which can lead to corrosion, insulation degradation, and reduced efficiency. In salt-laden air, cooling systems can clog or fail, causing component overheating. Salt-laden can cause corrosion of the copper or aluminium used for the conductors of the winding and the terminals, and also of the silicon steel core and the carbon steel used for the clamping structure. Moisture is the enemy of any electrical equipment, and the effects of moisture are a much greater threat in offshore applications. A moisture environment reduces the dielectric properties of the insulation, which is especially problematic for the transformer coils. Surface moisture can lead to tracking over insulation surfaces, particularly in the case of medium voltage transformers. Chemical contamination, many different chemicals are in use on drilling rigs and ships, and these chemicals can be damaging to the transformer insulation and conductors. For example, exhaust gases from engine-driven generators may enter the transformer enclosure, where they can leave carbon deposits on coils which will lead to tracking and eventual damage to the transformer insulation system. One of the potential risks on electrical equipment is the movement of floating platforms caused by waves and currents which transmits vibrations to inverters and transformers. Over time, this constant motion can lead to mechanical stress and wear on sensitive electrical connections and mountings (Derek Foster, 2021).

The consequences of transformer failures in offshore applications can be much more serious than similar failures in industrial and commercial applications. Failures may result in significant costs associated with lost production and transformer repair or replacement costs. Additionally, such failures will involve serious safety issues, such as the possibility of fire, explosion, smoke emission and toxic fume emission. Due to concerns regarding leaks from liquid-filled transformers and the need to contain the leaking liquid to prevent pollution and minimise the risk of fire – a major concern for offshore applications – dry-type transformers, either VPI (vacuum pressure impregnated) or cast coil (cast resin) are the preferred option for offshore applications (Derek Foster, 2021).

One of the most common technical issues with marine solar inverters is inefficiency in power conversion, which can lead to a significant loss of energy. This can occur due to several reasons, including poor installation, subpar quality of the inverter, or the presence of dust and debris on the solar panels. These common technical issues with marine solar inverters and Transformers can pose significant problems, but they can be fixed with proper maintenance and care. The key is to ensure regular inspection and preventive maintenance to


(a) Salt accumulation on MC4 connection.

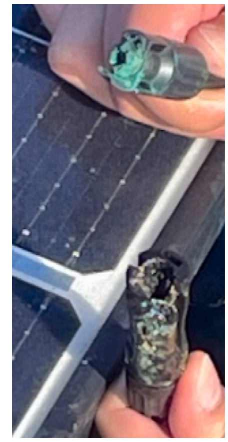

(b) Insulation breakage of MC4 connection.

Fig. 19. MC4 connection failures.

detect and fix problems early, thus ensuring the smooth running of the system (Gorillapowersolutions, 0000).

4.2.4. Lightning strikes and grounding failures

Offshore platforms face a heightened risk of lightning strikes, and the humid, saline environment can compromise the integrity of grounding systems. Insufficient or corroded grounding can result in severe damage to inverters and transformers during a lightning strike, leading to surges and permanent damage to electrical components. Implementing robust grounding and surge protection measures specifically designed for marine conditions, along with regular inspections, helps minimise the risk of lightning-induced failures.

4.2.5. Fouling - above water

Bird droppings pose a significant challenge for solar PV panels on offshore floating platforms, as these panels are often situated in open water environments that attract seabirds, as shown in Fig. 20. Droppings can create dense, localised shading on the panels, significantly reducing light absorption and, in turn, power output. Over time, this accumulation can cause “hot spots” due to uneven heating, potentially damaging the photovoltaic cells and further decreasing efficiency. The impact is especially pronounced offshore, where maintenance access is limited, making regular cleaning more challenging. To address this, some floating PV systems incorporate self-cleaning coatings or robotic cleaning systems to minimise the impact of bird fouling and maintain optimal panel performance.

5. Wind loads on FPV

Wind loads on floating photovoltaic (FPV) systems present a substantial engineering challenge due to the unique conditions in which these systems operate. Deployed on water bodies, FPV systems are exposed to dynamic wind conditions, generating complex aerodynamic forces that affect both structural integrity and operational efficiency. Accurately understanding these wind loads is essential to the design and longevity of FPV installations (Rosa-Clot and Tina, 2017).

5.1. Physical description of the problem

In land-based and rooftop photovoltaic (PV) systems, wind loads can significantly impact both structural stability and energy efficiency. Previous studies demonstrate that wind forces exert uplift and drag forces on solar panels, which may compromise the stability of mounting structures if not properly accounted for Chung et al. (2019), Stathopoulos et al. (2014). Panel orientation, tilt angles, and proximity to adjacent structures are critical factors influencing these aerodynamic loads, and careful design is required to mitigate potential damage (Chou et al., 2019; Aly and Bitsuamlak, 2013). The layout of PV arrays can also create sheltering effects, reducing wind loads on downstream panels and underscoring the importance of array configuration in PV system design (Chung et al., 2019; Stathopoulos et al., 2014).

Offshore FPV systems, however, introduce additional complexities in wind load dynamics due to their floating environment and exposure to water surface motions. Unlike static land-based structures, offshore FPV systems experience dynamic forces arising from the combined influences of wind, waves, and tidal motions. For instance, as illustrated in Fig. 2, which depicts tilting solar panels on a floating platform, the primary aerodynamic forces acting on FPV systems include drag and lift forces, both of which are influenced by the wind direction, wave angle, and the tilt angle (Su et al., 2020a; Ikhennicheu et al., 2021b).

When wind interacts with the FPV structure’s surface, it generates a pressure differential, resulting in both drag and lift forces. The drag force, which resists the movement of the panels, is a function of the square of the wind speed and the frontal area exposed to the wind. In contrast, lift forces can induce upward or downward motion in the panels depending on the angle of attack and the prevailing wind profile (Vo et al., 2021a; Song et al., 2023a). These forces are further complicated by the platform’s response to wave-induced motions, which may result in oscillations or tilting, amplifying the wind loads experienced by the system.

5.2. Prediction methods

Since the 1980s, wind tunnel testing has been a primary approach for studying the effects of wind on solar panel installations. In early work, Radu et al. (1986) performed wind tunnel tests on an array of solar panels mounted atop a five-story residential building, observing a reduction in mean force coefficients due to sheltering effects provided by the building and the first row of solar collectors. Similarly, Peterka et al. (1987) conducted a series of wind tunnel tests on heliostat arrays, examining wind load reductions resulting from sheltering by neighbouring upwind panels and the use of protective barriers. S. et al. (2001) further studied wind effects by testing solar panel arrays mounted on an industrial flat-roofed building, focusing on the impact of panel positioning on wind loads affecting both the roof cladding and the panel support structure. Kopp et al. (2002) observed the significant impact of vortex shedding and turbulent wind flow on the aerodynamic torque loads of solar arrays in their wind tunnel studies. Additionally, Hosoya et al. (2008) examined parabolic trough solar collectors, providing comprehensive data on force, moment, and local pressure coefficients. Aly and Bitsuamlak (2014) investigated the wind loads on solar panels installed on sloped residential roofs, adding insights

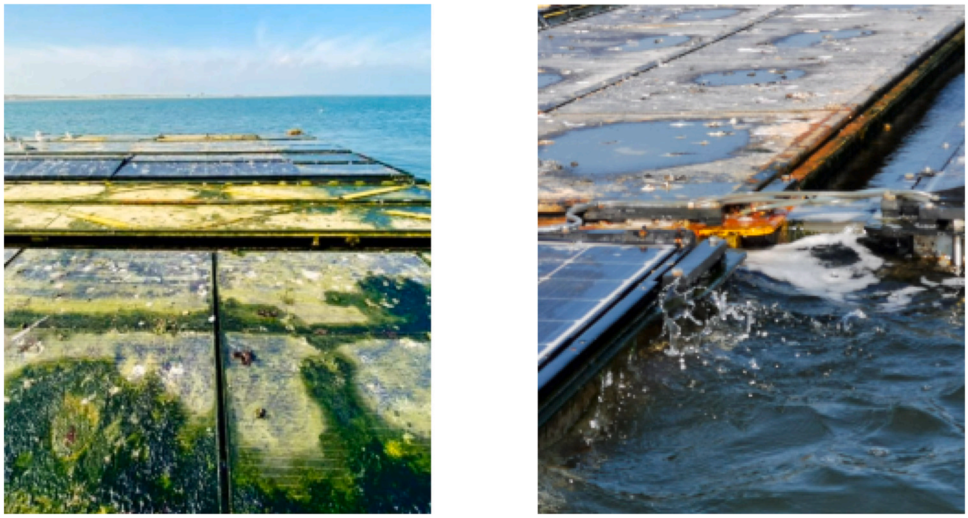


Fig. 20. Bird guano accumulation few months after installation in North sea (Hugo LARA, 2021).

into the effects of roof inclination on aerodynamic loads. Warsido et al. (2014) studied the influence of spacing parameters on the wind loads of the PV array.

While these studies have deepened understanding of wind loads on land-based and rooftop PV systems, only limited experimental work has addressed FPV systems in wind tunnel settings. Notably, Choi et al. (2022) conducted wind tunnel tests on an FPV model, positioning it on a rotating platform to simulate various wind directions relative to the PV array. This setup allowed for controlled adjustment of wind direction without introducing floating motion, enabling the accurate measurement of wind loads from multiple angles. However, this method lacks the representation of the complex motions that FPV systems undergo in real sea-state conditions, where floating motion significantly influences the aerodynamic forces.

In addition to experimental methods, mathematical models, including analytical and numerical approaches, offer valuable tools for predicting wind loads and analysing FPV behaviour in marine and ocean environments.

5.2.1. Analytical methods

In the analytical approach to modelling wind loads on FPV systems, wind forces are generally assumed to act in a steady state (Ikhennicheu et al., 2021b; Song et al., 2023a). The steady wind load acting along the wind direction on a floating structure can be expressed using the following formula, as described in Anon (2019):

$$F_{wind} = \frac{1}{2}\rho V^2 A C_d C_s \tag{4}$$

where ρ is the flow density, A is the area exposed to the flow, V denotes the wind velocity, C_s and C_d are the sheltering coefficient and drag coefficient, respectively, which depend on factors like the object's shape, surface roughness, and Reynolds number.

For FPV systems, wind loads are considered separately for both the PV panels and the floater freeboard. The drag coefficients used in these calculations are sourced from general specifications (Anon, 2019), which, while not specifically developed for floating solar applications, apply to FPV systems due to their suitability for any fixed structure under steady wind conditions. Depending on wind direction, the projected area of each component exposed to wind loads changes, and with it, the effective drag coefficient. These coefficients, as defined in Anon (2019), account for the object's shape and wind angle of attack.

While the analytical method provides a valuable basis for preliminary wind load predictions, it is important to note that comprehensive numerical simulations and experimental testing are recommended to refine these coefficients for the unique geometry and dynamic conditions of FPV installations.

5.2.2. Computational fluid dynamics (CFD)

Unlike the steady-state assumptions used in analytical methods, real-world wind conditions often exhibit complex, turbulent flows that require advanced modelling techniques for accurate load prediction. Computational Fluid Dynamics (CFD) simulations are widely used to address these complexities by analysing surface pressure patterns and calculating the lift coefficients for FPV systems (Korkmaz and Sahin, 2023). These simulations commonly utilise Reynolds-averaged Navier–Stokes (RANS) equations to model the flow behaviour. Among the available turbulence models, the shear stress transport (SST) model (Menter, 1992, 1994) has been extensively applied in aerodynamic studies, including wind load prediction for FPV systems (Su et al., 2020a; Choi et al., 2023). The SST model integrates the strengths of both the $k-\varepsilon$ and $k-\omega$ models, offering enhanced accuracy in capturing turbulent flows.

The governing equations of viscous fluid motion include both the continuity and Navier–Stokes equations, which are applicable to laminar and turbulent flows. For turbulent flow, however, each velocity and pressure term in these equations varies over time due to fluctuations. The equations are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{5}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}^T) = -\nabla P - (\mathbf{g} \cdot \mathbf{x})\nabla \rho + \nabla \cdot (\mu \nabla \mathbf{u}) \tag{6}$$

Where, $\mathbf{u} = (u_1, u_2, u_3)$ represents the velocity vector components in the $\mathbf{x} = (x_1, x_2, x_3)$ directions, respectively and the subscripts i and j in the following equations are indices denoting the spatial dimensions (1, 2, 3) in 3D space. ρ denotes the fluid density, t is time, P represents the pressure in excess of the hydrostatic part, $\mathbf{g}$ refers to gravity acceleration, and μ denotes dynamic viscosity.

In the $k-\omega$ SST model, turbulence is characterised by two main parameters: the turbulence kinetic energy, k, and the specific dissipation rate, ω, formulated as follows:

$$\frac{Dk}{Dt} = T_{ij}\frac{\partial u_i}{\partial x_j} - \beta^* \omega k + \frac{\partial}{\partial x}((\frac{1}{Re} + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}) \tag{7}$$

$$\frac{D\omega}{Dt} = \frac{\gamma}{\nu_t} T_{ij}\frac{\partial u_i}{\partial x_j} - \beta\omega^2 + \frac{\partial}{\partial x_j}((\frac{1}{Re} + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}) + 2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{8}$$

where T_{ij}, the turbulent shear stress tensor, is defined as:

$$T_{ij} = \nu_t(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \frac{2}{3}k\delta_{ij} \tag{9}$$

The blending function F_1 in the SST model, used to smoothly transition between $k-\varepsilon$ and $k-\omega$ regions, is defined by:

$$F_1 = \tanh(arg_1^4) \tag{10}$$

where arg_1 incorporates the distance d to the nearest wall boundary, Reynolds number Re, and other factors as detailed in Yusuf et al. (2020).

The SST model's eddy viscosity ν_t is calculated as

$$\nu_t = \frac{a_1 k}{\max(a_1\omega, \Omega F_2)} \tag{11}$$

where Ω is the vorticity magnitude, $a_1 = 0.31$, and F_2 is a second blending function, capturing boundary layer behaviour. Constants for the inner and outer regions (associated with $k-\omega$ and $k-\epsilon$ models, respectively) are blended through F_1, allowing the SST model to adapt to both near-wall and free-stream flow conditions, essential for accurate aerodynamic predictions.

By solving these coupled Navier–Stokes equations, CFD simulations provide detailed insights into wind loads by capturing the complex interactions of transient, turbulent flows around FPV systems. The Navier–Stokes equations govern the behaviour of viscous fluid flows by linking the momentum and continuity equations, allowing CFD to model flow velocities and pressure distributions accurately over the surfaces of the FPV structure. This pressure data, obtained from solving the Navier–Stokes equations, translates into surface forces that act on different parts of the FPV system, such as the PV panels and floating structures. In this context, the shear stress transport (SST) turbulence model plays a critical role in enhancing the accuracy of these predictions by providing realistic representations of the turbulent boundary layers and flow separation that occur in aerodynamic conditions around the FPV setup.

The pressure field derived from the Navier–Stokes equations is integral for computing the lift and drag forces acting on FPV systems under various wind conditions. Specifically, the pressure differential across the surfaces, calculated as a result of the resolved flow field, enables the accurate prediction of the aerodynamic loads. This capability is especially useful for estimating the load variations due to changes in wind speed, direction, and turbulence, which are challenging to capture through analytical methods.

Moreover, CFD's adaptability extends to simulating wave-induced loads, where the water flow is modelled in a similar manner, allowing the study of combined wind and wave effects on the floating system (as discussed in Section 6.2). However, the comprehensive nature of CFD comes with high computational costs, often making it best suited for advanced design stages where detailed analysis and precision are prioritised oversimplified assumptions.

5.3. Future research directions

Addressing the unique challenges posed by wind loads on FPV installations requires targeted research efforts to improve both understanding and management. The following directions outline key areas for advancing wind load prediction and mitigation for FPV systems.

5.3.1. Hybrid computational modelling

Developing advanced computational models is essential to accurately predict wind loads on FPV systems. Current models often rely on simplified assumptions that may not fully capture the complex interactions between wind, waves, and floating structures, and full-scale three-dimensional (3D) CFD simulations demand extensive computational resources. A promising area of research lies in hybrid models that integrate CFD with machine learning (ML) techniques. Machine learning algorithms, such as Gaussian Processes (Rasmussen, 2004) and neural networks (Krizhevsky et al., 2017), could enhance CFD by identifying complex patterns in wind load data and enabling real-time predictions. This integration could reduce computational costs while improving accuracy, especially for modelling transient and turbulent flow conditions.

5.3.2. Field testing and validation

While computational models are valuable for wind load predictions, field validation is essential for ensuring model accuracy. Current experimental setups, such as wind tunnel tests (Choi et al., 2022), do not fully replicate the complex conditions FPV systems face in open water environments. Establishing dedicated FPV test sites would enable the collection of wind load data under diverse real-world conditions, such as varying wave heights, wind speeds, and currents. These empirical data would not only validate computational models but also support the refinement of mitigation strategies and design adjustments.

5.3.3. Interdisciplinary approaches

Understanding the dynamic response of FPV systems to wind loads is crucial for ensuring their structural integrity. Research should focus on the effects of platform motion, such as pitch, roll, and surge, on the aerodynamic forces acting on PV panels (Song et al., 2023a). Investigating potential resonance phenomena and load amplification under variable wind conditions could reveal critical vulnerabilities in structural design.

Tackling the challenges of wind loads on FPV systems requires an interdisciplinary approach, integrating insights from aerodynamics, structural engineering, marine engineering, and environmental science. Future research should encourage collaboration among these fields to develop comprehensive solutions that account for the complex, multifaceted nature of FPV systems and the environments in which they operate (Vo et al., 2021b).

6. Wave loads on FPV

Wave loads on FPV systems introduce significant engineering challenges due to the dynamic marine environment in which these systems operate. Designed to function on the water's surface, FPV installations are subject to complex wave forces that vary with changing sea states. Accurate modelling and prediction of these forces are essential for maintaining the stability and functionality of FPV systems (Kaymak and Şahin, 2021b). This section provides an overview of wave load dynamics on FPV structures, followed by a review of existing prediction methods and future research directions.

6.1. Physical description of the problem

As waves propagate, they exert forces on the submerged portions of the floating platform, resulting in both vertical and horizontal motions (Song et al., 2023a). These forces vary based on parameters such as wave height, wave period, structural response, and the geometry of the FPV platform. For instance, higher waves can generate substantial upward and downward forces, affecting the stability and integrity of the FPV system (Magkouris and Belibassakis, 2024). These wave characteristics can be predicted by models and simulations, as demonstrated in Korkmaz et al. (2023).

The dynamic response of FPV systems to wave loads is characterised by their ability to oscillate with the water's surface, leading to complex motion patterns that include both translational movements (surge, heave, and sway) and rotational movements (yaw, pitch, and roll), as shown in Fig. 21. These responses must be accounted for during the design process, as they influence system stability and longevity. Studies have shown that the natural frequency of the floating structure is crucial in determining its response to wave action. If the frequency of incoming waves aligns with the natural frequency of the system, resonance can occur, potentially leading to excessive motions and accelerated structural fatigue (Song et al., 2023a).

The hydrodynamic characteristics of FPV systems also vary widely depending on design and configuration. For instance, twin-hull structures may respond differently to wave loads compared to single-hull designs due to variations in buoyancy distribution and hydrodynamic interactions between hulls (Magkouris and Belibassakis, 2024; Magkouris

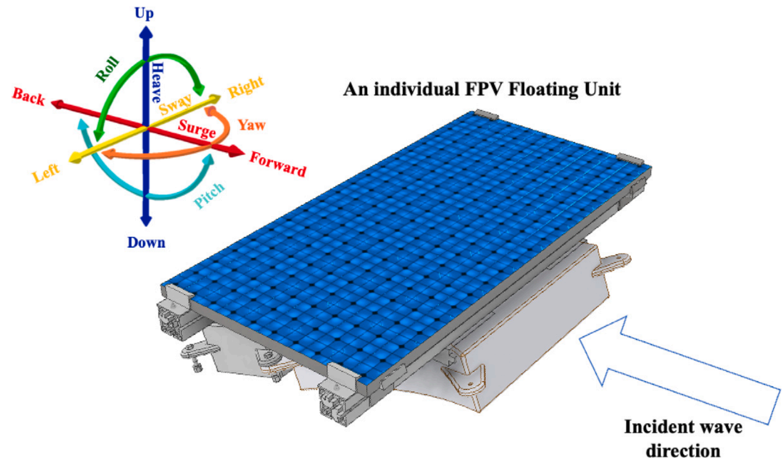


Fig. 21. Schematic illustration of the six degrees of freedom motions of an FPV floating unit interacting with waves.

et al., 2021). Research has indicated that the shape and arrangement of the floating platform can significantly influence its performance under wave conditions, with certain configurations providing greater stability and reduced motion response (Magkouris et al., 2021).

In addition to structural impacts, wave-induced motions can affect the FPV system's energy generation efficiency. The movement of the floating platform can alter the angle of incidence of sunlight on the photovoltaic panels, potentially reducing energy capture and output (Vo et al., 2021a; Huang et al., 2024). Therefore, a comprehensive understanding of the hydrodynamic behaviour of FPV systems under wave action is essential not only for structural integrity but also for optimising energy performance.

Wave loads on FPV systems are a critical factor influencing their design, stability, and operational efficiency. The interaction between waves and floating structures can lead to complex hydrodynamic responses that must be thoroughly understood to ensure the resilience and performance of these FPV installations.

6.2. Prediction methods

Accurate predictions of wave loads are crucial for understanding the interactions between waves and FPV systems, as these predictions impact both operational efficiency and structural integrity. A range of analytical, numerical, and experimental methods are used to predict wave loads, each with its own strengths and limitations.

6.2.1. Analytical method

The Morison equation, proposed by Morison et al. (1950), remains one of the most commonly applied empirical formulas for estimating wave loads on offshore structures. This equation calculates wave forces by combining drag and inertia components, making it suitable for predicting wave loads on submerged or partially submerged structures. Diffraction theory is another approach frequently used in wave load prediction. Kriebel's work (Kriebel, 1990, 1992, 1998) advanced diffraction theory by calculating second-order wave forces and applying nonlinear diffraction theory to offshore applications. Similarly, Boo (2006) analysed the harmonic components of wave forces on floating structures using a Faltinsen–Newman–Vinje (FNV) model to account for Stokes wave effects.

In addition, potential flow theory assumes an idealised fluid that is incompressible, uniform, and irrotational, with viscosity neglected. This method is commonly used in both frequency-domain and time-domain analyses to assess the wave-structure interactions of floating systems. Frequency-domain analyses are suited for steady-state response evaluation to periodic wave inputs, while time-domain simulations capture transient responses to more irregular wave patterns (Song et al., 2023a).

In time-domain potential flow theory, the total velocity potential in the fluid field is decomposed into incident potential ϕ_I, diffraction potential ϕ_d, and radiation potential ϕ_r.

$$\phi_{(x,y,z,t)} = \phi_I + \phi_d + \phi_r \tag{12}$$

The velocity potential can be solved by applying Laplace's equation, with boundary conditions to ensure solution uniqueness:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{13}$$

$$\frac{\partial\phi}{\partial z} = 0, z = -h \text{ or } z = -\infty \tag{14}$$

$$\frac{\partial^2\phi}{\partial t^2} + g\frac{\partial\phi}{\partial z} = 0, z = 0 \tag{15}$$

$$\frac{\partial\phi}{\partial n} = \sum_{j=1}^{6} \upsilon_j f_j(x,y,z) \tag{16}$$

$$\lim_{R\to 0}\phi_d = 0, \lim_{R\to 0}\phi_r = 0 \tag{17}$$

where h is the water depth, n represents the outward unit normal vector, υ is the velocity vector of the structure's displacement, the function $f_j(x,y,z)$ represent basis functions chosen to satisfy the boundary conditions of the potential flow problem capturing the spatial variation of the velocity potential in the domain, and R is the horizontal distance from the structure.

Once the velocity potential is obtained, the pressure distribution on the wet surfaces of the FPV structure can be derived using the linearised Bernoulli equation:

$$p = -\rho\frac{\partial\phi}{\partial t} - \rho g z = -\rho(\frac{\partial\phi_I}{\partial t} + \frac{\partial\phi_D}{\partial t} + \frac{\partial\phi_R}{\partial t}) - \rho g z \tag{18}$$

The total wave force $\vec{F}$ is then calculated by integrating the pressure across the structure's surface, combining contributions from still water forces $\vec{F}^{(S)}$, Froude–Krylov forces $\vec{F}^{(I)}$, diffraction wave force $\vec{F}^{(D)}$, and radiation wave force $\vec{F}^{(R)}$:

$$\vec{F} = \oint_S (p\cdot\vec{n})\cdot ds = \vec{F}^{(S)} + \vec{F}^{(I)} + \vec{F}^{(D)} + \vec{F}^{(R)} \tag{19}$$

These analytical methods can effectively predict both linear and some nonlinear wave load effects, but they are limited in their ability to simulate the complex motions of floating structures. For FPV systems, where interactions between wave forces and floating motions are significant, analytical methods alone are often insufficient. Consequently, numerical models (e.g., CFD) and physical experiments are typically required for more comprehensive analysis.

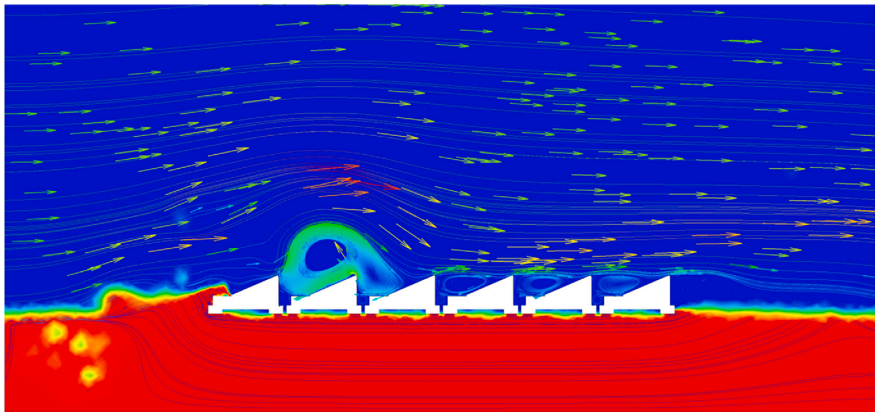


Fig. 22. CFD simulation of an FPV array on a lake with wind and hydrodynamic loadings Mut et al. (2024).

6.2.2. CFD

The wave loads calculated by CFD using the $k-\omega$ model follow the same equations as Eqs.(5)–(11) . Previous research shows that CFD is widely used for simulating wave interactions with floating offshore renewable energy structures, both in mesh-based Eulerian methods (Chen, 2015; Ding, 2024) and particle-based Lagrangian approaches (Lyu et al., 2022). Additionally, hybrid models, such as the Particle-In-Cell (PIC) model, have been developed to simulate complex wave-structure interactions in offshore environments (Chen et al., 2019; Ding et al., 2024).

However, there is currently limited evidence for the application of CFD in predicting wave loads specifically for FPV systems; most CFD research has focused on predicting wind loads on FPVs (Su et al., 2020b; Choi et al., 2023). Recent work by Mut et al. (2024) has begun to address this gap by using an ANSYS CFD model to simulate an FPV array on a lake in a 2D domain, as shown in Fig. 22. This limited application may be due to the high computational costs of simulating full 3D wave-structure interactions with CFD. Nonetheless, nonlinear wave loads are known to be significant under severe wave conditions, as demonstrated by Chen et al. (2018). Furthermore, Ding et al. (2023) emphasised the importance of accurately modelling viscosity to predict floating structure responses, which directly impacts the accuracy of both wind and wave load predictions. Analytical and potential flow theory methods are generally insufficient for capturing these complex interactions and nonlinearities.

6.2.3. Physical methods

Physical wave tank testing is one of the most reliable methods for predicting wave loads on FPV systems. This approach involves creating scaled models of FPV structures and subjecting them to controlled wave conditions in a laboratory setting. Wave tank tests allow researchers to observe the hydrodynamic behaviour of floating structures under various wave heights, periods, and directions. Studies have demonstrated that wave tank experiments can effectively capture the dynamic response of floating structures, including the effects of wave-induced forces on mooring systems and the overall stability of the FPV installation (Song et al., 2023a; Kang et al., 2023). The advantages of wave tank testing include the ability to replicate specific environmental conditions and the opportunity to gather empirical data on the performance of different design configurations. However, it is important to note that scaling effects must be carefully considered, as the behaviour of scaled models may not always perfectly represent full-scale structures.

In addition to laboratory experiments, field tests are crucial for validating the performance of FPV systems under real-world conditions. These tests involve deploying FPV installations in their intended operational environments and monitoring their response to actual wave conditions. Field tests provide valuable insights into the long-term performance and durability of FPV systems, as they account for the complexities of environmental interactions that may not be fully captured in controlled settings (Kim et al., 2020; Wang and Lund, 2022). Field testing can also help identify potential issues related to wave loads, such as structural fatigue and mooring line tensions, which are critical for ensuring the reliability of FPV systems over time. For example, the dynamic responses of floating structures under varying wave conditions can be monitored using sensors, allowing for real-time data collection and analysis.

6.3. Future research directions

Further research is essential to deepen our understanding of wave loads on FPV systems and to develop models that improve their resilience and efficiency. The following subsections outline key areas for future exploration: advancements in numerical modelling, analysis of hydroelastic responses, and long-term wave load predictions.

6.3.1. Numerical modelling development

The complexity of wave-structure interactions on FPV systems calls for advanced numerical modelling methods capable of capturing detailed hydrodynamic effects. While current CFD models are widely used, they are computationally intensive, particularly for simulating full 3D wave-structure interactions in real time. To address this challenge, future research could focus on developing hybrid models that combine traditional CFD with data-driven machine learning (ML) techniques. By training ML algorithms on CFD-generated datasets, researchers could create surrogate models capable of providing rapid load predictions without relying entirely on resource-intensive simulations. Tang et al. (2024) introduced a new ML-based reduced-order model, the Stokes-Gaussian Process model, which rapidly predicts nonlinear wave loads on offshore wind turbine foundations. While this model currently applies only to wave interactions with static structures, future developments could extend it to FPV systems, enabling real-time or near-real-time assessments of wave-induced loads.

6.3.2. Hydroelastic response analysis

Due to the large structural dimensions of FPV systems, understanding their hydroelastic responses to wave loads is crucial. Future research should examine how structural flexibility impacts the dynamic behaviour of FPV systems under wave action, including how different design configurations and materials affect hydroelastic response and overall stability (Tay, 2023). Huang and Li (2022) utilised a CFD model to predict the fully nonlinear hydroelastic performance of horizontal plates, a method that could be adapted for FPV systems. Expanding research in this area could lead to design guidelines that optimise the balance between structural integrity and energy generation efficiency.

6.3.3. Long-term wave loads

Long-term exposure to wave forces can lead to structural degradation and fatigue, especially in offshore FPV installations subjected to continuous cyclic loading. While existing models estimate wave loads over short timescales, further research is needed to predict the cumulative effects of wave forces across the lifespan of FPV systems. Future studies should aim to develop models that incorporate both short-term peak loads from extreme waves and long-term cyclic loads from regular wave action.

Field testing of long-term wave effects is also essential. Deploying sensors on FPV systems in operational environments would provide valuable data on wave-induced loads, allowing researchers to validate long-term predictions and adjust models for greater accuracy. This empirical data could inform improvements in materials and structural designs to enhance the lifespan and reliability of FPV systems under prolonged wave exposure (Kim et al., 2020; Wang and Lund, 2022).

7. Structural assessments

7.1. Fatigue assessment

FPV installations experience continuous fluctuating loading through a combination of wave-structure interactions, wind-induced oscillations, and changing environmental conditions. These complex loading mechanisms can significantly impact both the structural and mooring components of the system. The wave-structure interaction plays a critical role in determining the fatigue loading patterns. When the characteristic dimension (D) of the structural elements is less than 5% of the wavelength (λ), the response is dominated by Morison drag and inertia forces (Chakrabarti, 1987). For elements where D/λ exceeds 0.05, the loading is primarily influenced by diffraction and radiation forces.

The connection points between the floating modules have been identified as particularly vulnerable to fatigue loading. Experimental studies of a 5 MW coastal FPV installation have quantified the extreme loading conditions, with the outermost modules experiencing heave motions up to 5 cm (Zhang et al., 2024a). The response spectra for these systems demonstrate narrower frequency bands under higher wave conditions, indicating distinct loading patterns that require specific fatigue considerations (Trapani and Redón Santafé, 2015).

Material selection plays a significant role in the fatigue performance of FPV systems. Fibre-reinforced polymer (FRP) members have shown superior fatigue resistance, with a Young's modulus of 30.76 GPa and a tensile yield strength of 415.3 MPa (Lee et al., 2014). These findings have been validated through extensive testing of high-durability materials under cyclic loading conditions (Kim et al. 2020). In contrast, the use of high-density polyethylene (HDPE) for the floating modules, while allowing compliance with wave motions, introduces additional considerations for the design of the connections (Dai et al., 2020a).

The wave-induced motions of the FPV system can create complex fatigue loading patterns. Recent hydro-elastic analyses have demonstrated that the wave-structure interactions produce significant non-linear effects, particularly at the connection points (Xu and Wellens, 2022). While flexible connections between modules can reduce maximum yaw motions, they may also increase local stress concentrations (Cazzaniga et al., 2018).

The mooring system fatigue also demands particular attention due to the dynamic loading characteristics. Time-domain analyses have revealed that light mooring systems (2.2 kg/m) experience dangerous peak loads, while medium-weight systems (5.2 kg/m) demonstrate more stable behaviour with forces below 5 kN (Zhang et al., 2024a). These findings build upon earlier work by Ikhennicheu et al. (2021a), who established analytical methods for determining fatigue loads in various environmental conditions.

The combination of mechanical fatigue and environmental exposure, particularly in tropical environments, can lead to accelerated degradation and unique challenges. Liu et al. (2018) documented the compounding effects of temperature variations and mechanical stresses, while Yu et al. (2021) quantified the dynamic responses under combined environmental actions.

While current numerical approaches combining frequency and time-domain analyses have advanced the understanding of fatigue mechanisms, traditional methods may underestimate the cumulative damage in floating solar applications. The work of Friel et al. (2020) highlights the need for specific consideration of multi-body interactions in fatigue assessment, particularly for large FPV arrays where the dynamic responses become more complex.

In summary, the fatigue considerations in floating offshore solar installations are multi-faceted, involving complex wave-structure interactions, material selection, connection design, mooring system dynamics, and the combined effects of mechanical loading and environmental exposure. A comprehensive, systems-level approach is required to address these challenges and ensure the long-term durability and reliability of these emerging marine renewable energy technologies.

To address the challenges posed by fatigue in floating offshore solar installations, the development of improved numerical methods that can capture multi-scale effects is critical. Current boundary element approaches, while computationally efficient, may not adequately model the local stress concentrations at the connections where fatigue typically initiates. A hybrid analysis framework combining global hydrodynamic analysis with detailed finite element modelling of the critical regions would enable better prediction of fatigue life. Additionally, long-term monitoring of operational installations through strategically placed strain gauges and motion sensors would provide invaluable data for validating and improving fatigue life predictions.

7.2. Extreme environmental loads

FPV systems must be designed to withstand a range of severe environmental conditions, including combinations of waves, wind gusts, currents, and tidal variations. While numerical modelling techniques have advanced to capture complex hydrodynamic interactions, the real-world loading scenarios can exceed design assumptions, posing significant challenges for ensuring the structural integrity and safety of these systems. Time-domain simulations have been used to quantify the extreme loading conditions experienced by FPV installations. These analyses have demonstrated that the wave-induced forces and moments can substantially exceed the wind-induced loads, highlighting the critical importance of accurately capturing the wave-structure interactions (Claus and L'opez, 2023).

The wave-structure interactions under extreme conditions prove particularly challenging, as studies have revealed significant non-linear effects when the characteristic dimensions of the structural elements exceed a certain threshold relative to the wavelength (Xu and Wellens, 2022). This theoretical analysis of wave propagation on hydro-elastic structures has unveiled complex loading patterns that cannot be fully captured by linear theory, building upon earlier work on non-linear waves in floating elastic plates. In coastal installations, ship wakes present an additional challenge. Empirical studies have provided methods for estimating the wake-induced loads, which can combine with the primary wave effects to increase the dynamic responses of FPV systems by approximately 20% (Ikhennicheu et al., 2021a).

Structural verification of the FPV components has demonstrated varying levels of safety margins, with the HDPE floating modules and FRP support beams exhibiting maximum stresses well within their design limits (Claus and L'opez, 2023; Dai et al., 2020b). However, the multi-body interactions within large FPV arrays can significantly influence the extreme loading patterns, as research has shown that the corner modules can experience significantly higher stresses due to complex hydrodynamic and aerodynamic effects (Lee et al., 2022). The installation angle of the FPV system relative to the predominant wave direction can also significantly affect the extreme load response, with

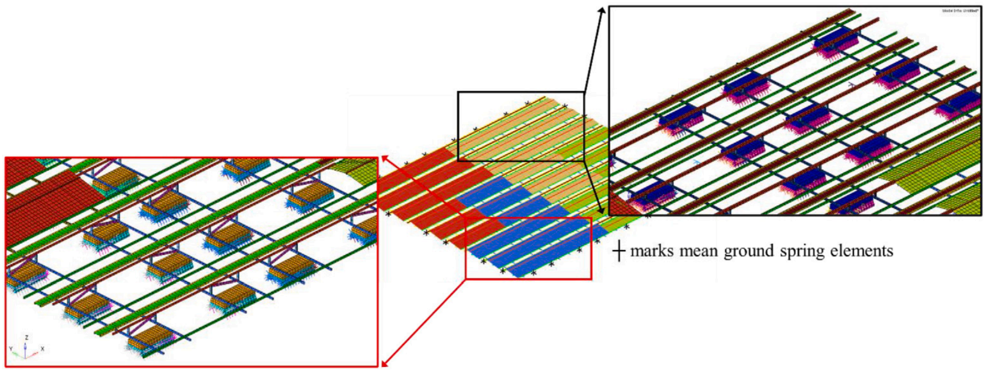
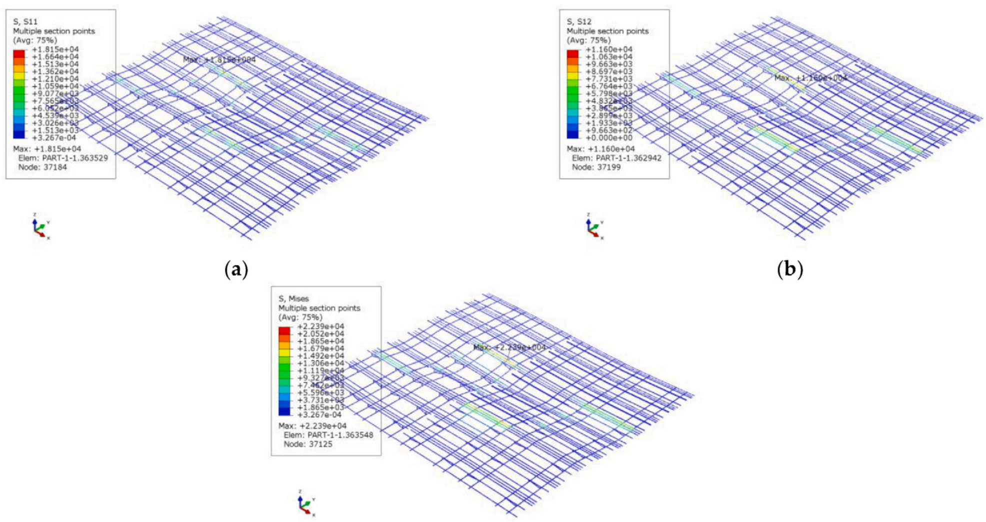


Fig. 23. A typical finite element structural analysis model (Li and Choung, 2022).



(a) (b) (c)

Fig. 24. Stress distribution for a typical analysis case: (a) normal stress; (b) shear stress; (c) von Mises stress (Li and Choung, 2022).

angles greater than 15 degrees from the wave direction reducing the dynamic responses (Yu et al., 2021).

A typical structural analysis model for the floating solar array is presented in Fig. 23, taken from Li and Choung (2022). The key components of the model include the buoys, frame structures, solar modules, hinge joints, and mooring lines. The PE buoys are modelled using solid elements, while the frame structures are represented by beam elements. The solar modules are modelled as elastic shell elements. The floater units are connected using pin-type hinge joint elements, which allow relative rotations between successive units to minimise the generation of bending moments. Kinematic coupling elements are used to bond the buoys and frames to avoid stress concentration at the hinge joints. The fairlead points, where the mooring lines are tied, are supported by grounded spring elements with a very small stiffness to avoid rigid body motion in the structural analyses. Stress analysis results using this model are shown in Fig. 24.

The development of reliable design approaches for extreme loading conditions requires a comprehensive consideration of combined environmental actions. Documented cases of catastrophic damage to FPV installations during severe weather events highlight the importance of proper extreme load analysis and the need for systematic studies on failure mechanisms under these extreme conditions (Song et al., 2023b). Furthermore, the environmental impact assessment should be conducted alongside the extreme load analysis to ensure a holistic approach to the design and operation of these floating solar systems (Hooper et al., 2021).

Addressing the challenges of extreme environmental loading in floating offshore solar installations will require the development of a more comprehensive probabilistic framework for combined environmental actions. The current deterministic approach using safety factors may prove either over-conservative or potentially unsafe. New methodologies should incorporate detailed meteorological data, site-specific vessel traffic patterns, and advanced fluid–structure interaction models. Physical testing at larger scales is also essential, particularly examining the behaviour of multi-module arrays under combined wave and wind loading, where current scaled testing may not capture all relevant physics.

7.3. Corrosion and bio-fouling

Corrosion and bio-fouling present perhaps the greatest uncertainty and risk in the development of marine floating solar technologies. The industry's rapid transition from freshwater to marine environments has outpaced our comprehensive understanding of the long-term degradation mechanisms that these systems may face. The interaction between mechanical stresses and environmental degradation, particularly at critical connection points, could lead to unexpected failure modes that are not adequately captured by current design standards. Furthermore, the impact of marine growth on the dynamic behaviour and thermal performance of these systems remains poorly understood. This gap in knowledge potentially affects both the structural integrity and energy generation efficiency of floating solar installations. Systematic long-term studies under actual marine conditions are urgently needed to address these critical knowledge gaps.

FPV installations face specific challenges from saltwater exposure and bio-fouling. To address corrosion concerns, recent designs have adopted the use of alternative materials, such as nylon, for inter-module connections instead of traditional stainless steel components. Design calculations also incorporate allowances for the expected accumulation of marine growth on both the walkway and PV module surfaces (Zhang and Schreier, 2022). HDPE floating modules, while generally resistant to chemical attack, still require protective measures against the detrimental effects of marine growth. Despite HDPE's inherent corrosion resistance, long-term exposure to marine environments necessitates careful consideration of surface degradation mechanisms. The combination of mechanical loading with environmental exposure introduces particular challenges for maintaining the structural integrity of these systems over their design lifetime (Shi et al., 2023).

While the available literature documents some specific material selections and bio-fouling allowances, there remains a critical gap in comprehensive long-term performance data for marine floating solar installations. The transition from stainless steel to alternative materials, such as nylon, demonstrates an awareness of corrosion challenges, but detailed studies quantifying corrosion rates and mechanisms in marine FPV applications are notably absent. The specified bio-fouling allowance may prove to be conservative for temperate water environments but could potentially be insufficient in tropical regions where marine growth rates accelerate significantly. Current designs focus primarily on the structural loading implications of bio-fouling, potentially overlooking the critical effects on hydrodynamic coefficients and thermal performance. The alteration of module hydrodynamics through marine growth could substantially modify the response characteristics established through clean-condition testing (Zhang and Schreier, 2022).

Several critical aspects demand urgent research attention. Firstly, the combined effects of mechanical fatigue and corrosive degradation, particularly at connection points where stress concentrations coincide with environmental exposure, require thorough quantification. Secondly, the long-term effectiveness of protective coatings under cyclic loading conditions needs systematic investigation. Finally, the impact of bio-fouling on thermal management and power generation efficiency requires detailed study, as marine growth may significantly alter the water-cooling effects that partly justify the use of floating deployments (Shi et al., 2023).

Without comprehensive long-term performance data from actual marine installations, current designs rely heavily on conservative safety factors and frequent maintenance intervals. While this approach is prudent, it may result in over-engineered solutions that impact the economic viability of these systems. Future research must establish degradation rates and mechanisms specific to marine FPV applications, enabling more optimised designs that balance durability against cost-effectiveness.

Addressing the corrosion and bio-fouling challenges in floating offshore solar installations will require a comprehensive research programme that combines materials science and marine engineering expertise. Systematic studies of various coating systems under realistic loading conditions are needed, along with the development of novel connection designs that better resist environmental degradation. Advanced monitoring techniques, possibly including embedded sensors, could help track the progression of corrosion in critical areas. The industry would benefit significantly from a shared database of degradation rates and mechanisms observed in different marine environments, facilitating more informed material selection and maintenance planning.

7.4. Mooring system integrity

The mooring system plays a critical role in the long-term operation and safety of FPV installations, but it faces unique challenges compared to traditional offshore moorings. Recent comprehensive time-domain analyses have revealed that the mooring line response can vary significantly depending on the configuration type, with taut systems exhibiting lower motion responses but higher peak loads, while catenary systems show larger displacements but more stable tension patterns (Song et al., 2023b).

The initial tension and overall configuration of the mooring system have a substantial impact on its performance. Researchers have developed and validated fundamental analysis methods to capture the coupled dynamic responses of FPV mooring systems (Dai et al., 2020a). These studies have shown that for taut mooring systems, the initial tensile forces can range from 0.5 kN to 2.2 kN, depending on the chain weight, but the maximum forces can reach up to 64.2 kN for lighter chains (Song et al., 2023b). These findings align with the theoretical understanding of wave-structure interactions and marine hydrodynamics.

The interactions between multiple floating modules introduce additional complexity to the mooring system dynamics. Recent research has specifically highlighted the challenges associated with interconnected floating modules, demonstrating the need for a more comprehensive understanding of these multi-body interactions. Insights from studies on high-durability mooring configurations for composite floating structures (Kumar et al., 2014) provide valuable context, while theoretical frameworks for analysing non-linear fluid–structure interactions in mooring systems (Xu and Wellens, 2022) offer potential avenues for addressing these complexities.

Tidal variations can significantly impact the mooring system performance, with studies documenting the effects of water level changes up to 4 meters in nearshore regions (Zhang et al., 2024a). The importance of considering these tidal effects in the mooring design has been emphasised, as they can lead to performance variations under different environmental conditions (Hooper et al., 2021). Furthermore, the dynamic response characteristics of the mooring system can vary significantly with the size and scale of the FPV array. Studies have demonstrated performance variations in integrated systems and have documented specific challenges for large-scale deployments. The documented cases of catastrophic failures (Song et al., 2023b) underscore the critical importance of proper mooring system design for these floating solar installations.

Current design approaches for mooring systems in floating solar installations require significant evolution beyond traditional offshore methods. While initial industry guidelines, such as the Det Norske Veritas guidelines (Veritas, 2021), provide a foundation, they need to be adapted and further developed to address the unique characteristics of FPV systems. The need for specific consideration of dynamic effects has been highlighted (Friel et al., 2020), and analytical methods for load determination have been established (Ikhennicheu et al., 2021a). Comprehensive market analysis also supports the need for standardised mooring design approaches tailored to the floating solar industry.

To sum up, the mooring system integrity is a critical aspect of floating offshore solar installations, with distinct challenges and performance characteristics compared to traditional offshore structures. These challenges include the influence of mooring configuration, the impact of initial tension and water level changes, the complexity of multi-body interactions, and the scaling effects associated with array size. Addressing these challenges will require a comprehensive, multidisciplinary approach to develop reliable design methodologies for the emerging floating solar market.

8. Discussion, research gaps, and conclusions

8.1. Research gaps

Based on the review presented, significant research gaps are identified and discussed as below.

8.1.1. High-fidelity modelling approaches

The wind-and-wave coupled loading presents difficulty to modelling while dominating the dynamic response of FPV at seas, where the wind speed can be more than 20 m/s and the wave heights can be more than 2 meters in normal operating conditions (Wei et al., 2025). Moreover, these loads dictate fatigue prediction and structural lifetime.

CFD is suitable for model wave-structure interactions (Huang et al., 2022), but the challenge lies in FPV's special structural features. The FPV can consist of numerous individual bodies connected by joints, and the shielding and damping effects from upstream bodies will influence those downstream (Nelli et al., 2020; Liu, 2023). Ideal modelling of them would induce Numerous-Multi-Body-Dynamics (NMBD), which brings about a dilemma due to mesh waves at large scales and mesh the individual structure at localised scales. A very small project of a 5 kW power plant consists of around 60 moving floating parts and their connecting joints. Although a simulation of such a power plant would be costly, it is doable within the computational limitations. Nevertheless, for medium scale projects of the size of 1 MW, performing CFD is out of reach with the current industrial tools as it forms a multiscale simulation problem with thousands of floating moving parts. The length scale of one floater is around 1 or 2 meters and the 1 MW floating plant would occupy at least a surface area of 100 m x 60 m. The problem becomes even more complex for 1 GW projects (approximately 165 Acres (Wei et al., 2025)) which is a common size for large-scale power plants required to meet offshore's ambition and potential for clean energy.

One way to tackle this is to consider the structure as a very large floating body as a whole Huang et al. (2019), and Wei et al. (2024d) suggested that the results can resemble those modelled by NMBD when the waves are sufficiently long. However, when winds are required to be coupled, the superstructure of the FPV may need to be modelled in detail to consider the tilting panel and the associated vortexes (Panjwani, 2024), which further increases the demand for meshing and NMBD. Coupling with a structural solver for mechanical analyses exposes another layer of challenge (Wang et al., 2024a). The way forward could be designing a multiscale and multiphysics computational approach to model these effects separately and couple them through a reasonable algorithm (Liu et al., 2017; Tuković et al., 2018; Karač et al., 2018; Liu and Xiao, 2019; Wei et al., 2024a; Wang et al., 2024b).

8.1.2. Optimal mooring design

A correct mooring design is essential for the safety and integrity of the system. Conventionally, mooring simulation software coupled with experimental and CFD-calibrated parameters provides accurate estimates for the forces on the mooring lines. However, all of the mooring simulation software, such as OrcaFlex, MOSES and Aqwa, have limitations on the number of bodies that can be simulated, which is normally in the order of 100 moving parts. As the number of parts increases the non-linear problems get more stiff and it is harder to solve and estimate the wave behaviour. Nevertheless, a 1 MW FPV would consist of thousands of floating parts, let alone for GW-order power plants.

The wide span of FPV means that contemporary moorings, which apply to the edges of a floating structure, may not be applicable. There can be the necessity to add mooring points in the middle of an FPV power plant (Yang et al., 2024b). However, the design and optimal interval of these internal mooring points need to be developed. Therefore, a simulation methodology and industrial tool for the mooring design should be developed to predict the expected forces on ocean-based FPV. In addition, research is lacking for the floating and submerged cables of FPV (Cerik and Huang, 2024).

8.1.3. Environmental and ecological interactions

The introduction of FPV technology has gained significant interest globally as a renewable energy source alternative. However, the environmental impact of FPV is not fully understood nor addressed enough since the technology is relatively new to be adopted in seas and oceans. The negative and positive effects of the system on the marine environment need to be examined. Such environmental studies can help policymakers, regulators, and clients to compare the environmental impacts of FPV technologies to other energy generation alternatives. The environmental effects mainly come from the large-span non-natural structure. Possible positive environmental impacts can include artificial shielding and habitation for marine faunal and vegetation, while the long-term impacts are uncertain (Pouran et al., 2022; Wei et al., 2025). The shielding can create a lower-temperature region underneath the floating platform, potentially influence water evaluation and circulation. In addition, marine cables can generate disturbing electromagnetic fields (Taormina et al., 2018). The anchors will also influence the seabed (Wang et al., 2020). Once the environmental effects are accurately identified, the negatives may be effectively addressed in design and operations.

Environments can also induce significant effects on FPV. It has been widely introduced that installing the PV modules on water reduces the temperature of the PV modules during peak sunlight hours and thus enhancing the efficiency of electricity generation (Ramanan et al., 2024). However, the effect of the cooling is not well studied yet as it depends on multiple factors, mainly, the geographical location, air and water temperatures, weather and clouds, and the design of the floating system. The cooling effects can also enhance the performance of the inverter, batteries, cables, and all electrical components. Comparing ocean-based and calm-water-based FPV, the front could have cooling effects enhanced by marine flows and waves, i.e. more convection and contact. It is important to understand and quantify the energy efficiency so it would help comparing the ocean based FPV vs other PV solutions in terms of energy generation, determining LCOE. A theoretical or experimental approach can be used to better understand this cooling effect.

Marine environments also can induce corrosion, biofouling, bird droppings, and salt soiling on FPV systems. This influences both structural integrity and energy generation. Anti-corrosion and anti-biofouling coatings are worth research and developments. Whilst on-land and calm-water FPV projects are mainly cleaned by human labour, this could be unrealistic offshore, and anti-soiling mechanisms such as electrodes are needed to be developed for FPV (Ren et al., 2023).

8.1.4. Sensing and digitalisation

Safe, stable and efficient operation and control of FPV systems requires real-time monitoring of a range of parameters, such as irradiance, ambient temperature, water temperature, wave conditions, motions. It help prediction of FPV power output and inform maintenance decisions. Monitoring these parameters can be challenging at seas as existing commercial sensors may be hard to attach to FPV due to bulky geometries, cumbersome operations, or being vulnerable to the sea environment. To address this issue, it is recommended to develop smart sensors that are embedded under the structural surface of FPV components (Gaddam et al., 2021; Adothu et al., 2022; Biswas et al., 2024).

With suitable telecommunication technology also embedded with the FPV power plant, monitored data can then be transferred back to a onshore workstation on a real-time basis. This will inform the development of AI-based models for energy management systems and structural integrity monitoring. In long-term, this helps achieve optimal energy yield and reduces the costs of maintenance, minimising the LCOE.

8.2. Epilogue

Boosted by the global clean energy requirements, the potential of deploying FPV on seas has attracted spectacular interest. Aiming to ensure the reliability and sustainability of FPV in harsh marine environments, this work has reviewed published literature on this topic, and in combination with industrial expertise, provided comprehensive insights into the relevant design, modelling, structural integrity and research gaps.

One of the dilemmas in the current design is the over-costly floating structure and survivability at sea, which motivates innovative designs to come. The review has shown that FPV can be designed following a modularised approach, enabling an FPV farm to have flexible size, scale, and possible extension to additional components such as a breakwater or a wave energy converter. A specific risk assessment framework is required for this sector, but the prerequisite is to have accurate predictive approaches for loading from wind and wave. A mooring methodology is still missing, due to the significant difference between a conventional concentrated-mass floating structure and a vast-span FPV coverage. Anti-corrosion/biofouling/soiling inventions will bring essential insurances to this field that help maintain the system at its designed conditions. Altogether, these innovations are expected to enhance FPV's system reliability, sustainability, energy performance, and continuously lower the LCOE. Once the survivability and expenditure factors are addressed, it is envisioned that FPV will unlock its enormous potential on seas and become a vital part of the world's future energy portfolio.

CRediT authorship contribution statement

Luofeng Huang: Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Hashim Elzaabalawy:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Mohamed Sarhaan:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Ahmed Sherif:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Haoyu Ding:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Binjian Ou:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Danlei Yang:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization. **Burak Can Cerik:** Writing – review & editing, Writing – original draft, Resources, Investigation, Conceptualization.

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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Data availability

All data underlying the results are available as part of the article and no additional source data are required.

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