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Key issues in the design of floating photovoltaic structures for the marine environment

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ABSTRACT

The floating photovoltaic (FPV) market has been expanding at an impressive rate over the last decade, doubling its global installed capacity year after year. This growth was possible due to the numerous advantages FPV plants pose over ground-mounted plants, which are mainly related to land occupation and energy efficiency. However, this expansion has been limited to freshwater applications, despite the vast potential that the offshore environment entails. The lack of maturity of the sector and the harsher environmental conditions have hindered the transition of this technology to the marine environment. Furthermore, a lack of publications regarding the structural analysis of this technology was found, as well as no specific designs standards for marine FPV. On these grounds, this article reviews the design aspects of this technology with a focus on marine applications, highlighting relevant aspects to be tackled. First, the main components of the FPV technology are described and their compatibility with the marine environment is assessed. Then, a structural classification of the current plants is proposed. This allows the individual suitability analysis of each typology for the marine environment. Existing marine FPV projects are described and classified. Afterwards, synergies between marine FPV plants and other sectors are gathered and discussed. Finally, general design guidelines are provided, with a focus on the structural response of FPV structures subjected to marine environmental actions. Insight on the nature of these actions (wind, waves, currents, and tides) as well as how they interact with FPV plants is provided.

1. Introduction

Solar PV energy is playing a key role in the transition to renewables due to its potential to fulfil the global energy demand [1] and the recent decline in solar technology costs [2]. However, large areas of land are required for multi-megawatt scale electricity generation, which limits possible agricultural uses [3]. This comes in conflict with the energy versus food debate [4] and the growing problem of land scarcity [5]. Overcoming this problem was the *raison d'être* of floating photovoltaic (FPV) plants. In fact, the first non-experimental FPV plant was installed in a Californian winery to generate electricity without compromising a vineyard [6]. Since then, these plants have been installed on freshwater bodies such as artificial and natural lakes [7] and abandoned mine lakes [8].

FPV technology has grown at an impressive rate of 133% per year over the last decade [9]. The cumulative global installed capacity broke the gigawatt barrier in 2018 [10] and its currently doubling its capacity each year [11]. However, this market has not expanded to the marine environment yet, due to the harsh conditions it presents [12]. The rapid expansion of FPV plants for freshwater applications was possible due to the many advantages they pose over ground-mounted systems [7,13,14]. The marine environment exalts some of these advantages at the cost of some drawbacks:

- The PV modules show higher efficiencies due to the cooling effect of the water. This aspect was addressed by many studies and, while some authors claim the efficiency increase to be between 5 and 15% [15–22], others found it to be below 5% [23–29]. Wind is also a demonstrated cooling mechanism [30] and the marine environment would be a prime location due to the presence of stronger winds and the absence of abrupt thermoclines.
- The usual sites for the deployment of FPV plants are not expected to cast shadows over the PV modules, minimizing losses [31]. This is especially relevant in open areas, such as the oceans.
- This technology does not compromise valuable land and its possible uses [32]. The ocean provides practically unlimited space to deploy

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List of abbreviations

A	Reference area [m^2]
AC	Alternating current
BEM	Boundary element method
CAES	Compressed-air energy storage
CFD	Computational fluid dynamics
C_D	Drag coefficient [−]
C_m	Inertia coefficient [−]
C_S	Sheltering coefficient [−]
D	Characteristic dimension of a structural element [m]
DC	Direct current
DNV	Det Norske Veritas
F	Directional spreading function [−]
FEM	Finite element method
FPV	Floating Photovoltaic
FRP	Fibre-reinforced polymers
F_{awn}	Wave force [N]
F_{win}	Wind force [N]
f	Frequency [Hz]
H	Wave height [m]
H_s	Significant wave height [m]
HDPE	High-density polyethylene
h	Water depth [m]
IACS	International Association of Classification Societies
MRE	Marine renewable energy
OWT	Offshore wind turbine
O&M	Operation and maintenance
PV	Photovoltaic
S	Exposed surface [m^2]
S_U	Wind speed spectrum
S_{wav}	Wave power spectrum
T	Wave period [s]
T_p	Wave peak period [s]
t	Time [s]
U	Wind Speed [m/s]
U_{ref}	Wind speed at the reference height z_{ref} [m/s]
UV	Ultraviolet
u	Flow velocity [m/s]
V	Volume of a body [m^3]
WEC	Wave energy converter
WVC	Water Veil Cooling
z	Height above the ground or ocean surface [m]
z_{ref}	Reference height above the ground or ocean surface [m]
α	Terrain roughness [−]
η	Water surface elevation [m]
ω	Angular frequency [rad/s]
λ	Wavelength [m]
θ	Wave propagation direction [deg]
ρ	Fluid density [kg/m^3]

these systems. This could also lower the total cost of energy, given the important role played by the total system capacity on it [33].

- Large floating structures are already being used to reflect waves and grant shelter [34]. Marine FPV structures could function as or be attached to a floating breakwater. This feature could be further exploited in the marine environment, where generating sheltered areas is a common practice.
- A large number of new synergies were found for marine FPV systems, including aquaculture [35] and other renewables [36].

There are, however, several holdbacks and challenges to the deployment of this technology on the marine environment:

- Marine FPV plants are exposed to great wind and wave loads (Fig. 1) during their service life, which is commonly 25 years [37]. They have to survive extreme environmental events, fatigue on joints and connections, saltwater corrosion, UV degradation and biofouling [31].
- The PV modules are subject to constant movement, which could result in microcracking and dealignment, both phenomena that lessen production. Notwithstanding, the losses due to the dealignment of the panels were modelled by Refs. [38,39] and it was concluded that they were overcompensated by the cooling effect of the marine environment.
- These plants could interfere with other marine activities, such as fishing or navigation.
- Some benefits of freshwater FPV plants are neglected, such as limitation of evaporation losses [40], algae growth reduction [41], eutrophication prevention [42,43] and a strong synergies with hydroelectric power [44,45]. This is hardly relevant for marine applications.
- The low technological maturity implies a lack or absence of design standards, guidelines and legal regulations [46].

Despite the recent growth of FPV technology, information on how to design these systems is limited. This lack is further accentuated when it comes to marine applications where, given the environmental conditions, it is most needed. Freshwater applications have been assessed during the last decade. As a result, a few books [21,47,48] and standards [49] are available for their design and analysis. This is not the case for marine applications, forecasted to reach maturity by 2030 [50].

The main purpose of this work is to provide key insight on the design of marine FPV structures. To do so, knowledge about the current freshwater FPV market and several offshore sectors was gathered and crossed to assert the suitability, issues, and limitations of marine plants.

The remainder of this paper is structured as follows: Section 2 discloses the different elements and materials that are required to assemble an FPV system, bearing in mind marine applications. Section 3 presents a classification of the existing technology and evaluates its suitability for the marine environment. Examples of marine FPV projects are also provided and classified in this section. Section 4 reviews the potential synergies of offshore applications. General design guidelines for these marine structures are presented in Section 5. These guidelines feature an in-depth analysis of the marine environmental actions to be withstood by the FPV plant and how to estimate loading on the structure through several approaches. Finally, key points of this work are summarized in Section 6.

2. Elements of a FPV system

A generic FPV system is commonly composed of: PV modules to harvest the solar energy, floats that provide buoyancy, a structure that supports the PV panels, a mooring system that forestalls the free movement of the plant, electrical components and optional efficiency systems (Fig. 2). These elements are described in the following subheaders.

2.1. Floats

The floats provide buoyancy to keep the structure afloat. They are usually made of UV light-resistant, non-hazardous, maintenance-free plastic materials with high tensile strength such as high-density polyethylene (HDPE) [37]. However, some denser materials, such as concrete [51] or steel [52], have been considered. Other key aspects of the

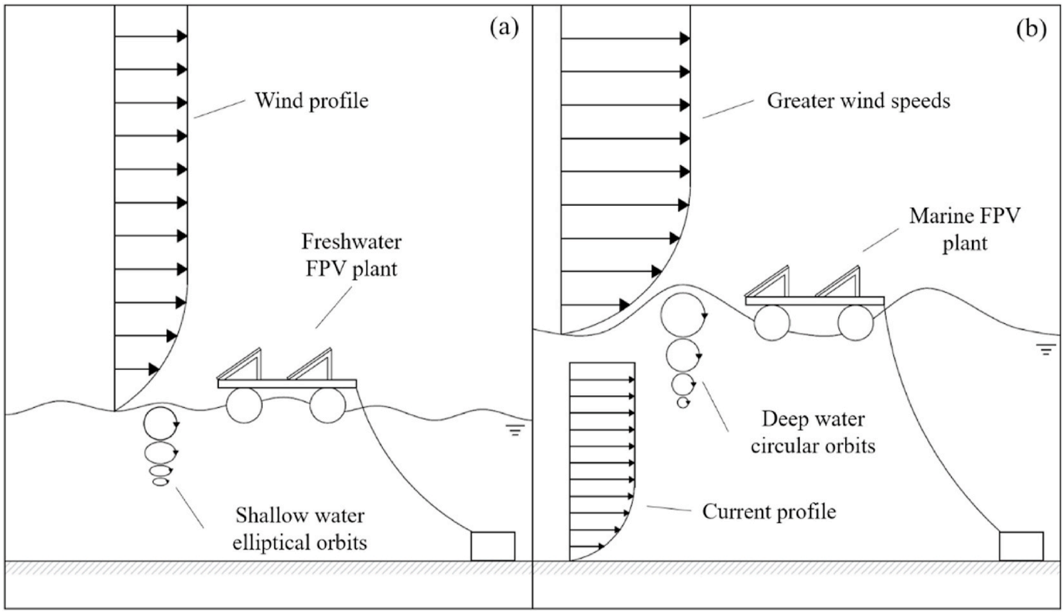

Fig. 1. Environmental loads on FPV structures in (a) continental water environment, and (b) marine water environment.

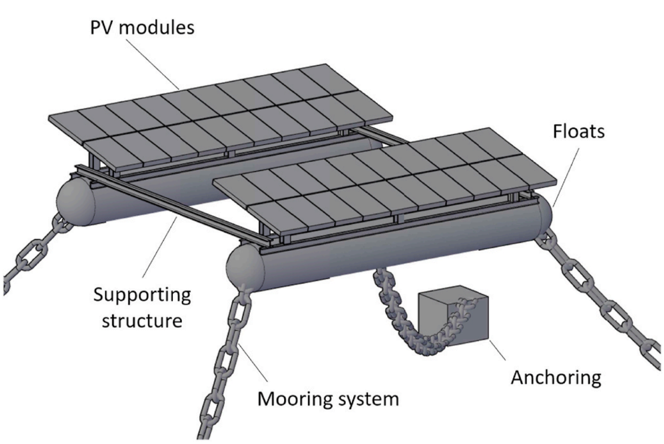

Fig. 2. Components of a generic FPV system.

chosen material are rot, fire, and penetration resistance. This last feature can be enhanced using expansive filling foams to avoid loss of buoyancy due to perforation of the floats [53].

In marine applications, the floats are expected to withstand greater loads and the effect of saltwater corrosion [54] and biofouling [55]. Despite the corrosion resistance of HDPE, floats may require antifouling coatings to prevent loss of mechanical properties [56]. On another note, plastic debris represents a major environmental problem and HDPE has been identified as a potential source of microplastics [57]. To reduce environmental impacts associated with the disposal of plastics, sustainable plastics should be considered [58].

2.2. Supporting structure

Most FPV designs include a metallic structure to support the PV modules and transmit stresses between components. Nonetheless, some designs lack this element and accommodate a single PV module per float instead [59]. In marine applications, the supporting structure may also play a significant role in keeping the panels at a safe height from sea level [46].

The structural members are usually made of materials such as galvanized steel (e.g. Ref. [60]), high durability steel (e.g. Ref. [61]), or aluminium (e.g. Ref. [62]). The major issue regarding steel or aluminium in marine structures is corrosion. Composite materials and, specifically, fibre-reinforced polymers (FRP), are being incorporated into the marine industry due to their outstanding corrosion resistance against seawater [63] and their lower density [64]. In fact, FRP was selected above steel or aluminium on several FPV designs [28,65].

2.3. Mooring system

The mooring system secures the FPV plant, limiting its free movement to prevent damage or hazard to itself or other floating bodies. Synthetic fibre rope, elastic rubber hawsers, or combinations thereof are used in freshwater projects [48]. However, in marine floating structures, mooring lines are usually made of steel chains or wire ropes [66].

A general classification of mooring systems is catenary, compliant, taut, and rigid moorings (Fig. 3) [67]. The catenary mooring system consists of chains that use their self-weight to provide a spring rate to the moored float. Compliant moorings are catenary moorings that use floats and weights to adjust the layout of the mooring lines. A taut mooring system uses buoyancy excess to keep the mooring lines in tension. This array limits vertical motion, which can be problematic for important water level variations, given the limited freeboard of FPV structures. A solution could be using elastic mooring lines, like Seaflex®, which can adjust their length and tension [68]. A rigid mooring system consists of an anchored rigid structural member that allows heave movements but restricts surge and sway. This solution, which is optimal from the station-keeping point of view, is only economically reasonable for shallow waters.

Mooring systems for marine FPV plants are still far from being resolved, but a good starting point can be obtained from traditional marine structures designs (*e.g.* Ref. [69]) and from other marine

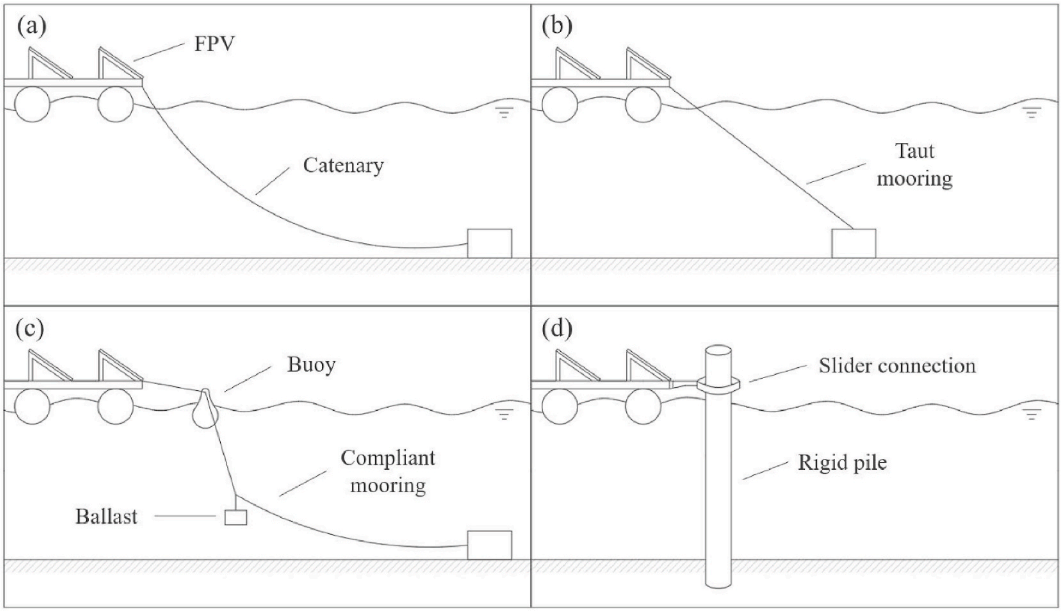

Fig. 3. Examples of mooring layouts for FPV systems (a) catenary, (b) taut mooring, (c) compliant mooring, and (d) rigid mooring.

renewable energy (MRE) technologies, such as offshore wind (*e.g.* Ref. [70]) and wave (*e.g.* Ref. [71]). The mooring system represents about 10% of the capital expenditure for a wave energy converter (WEC) [72] and even greater values for offshore wind turbines (OWT) [73], meaning that specific mooring designs for the marine FPV industry are paramount from an economical point of view.

In freshwater plants, the mooring lines are usually anchored through dead weights or helical anchors [48]. There is no specific literature on anchoring systems for marine FPV, but traditional marine anchoring systems may be used. Examples are dead weights, drag anchors, embedded anchors [74], or suction foundations [75] (Fig. 4). In addition, the seabed stability around the foundation should be analysed to assess the need for scour protection [76].

2.4. PV modules

PV modules are made of solar cells that require light-absorbing materials to absorb photons and generate free electrons through the photovoltaic effect [77]. PV modules are generally based on silicon technology, cadmium telluride, cadmium sulphide, organic and polymer cells, hybrid photovoltaic cells, and thin-film technology [78]. An in-depth review of these materials and technologies is found in Ref. [79]. Large-scale FPV installations to date have almost exclusively employed crystalline silicon wafer-based modules [48]. However, flexible membranes, based on thin-film technology, have also been proposed [80–82]. This flexibility could be beneficial to endure the wave loads in marine FPV systems [80].

In offshore environments, the PV modules will be required to resist

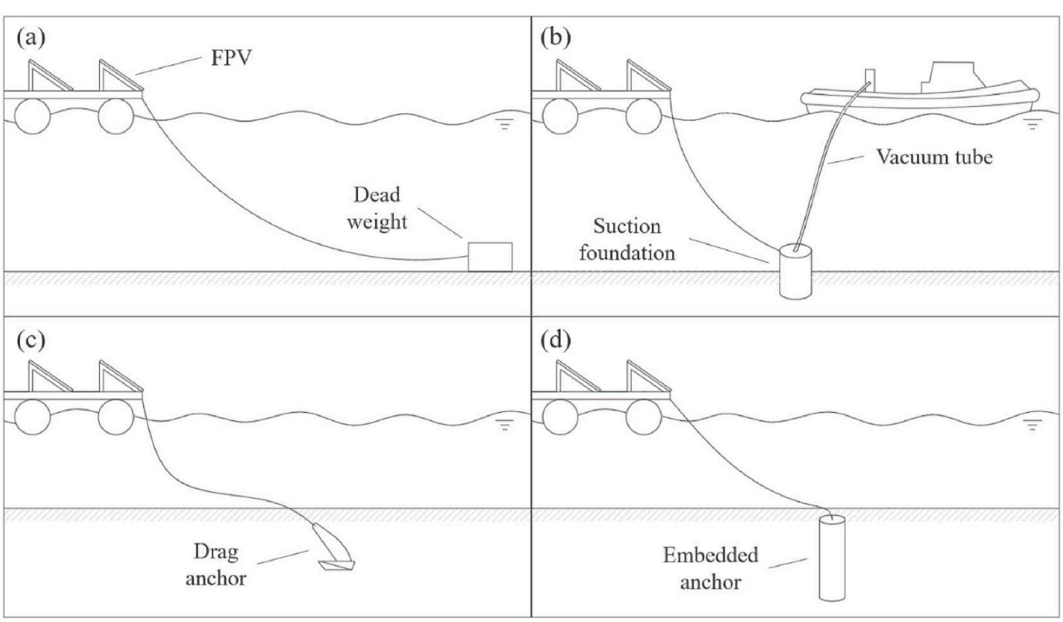

Fig. 4. Examples of anchoring systems for the marine environment layouts for FPV systems (a) dead weight, (b) suction foundation, (c) drag anchor, (d) embedded anchor.

higher loads and withstand saltwater corrosion [12]. Mechanical properties can be enhanced by increasing panel stiffness or by mounting strings and cells on the neutral axis. Crack formation can be partially mitigated using encapsulants with lower elasticity. Using half-cut cells can also reduce the impact of fatigue [48]. The offshore environment may also accelerate PV module degradation, affecting the reliability of the plant [83]. The solar panel cover glass will be damaged, decreasing its spectral transmittance [84]. Accumulated salt particles may also hinder production [85].

2.5. Electrical components

An array of cables and electrical components is required to transform and transport electricity from the FPV plants to land. Wiring can be performed above or underwater. Most electrical components are kept above water to mitigate risks, but this does not preclude the need to make them waterproof. Most cables that interconnect the system suffer high levels of UV radiation and great temperature fluctuations that must be considered when designing the cabling system [13]. Because of the intermittent nature of solar power plants and the variations in the load demand, the output voltage of PV modules does not meet the AC grid voltage [7]. The use of DC DC converters is recommended to reach the required voltage [86]. Once the required voltage is met, an inverter connects the plant to the AC grid. These components are better kept on ground, but on large-scale projects and offshore applications they can be installed on floating islands [48]. The way the modules are interconnected affects the productivity of the plant due to partial shading. The losses caused by partial shading can cause an annual energy loss of 5–10% [87,88]. The severity of these effects is dependent on the array configuration [89–91].

2.6. Efficiency systems

A variety of optional systems can be accommodated in FPV plants to maximize production. Examples of these are the tracking, cooling, cleaning, and storage systems. Although the industry is betting on simple designs, some authors have proposed concepts that integrate these components.

2.6.1. Tracking system

For each location and time, there is an optimal alignment of solar panels that grants a peak performance. Accordingly, the purpose of the tracking system is to maximize the energy gains during the entire lifetime of the PV system. The solar tracker drive systems can be classified as active, passive, semi-passive, manual, and chronological [92].

Since the panels are floating, some disturbances in their alignment should be expected and the impact on electricity generation must be studied [23]. The trackers can rotate around a single axis (horizontal or vertical) or dual-axis (tip-tilt or azimuth-altitude) (Fig. 5). Tracking around the horizontal axis can be performed in systems that allow tilting, mostly pontoon based. Tracking around the vertical axis in FPV can be performed in several ways. Some proposals, patents and commercial designs include rotating platforms for this purpose (e.g. Refs. [46,65, 93–95]). Tracking can be combined with concentrating, which is using reflectors to increase energy harvesting [96]. The tracking system is usually powered by a motor as the actuation method, but a design that uses wave energy to adjust the angle of the PV module for solar tracking has also been proposed [97].

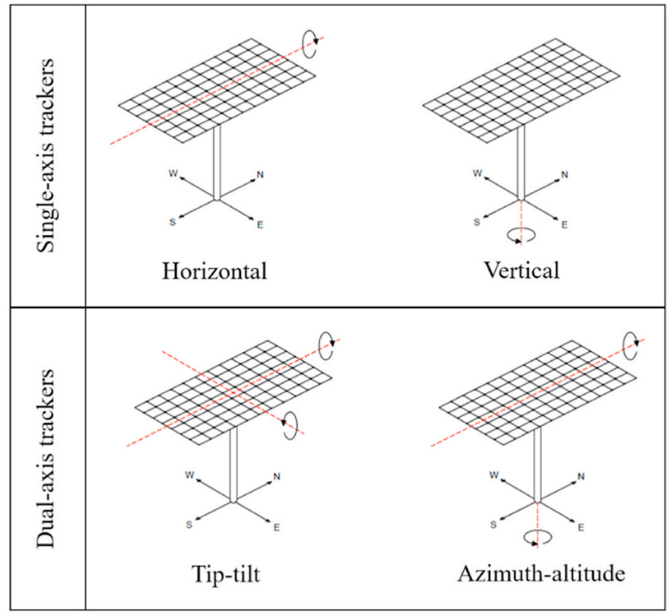

Fig. 5. Tracker types for conventional photovoltaic modules.

2.6.2. Cooling and cleaning system

Only a fraction of the solar spectrum is used to harvest energy through the photoelectric effect. The remaining spectrum is unwanted irradiation that causes the operating temperature of the panels to rise, which lowers their efficiency [98]. The water cooling effect can be maximized by locating the panels on the water surface, as seen on semi-submerged and thin-film arrays [99]. A different approach to ensure a low operating temperature is the cooling systems.

Some of the proposed cooling techniques are forced air, Water Veil Cooling (WVC), and water spraying [100]. These methods have been evaluated by several authors [101–103]. Water-based techniques are considered the best [104] and the location of FPV systems ensures water availability [105]. Techniques based on applying water to the PV cells have additional effects apart from a lower operating temperature, such as solar spectrum modification [106], a change in the reflected light [107] and panel cleaning benefits [108].

These methods require an energy input that must be coherent with the gains due to operating at cooler temperatures and mitigating negative dust effects. To run a WVC system, less than 1% of the produced energy is needed, whereas the energy gain is expected to be around 10% [100]. The WVC also takes advantage of the reduction of the reflected radiation. Reflection of irradiance typically reduces the electrical yield of PV modules by 8–15% [109]. Reducing reflection is beneficial at high latitudes, where energy gains can increase by 4% [96]. Some studies show beneficial results to spraying water over the modules [110], since the energy needed to pump the water is also overcompensated with the efficiency gains.

Temperature, humidity and UV radiation are the main factors of PV module degradation [111]. The overheating of the PV modules is the cause of several ageing mechanisms, like delamination, cell cracking and solder bond degradation [112–114]. Thus, cooling techniques may also extend the lifespan of FPV technology.

2.6.3. Storage system

Integrating renewable energy sources into the electric grid is challenging due to the variations between demand and generation, and the high cost of transmission cables for peak power levels [115]. These issues may be addressed by means of storage systems [116]. Energy storage solutions for renewable energies include batteries, compressed-air energy storage (CAES), pumped water storage, and hydrogen production.

The main storage system for PV energy has been restricted to batteries [117]. However, batteries are expensive and have a short life cycle which ends with the generation of hazardous waste [118].

CAES are a well-known technique that is used in other renewable energies such as offshore wind [115]. Some authors proposed the integration of this technology with FPV, using the pontoons of the structure as reservoirs for CAES [52].

Another option would be storing the potential energy of pumped water. An FPV plant with an integrated pumped storage system was proposed and evaluated by Ref. [119]. A seawater pumped hydropower plant powered by solar energy was analysed by Ref. [120]. A photovoltaic plant in which battery storage was partially replaced by a micro-hydraulic system was also installed [121].

An electrolyser can be used to produce and store hydrogen in a fuel cell generator. Wind/hydrogen hybrid systems are considered a great opportunity to provide consistent renewable energy [122] and there is an increasing interest in using hydrogen for transportation purposes [123]. A design and analysis of a combined FPV system for electricity and hydrogen production were performed by Ref. [124]. A plant that could produce hydrogen using its generated power was designed and analysed by Ref. [125].

3. Classification of FPV designs

A large and growing number of FPV designs have been already deployed in freshwater plants, which can be classified according to different criteria [126,127] Now, the transition to offshore has begun and new designs are arising to survive the harsh marine environment. A classification of FPV typologies based on their structural arrangement is presented (Fig. 6), along with an assessment of their suitability for the marine environment as well as examples of application.

A first division is made regarding the position of the PV modules with respect to the waterline. Installing the modules directly over the water surface leads to a greater cooling effect that should yield a higher efficiency. However, this approach may expose the modules to wave loads. FPV systems can be superficial, in which the PV modules are directly installed over the water surface, or pontoon-type, in which an intermediate floating platform is arranged.

3.1. Pontoon-type

The main idea behind pontoon-type systems relies on designing a raft or pontoon to establish a stable floating platform for the solar modules to be installed on. A structural classification of the existing designs is found in Ref. [127], where the PV plants are divided into Class 1, Class 2 and Class 3 plants.

3.1.1. Class 1

The earliest designs of FPV structures correspond to Class 1 pontoons, which consist of rafts built with parallel HDPE cylinders as floats and steel, aluminium or FRP members as the supporting structure. These structures have a low contact surface with the water and can easily accommodate a single-axis tracking system and a CAES system [52]. This type of FPV is robust and versatile but is somewhat expensive compared to the alternatives [127].

The first non-experimental FPV plant belongs to this subtype [128]. Other examples of designs meant for freshwater can be found in Refs. [129–131]. As for marine applications, a Class 1 design was proposed,

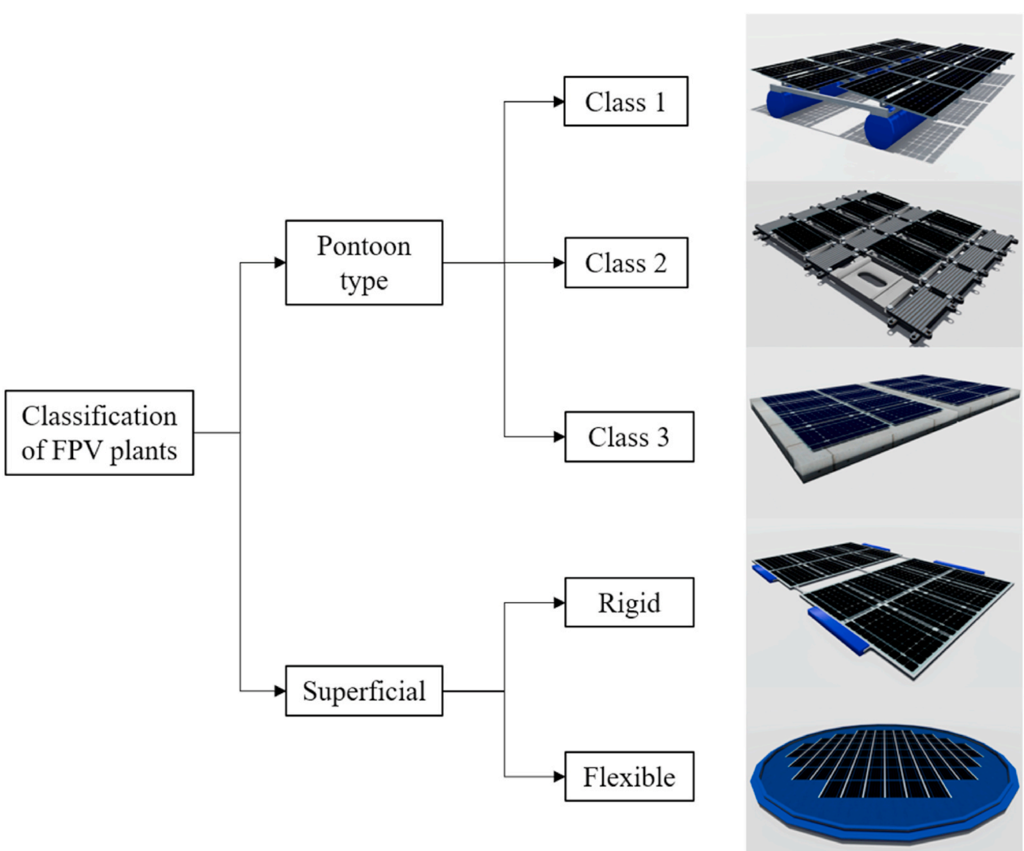

Fig. 6. Classification of FPV systems (based on [127]).

calculated and installed in a mild marine environment (*i.e.*, wave heights up to 1.35 m) by Ref. [28].

This typology has its limitations in the marine environment. The incoming waves can result in an excessive flexural moment on the components aligned with the wavefront, an issue that can be resolved using hinged structural members [61]. Another issue lies in the height at which the panels are installed. Swimsol SolarSea® is a Class 1 system designed for the marine environment that, instead of cylinder-shaped floats, uses an array of aligned floaters [132]. These floaters are connected by an aluminium truss that keeps the panels well above water, preventing them from saltwater splashes. However, this system can just withstand wave heights of up to 2 m [133]. It is clear that a simple scale-up of the existing Class 1 plants is not enough and substantial design modification should be performed to achieve a fully offshore FPV plant.

3.1.2. Class 2

Class 2 plants were first proposed by Ciel & Terre in 2011 under the commercial name Hydrelio® [134]. The key concept is that each individual PV panel is held by a single float with built-in rails. These floats can also accommodate electrical components, act as a perimeter barrier or create catwalks. Since the different float units are connected to each other through pins, no additional supporting structure is required. This solution is cheaper than Class 1 plants but is not as customizable, limiting the use of efficiency systems [135]. The contact surface between the plant and the water is much higher, which can lead to quicker degradation of the exposed materials and a higher environmental impact. However, due to its cost benefits, some companies have proposed similar designs [136–139].

These are the most common type of FPV in freshwater applications [140] and can withstand waves of up to 1 m [12]. Although this limitation makes them unsuitable for open sea applications, adaptations of this technology are currently under development [59]. Despite the limitations of Class 2 plants for marine applications, a nearshore plant was recently built on the Persian Gulf [141]. The chosen site was naturally sheltered, and bifacial solar modules were used to survive the constant salt spray from the waves [142]. Chenya Energy constructed a Class 2 FPV plant on the coast of Taiwan that, upon installation, was the world's largest offshore solar plant [143]. Nonetheless, these designs may not be suitable for a fully offshore environment since the very conception of Class 2 plants relies on cost savings rather than structural performance.

3.1.3. Class 3

In Class 3 plants, floats are assembled to create a large floating platform or island where the PV modules and electrical components are installed independently. This rigid structure is generally walkable, so there is no need for catwalks. This approach results in stable, safe structures with easier maintenance, but at a higher cost [127]. This sort of floating platform was constructed long before the appearance of FPV technology through a large variety of designs. Some examples of this typology can be found in Ref. [144] and a design where the usual HDPE floats are substituted by a concrete platform was proposed by Ref. [51].

Class 3 plants could be suitable for the marine environment if the designs are properly rescaled and/or structurally adapted. In fact, the first high-wave offshore solar farm in the world could be classified in this subtype. It was installed in the Dutch North Sea where it has survived storms with waves up to 10 m [145].

3.2. Superficial

The benefits of having a thin layer of water covering the PV panels were discussed in Section 2.6.2. To take full advantage of these benefits, some plants were designed to have the PV modules resting on the water surface or even partially submerged. This location is a double-edged sword since while it mitigates the effect of wind loads on the structures, it exposes the PV modules to direct wave loads. For deep waters, wave-induced velocities decrease significantly with water depth [146]. This means that a sufficiently submerged PV module would be sheltered both from wind and wave loads. However, since water is a light absorber, the total available solar energy would be reduced, as well as the spectral width [147,148]. The filtered underwater solar spectrum is biased toward the green/blue portion of the spectrum with useful power to harvest at different depths [149]. Several studies show that a small water depth of 4 cm grants a higher efficiency and a substantial reduction in the temperature of the modules, extending their lifetimes [21,150].

Other benefits of this configuration are its self-cleaning nature, a steady temperature, and a reduced visual impact, which also opens new possible site locations. This, however, means that the exposure of the panels to wave loads is still an issue to be addressed. Two main strategies were proposed for the modules to withstand these environmental conditions: the rigid approach and the flexible approach.

3.2.1. Rigid

A rigid sinkable FPV plant was proposed by Ref. [151]. The PV modules can submerge up to 2 m to be able to withstand moderate waves. Although it normally operates under a thin layer of water, it can submerge and float back by pumping water in and out of its buoys. This design must be adapted to operate in the marine environment since a 2 m descend will barely impact the orbital flow velocities under high waves. Its offshore reliability is yet to be determined.

3.2.2. Flexible

The flexible strategy has two approaches, namely, using thin-film flexible modules or using crystalline modules backed with flexible foam. The thin-film flexible FPV array was designed for offshore electricity generation [80]. These modules are made of amorphous silicon, the key material for this flexible approach. The main benefits of thin-film solar cells are their minimum material usage and flexibility [152]. The buoyancy is obtained with a uniformly distributed neoprene sheet, in addition to regular perimeter floats. Some of the benefits of the thin-film floating concept are the elimination of the pontoon structure, a self-cooling and cleaning nature, an overall lighter weight, a reduced number of components and a superior mechanical behaviour against incoming waves and possible collisions with other floating bodies [3,153,154]. Furthermore, the hydrodynamic properties of the thin-film technology become equal to that of waves due to its low energy interaction [80]. This results in a less loaded, hence cheaper, mooring system, which is a major issue in the reliability of offshore structures [155]. However, this system is unable to tilt the modules let alone accommodate a horizontal axis tracker. Moreover, the alignment of the modules will change when the system is undergoing wave motions. This can result in an inferior energy absorption per unit area when compared to pontoon type FPV systems [156].

A thin-film concept named SUNdy was proposed by Det Norske Veritas (DNV) for offshore applications. The array has a spider web hexagonal shape and a transformer installed at the centre, from which the electricity would be delivered to shore [32].

Using flexible crystalline silicon-based modules backed with foam may be less expensive than pontoon-based FPV systems [157]. The Ocean Sun technology lays rigid crystalline silicon modules on a reinforced flexible membrane. The operating temperature of the module is reduced due to direct heat transfer into the water below, exhibiting higher yields than air-cooled systems [158]. Buoyancy is obtained by an HDPE ring that encloses the membrane. A full-scale floating solar power unit is going to be tested in the Canary Islands [159]. Since the air gap between the modules and the water level is reduced, the additional cooling effect could grant a 5% increase in yield when compared with pontoon type designs [160]. Ocean Sun has also entered a technology license agreement for the installation of a demonstration system on the southwest coast of South Korea [161].

A Dutch consortium will be testing a 20-kW pilot flexible FPV plant until mid-2022 [162]. This plant will be installed at an artificial extension of the Port of Rotterdam and is meant to prove the feasibility of a 5 MW plant to be installed on the North Sea, attached to an existing OWT.

4. Synergies of marine FPV plants

Marine FPV plants may synergize with other MREs such as offshore wind [36] (Fig. 7), but also with other marine activities such as oil and gas platforms [163,164], aquaculture [35], desalinization [165] and port activities [46]. Moreover, system hybridization aims to improve MRE production [166] and FPV energy offers a wide range of possibilities [167–169].

Installing FPV systems in the idle spaces between wind turbines posess several benefits:

- Higher capacity density, up to 7 times the typical values for stand-alone OWTs [36].
- Increased and smoother power output since the diurnal nature of PV technology is compensated by the restless OWTs [170].
- Reduced environmental loads due to park effects. OWTs and FPVs can significantly change local sea-level climate and, similarly to other combinations of MRE, wind and wave shadows may result in lower environmental loads on FPV systems and OWT plants, respectively [166].
- Shared grid infrastructure and operation and maintenance (O&M) costs, which are some of the highest costs of both FPV [33,171] and OWT [73,172] projects.

Offshore oil and gas platforms demand large amounts of power, which are typically met through gas turbines [173]. However, for economic and environmental reasons, this task could be performed through MREs [174]. In fact, a methodology to assess the combination of wave and solar energy for this purpose was proposed by Ref. [163]. This combination resulted in an increased capacity factor and smoother power output.

Aquaculture farms consume large amounts of electricity and their self-sufficiency through renewable energies has been studied [175]. The dual-use of water for PV electricity generation and aquaculture is also known as aquavoltaics [35]. Furthermore, a hybrid platform that combines wind energy, solar energy, and aquaculture was proposed, taking full advantage of both of the aforementioned synergies [176].

Another marine activity that requires a large supply of electricity is seawater desalination, a solution to water scarcity that can be powered through several renewable energies [177]. Coupling nearshore FPV plants with technologies for the desalination of water can be a sustainable approach to meeting both energy and water demands. In fact, many countries at risk of a water crisis [178] have both access to shoreline and high irradiance levels [179]. A hybrid wind-solar floating platform for desalination was proposed for Egypt, a country below the water scarcity limit [180].

A different synergy is obtained installing FPV plants in ports. Seaports need high-energy supplies and are a source of air pollution, two environmental problems that can be settled through MRE. The port offers shelter, an existing infrastructure, a simpler grid connection and reduced O&M costs, while the FPV technology harvests energy for its supply. However, the presence of these plants can interfere with ship manoeuvring and port operation, so they are suitable for ports with a large water surface area. Hybrid floating breakwater-WEC systems have already been proposed [181]. A similar synergy could be obtained by attaching PV modules to these sheltering structures, resulting in an FPV plant that not only supplies energy demand, but also provides shelter.

5. Structural design and loads

5.1. General design procedure

The design of an offshore FPV plant encompasses several lifetime requirements, which include harvesting solar energy, withstanding the marine environment, and doing so in an environmentally friendly manner. To survive in the marine environment, the configuration of the device must satisfy several design constraints, such as excessive deformations, fracture criteria, weight and size, among others. This section focuses on structural design, defined as the process which procures a structural configuration that satisfies all of these constraints. FPV plants are exposed to permanent loads, operational loads, environmental loads, installation loads and accidental loads [182]. Only environmental actions will be considered since they are the most hindering aspect regarding the transition of these plants to the marine environment [12].

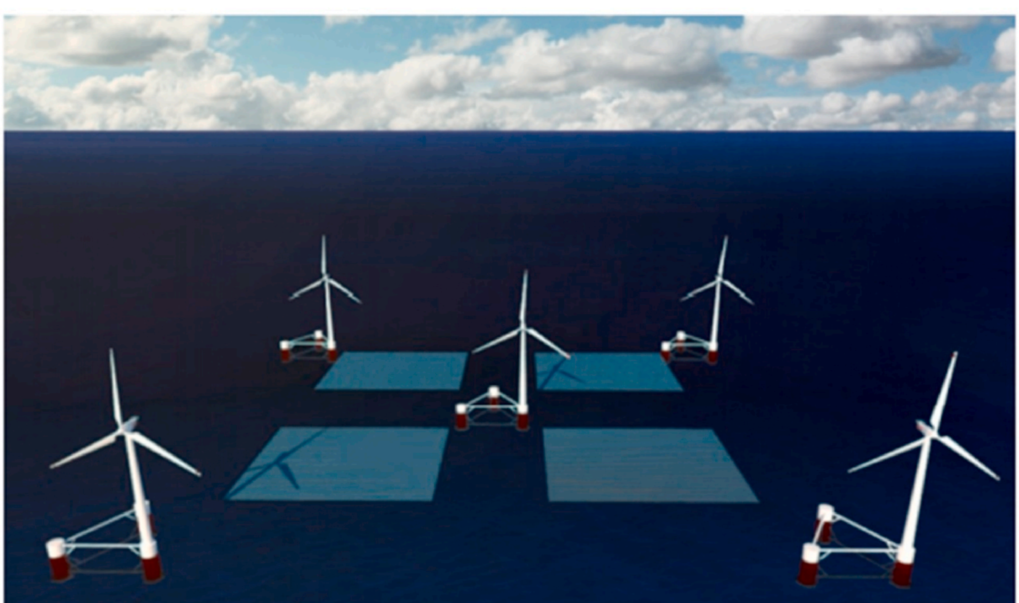

Fig. 7. Hybrid solar-wind farm concept [36].

Different methodologies can be applied to the structural design of FPV systems, and these can be classified according to the loading model and the response model. The purpose of the loading model is to estimate the forces and moments acting on the structure. The purpose of the response model is to take those forces as input and provide the displacements, rotations, stresses, and deformations of the structure. If the results of the response model affect the loading conditions, both models must be solved through iteration. The results of the response model are treated and compared to reference allowable values, which can be found in design standards (reviewed in Section 5.2).

Environmental loads, namely waves, winds and currents vary through time and space and may be estimated through analytical formulations or numerical methods (see section 5.3). Most analytical expressions contemplate the dynamic nature of the environmental actions through parameters and simplify the estimation of loads through a static approach [61,183,184]. These parameters are usually obtained through experimental testing. This approach entails great uncertainty, that must be countered through appropriate safety factors. Since environmental loads are generated by fluids, the numerical methods that estimate them are based on Computational Fluid Dynamics (CFD). Examples of application of these methods in the design of FPV systems can be found in Refs. [28,46,183,185,186].

As for the response model, the approach can be either static or dynamic. Static approaches are based on Newton's 1st law, whereas dynamic approaches are based on Newton's 2nd law. In a static response, loads are applied slowly, and inertial forces are not relevant. Stresses and deformations on the structure can be obtained through analytical formulations [184] or the finite element method (FEM) [61,129,186]. However, given the nature of environmental actions, marine structures require a dynamic response model. A rigid-body dynamics analysis can be applied to an FPV structure, providing a description of its position, velocity and acceleration throughout the frequency or the time domain [46,185]. Since these results influence the boundary conditions of the loads acting on the body, the loading and response models must be analysed through an iterative process. This analysis assumes non-deformation under the applied forces and excludes structures that display fluid, highly elastic or plastic behaviour. Rigid FPV structures (including all pontoon-type and rigid superficial systems, Fig. 6) may be analysed in this manner. Stress and deformation may be obtained through a subsequent structural static or dynamic analysis.

The design of flexible FPV systems (Fig. 6) should consider a different approach since deformations and loads are highly interrelated and should be coupled. Hydroelasticity, which uses the deformations of the structure as a boundary condition of the loading model, may be applied in this case [187,188]. The model can be constructed by coupling a potential flow solver for the fluid and a FEM model for the structure [189]. Examples of these approaches can be found in Refs. [28,186].

5.2. Design standards

The low maturity of marine FPV technology results in a lack of specific design standards, but some useful insight can be found in Refs. [21,47,48]. In addition, a recommended practice on the design, development and operation of FPV systems was recently published by DNV [49]. Nevertheless, all this literature is mainly focused on the design of plants located on inland water bodies. As of today, the is no specific standard for marine FPV applications. Standards and technical specifications from mature marine sectors (such as oil & gas or marine renewable energies) can provide further guidance for the design and analysis of marine FPV plants. These standards provide design bases, insight regarding metocean conditions and the estimation of environmental actions and guidelines for the verifications of different limit states, including ultimate, fatigue, service and accidental.

Standards are generally established by classification societies or government associations. There are more than 50 organizations that conduct marine classification, 12 of which are members of the International Association of Classification Societies (IACS). These are the following:

- American Bureau Shipping (ABS) [190];
- Bureau Veritas (BV) [191];
- China Classification Society (CCS) [192];
- Croatian Register of Shipping (CRS) [193];
- Det Norske Veritas (DNV) [194];
- Indian Register of Shipping (IR) [195];
- Korean Register (KR) [196];
- Nippon Kaiji Kyokai (NKK) [197];
- Polski Rejestr Statków (PRS) [198];
- Regsitro Italiano Navale (RINA) [199]; and
- Russian Maritime Register of Shipping (RS) [200].

Many design aspects are common to a wide variety of structures. In Europe, the Eurocodes specify how structural design should be conducted within the European Union, providing a means to prove compliance with the requirements (mechanical, stability, safety, etc.) and a basis for construction and engineering. Some useful standards are the following [201]:

- Eurocode 0: Basis of structural design (EN 1990);
- Eurocode 1: Actions on structures (EN 1991);
- Eurocode 2: Design of concrete structures (EN 1992);
- Eurocode 3: Design of steel structures (EN 1993);
- Eurocode 4: Design of composite steel and concrete structures (EN 1994); and
- Eurocode 9: Design of aluminium structures (EN 1999).

In the US, several governmental associations provide transversal insight into this matter through standards. These are listed below:

- American Petroleum Institute (API) [202];
- American Institute of Steel Construction (AISC) [203];
- American National Standards Institute (ANSI) [204];
- American Society for Testing and Materials (ASTM) [205];
- American Society of Civil Engineers (ASCE) [206]; and
- American Society of Mechanical Engineers (ASME) [207].

5.3. Environmental loads

5.3.1. Wind

Wind speed (U) varies with height above the sea surface across the atmospheric boundary layer. The mean wind speed is commonly measured at a reference height above the sea level of $z_{ref} = 10$ m and averaged over 1, 10 or 60 min. Note that solar modules are usually installed at lower heights and therefore wind speeds must be adjusted through a wind profile model. In the case of FPV plants, due to the usual lack of obstacles in their surroundings, a boundary layer model such as the power law can be used:

$$U(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (1)$$

where U_{ref} is the wind speed at the reference height z_{ref}, z is the height above the ground or ocean surface, and α is a parameter dependent on terrain roughness, which is site-specific.

The mean wind speed provides a rough estimate of the wind intensity for short-term stationary wind conditions (commonly 10-min averaging time). A more realistic description of these conditions can be obtained with wind speed spectra. Spectral models suitable for offshore conditions include the Ochi and Shin spectrum [208], the Simiu and Leigh spectrum [209] and the Frøya spectrum [210–212]. The latter has the following distribution:

$$S_U(f) = 320 \cdot \frac{\left(\frac{U_{ref}}{10}\right)^2 \left(\frac{z}{10}\right)^{0.45}}{\left(1+\tilde{f}^n\right)^{5/3n}} \tag{2}$$

where

$$\tilde{f} = 172 \cdot f \cdot \left(\frac{z}{z_{ref}}\right)^{2/3} \cdot \left(\frac{U_{ref}}{z_{ref}}\right)^{-0.75}, \quad \text{and} \tag{3}$$

U_{ref} is averaged over 1 h and $n = 0.468$.

The wind speed distributions should be obtained for the long-term analysis, which commonly requires 10 years of site-specific records or hindcast wind data [213]. The data records can be fitted to theoretical distributions such as Weibull and Gumbel in order to obtain the wind speed for a given return period and obtain wind loads on the structure for each phase of the project. The wind direction should be accounted for in the long term analysis. Otherwise, the most unfavourable wind direction should be considered for calculating the wind loads on the structure.

Wind pressure acts on the external and internal surfaces of the structure. The most intuitive forces are associated with the wind pressure and are normal to the exposed surface. It may be the most relevant due to the exposed flat surface of the PV modules. Frictional forces due to tangential drag should also be considered in large structures. Lift forces due to wind-induced pressures may also be relevant since they can compromise buoyancy or exert excessive loading on the mooring system. Dynamic effects such as vortex shedding, galloping or flutter should also be accounted for. The wind loading is a superposition of the static response and the resonant response due to dynamic effects. Wind forces on structures were addressed at length by Ref. [214].

In the case of FPV plants, wind loads should be considered on the PV panels and the floater freeboard as well as any other relevant exposed elements. The forces on the structure due to a steady wind load can be estimated through a static approach with the following formula [213]:

$$F_{win} = \frac{1}{2} \rho C_D C_S S u^2 \tag{4}$$

where ρ is the fluid density, C_D is the drag coefficient, C_S is the sheltering coefficient, S is the exposed surface and u is the flow velocity. Specific drag coefficients for FPV structures are not available in the specifications and therefore should be obtained through numerical and experimental testing, especially in the case of complex shapes.

In the case of floating platforms, low-frequency wind forces may result in resonant motions, thus a dynamic approach is required. CFD can be used to calculate wind loads on these structures. They solve the Navier-Stokes Equations for the air motion, but special attention must be paid to the turbulence model, the grid resolution and the boundary layer effects. Numerical models should be validated by experimental models in wind tunnels.

Many authors have published their findings regarding the effect of wind in ground-mounted PV plants. These methods are transferrable to FPV plants if the boundary conditions are adjusted. Some authors have analysed the effect of wind loads on these structures using different codes and standards [61,184,215] as well as wind tunnel testing [65]. The wind loads on FPV structures were analytically estimated by Refs. [46,61,129,184] and numerically analysed by Ref. [216].

5.3.2. Waves

The action of wind-generated waves was not the most hindering aspect of the structural design for most of the FPV projects due to the reduced fetch length (the horizontal distance over which wave-generating winds blow) of freshwater bodies. However, as the fetch length grows offshore, the wave height increases significantly. As a result, the wave action could be the major forcing factor in exposed coastal areas.

The statistical characteristics of wind waves in short-term (minutes to hours) and long-term scales (order of years) are required for a precise estimation of this action [217]. These statistics relate to cumulative effects related to fatigue, and extreme events related to the maximum load-carrying resistance [146].

To define wave loads on a marine FPV structure, a wave kinematics theory should be considered. The Airy wave theory is the most extended among them. This theory describes the instantaneous water surface elevation under a wave propagating along the x direction as follows

$$\eta(x,t) = \frac{H}{2} \cos\left(\frac{2\pi}{\lambda} - \frac{2\pi}{T} t\right) \tag{5}$$

where: t is the time, H is the wave height, λ is the wavelength, and T is the wave period. However, depending on the water depth and the local wave climate at the FPV plant site, a different theory may be applied. If the waves are too steep (wave steepness is defined as the ratio H/λ) or the water depth (h) is too small, a non-linear regular wave theory should be applied (Fig. 8) [218]. A typical design wave state for a freshwater FPV plant could be $h = 10$ m, $H = 1$ m and $T = 5$ s. The most suitable theory for these intermediate-depth conditions would be 2nd order Stokes. Marine FPV plants may be subjected to deep water waves. In this case, wave steepness alone will define the most suitable wave theory, ranging from linear theory to the higher-order theories.

Regular wave sea states are suitable for a preliminary design of FPV structures or if the expected dynamic response is limited [213]. For an accurate design, irregular sea states should be analysed by considering wave theories different from linear theory. The short-term distributions of waves are defined by means of wave spectral models such as the Pierson-Moskowitz spectrum [219] and the JONSWAP spectrum [220].

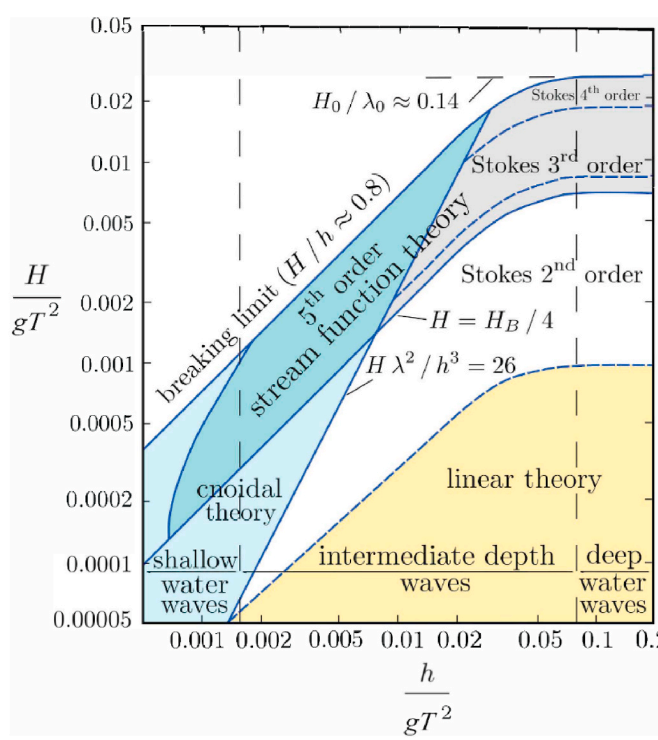

Fig. 8. Ranges of applicability of several theories for periodic water waves, according to Le Méhauté (adapted from Ref. [218]).

As an example, the former defines the power spectral density as

$$S_{wav}(\omega) = 4\pi^3 \frac{H_s^2}{(1.408 \cdot T_p)^4} \frac{1}{\omega^5} e^{-\left(\frac{16\pi^3}{(1.408 \cdot T_p)^4} \frac{1}{\omega}\right)} \quad (6)$$

where H_s is the significant wave height, T_p is the peak wave period, and $\omega = 2\pi/T$ is the angular wave frequency. Wave propagation direction (θ) is also a parameter that should be accounted for in the estimation of wave loads on an FPV system. Apart from the main wave propagation direction, the two-dimensional wave spectrum can be used to model the short-term distribution of waves in short-crested seas as

$$S_{wav}(\omega, \theta) = S_{wav}(\omega) F(\theta) \quad (7)$$

where $F(\theta)$ is the directional spreading function.

The design wave parameters for each significant phase of the project can be obtained from the long term distributions of the main wave parameters (mainly: wave height, period, and propagation direction) and their joint distributions. The return period should be consistent with the duration of each phase. For example, a service life of 25 years may be assumed for ultimate limit state design [37]. As a reference, at least 10 years of historical wave data are required to perform a proper extreme value analysis [213]. The consequences of failure of the structure should also be considered in the design wave parameters. Risk may be set as a function of the physical and economic characteristics of the marine structure or its components, as well as the direct and indirect economic repercussions, and the human loss in case of failure. Consequences of failure of marine FPV are mainly of an environmental and economic nature, such as collision with structures and ships, and environmental impacts [49].

Analytical methods are commonly used to estimate wave loading on freshwater FPV systems [221–225]. However, a detailed analysis of the wave regime is convenient for the design of marine structures [226]. Subject to the prevailing wave force (diffraction, drag or inertia) on a structural element of characteristic dimension D, wave force regimes can

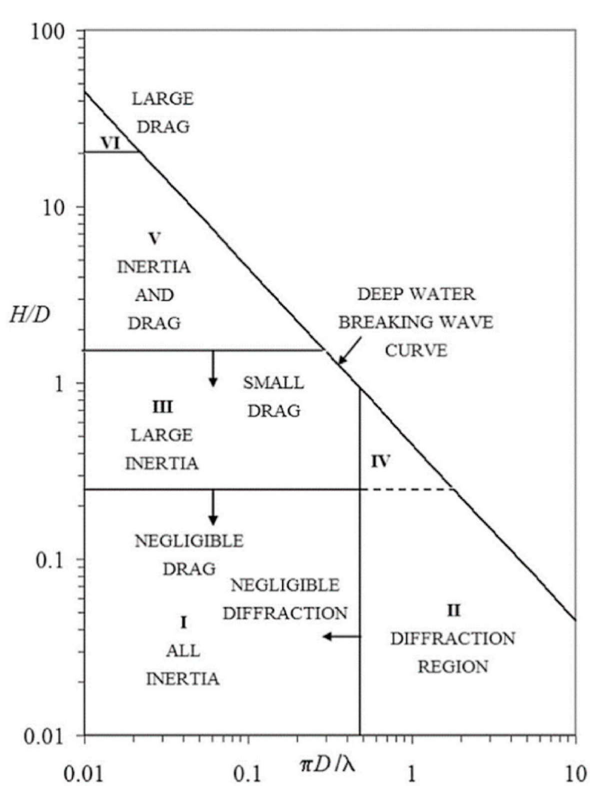

Fig. 9. Wave force regimes according to Ref. [226].

be defined as a function of the ratios D/λ and H/D (Fig. 9). Some of these hydrodynamic loads can be linearized into a frequency domain approach, whilst non-linear effects must be handled in the time domain. Other types of non-linear wave loads include slamming, breaking and overtopping.

The Morison approach, which assumes that wave properties are not affected by the presence of the structure, is suitable for slender elements with a small cross section ($D/\lambda < 0.05$). The wave force on a slender body (wave force regimes I, II and V in Fig. 9) can be expressed as a sum of drag forces and inertia forces [227] as follows

$$F_{wav} = \frac{1}{2}\rho C_D A u|u| + \rho V C_m \dot{u} \quad (8)$$

where C_m and C_D are the inertia and drag coefficients (to be obtained experimentally for complex geometries), V is the volume of the body, and A is its reference area. In the design of FPV systems, Morison's equation may be used to obtain wave loads on the mooring system and any other slender components of an FPV system [46,183,185].

Most FPV designs present a combination of slender and large volume elements depending on the wave conditions. Diffraction and radiation forces (wave force regimes II and IV in Fig. 9) may be dominant in large volume elements such as floaters. These hydrodynamic loads are commonly obtained by means of the potential flow theory, which assumes an incompressible and inviscid idealized fluid with an irrotational velocity field. Traditional numerical computational methods include the finite element method (FEM) [228], the Galerkin method [229], and the boundary element method (BEM) [230]. The latter is the most extended approach and has been successfully applied in other floating marine renewable energy devices (e.g. Ref. [231]). BEM models, also known as panel models, solve the frequency-dependent hydrodynamic coefficients (radiation damping and added mass) of the structure after solving the velocity potentials. These coefficients can be used as inputs for a subsequent time domain analysis. Some codes also allow the computation of the instantaneous hydrostatic and Froude-Krylov forces over the wetted surfaces for each time step, which reproduces some non-linear effects [232]. The models based on potential flow theory are suitable for the initial and intermediate design stages of an FPV system, due to their good compromise between accuracy and computational requirements. For instance, a BEM analysis of a novel Class 1 system was performed by Ref. [185] for marine conditions.

However, these linear models are unsuitable if non-linear hydrodynamic phenomena (viscous flow separation, wave breaking, and wave overtopping) are relevant. In this case, other CFD methods are required, namely: (i) the finite volume method, based on structured Eulerian meshes, and the volume of fluid technique for tracking the liquid-gas interface [233], or (ii) the smoothed-particle hydrodynamics, based on Lagrangian mesh-free methods [234]. Both include nonlinear hydrodynamic effects but at a high computational cost. These models have been applied to other floating technologies (e.g. Refs. [235,236]), and represent an interesting approach for a detailed analysis of FPV systems. The response of a Class 1 solar farm was validated through CFD in Ref. [183] and an example of coupled CFD-FEM analysis using an Arbitrary Lagrangian-Eulerian formulation can be found in Ref. [28].

Previous works on FPV design failed to address waves in a comprehensive manner. A static calculation was performed by Ref. [184], where floating islands were considered large rigid bodies instead of individually connected floaters. A single wave height and three directions were evaluated. In the static approach proposed by Ref. [61], a displacement load was applied to certain parts of the FPV to simulate waves, defining 3 scenarios. An analytical approach using the Morison equation was performed by Ref. [183], where results were validated through a CFD model. Even though different combinations of wave height and period were considered, just a single wave direction was analysed. A rigid body dynamics analysis was performed in the frequency and time domain in Refs. [46,185]. Both analyses were multidirectional, but only addressed a single combination of wave height and period. In the hydroelastic analysis performed by Ref. [186], only a single combination of wave height and period, for 3 directions, was considered. In the hydroelastic approach performed by Ref. [28], only a few wave heights and periods and a single wave direction were evaluated. None of the mentioned analyses considered irregular sea states.

An accurate approach to estimate wave loads on marine FPV structures should consider multidirectional wavefronts and perform simulations of irregular wave conditions. The dynamics of the floating body cannot be ignored, and the impact of non-linear phenomena must be assessed beforehand.

5.3.3. Currents

Most FPV plants have been installed in lakes and reservoirs where currents are not a major concern. However, the effect of currents in some marine applications could be relevant. Deep-water current profiles can be very complex, and directions can adopt opposing directions with depth [237]. A strong enough current can also modify the wave conditions and vice-versa [238].

There are several types of currents, and their joint action should be considered at the studied location [213]. Ocean currents are large-scale currents driven by density and temperature gradients (thermohaline circulation) and constitute the global conveyor belt. Tidal currents follow a regular pattern, and their maximum values usually follow extreme tide events. These are very relevant in estuaries, inlets, or straights where the coastal morphology accelerates the flow. Wind-generated currents are mostly superficial, can present a linear or slab profile and vanish under a certain depth. Wave-induced currents are originated due to the oblique breaking of waves with respect to the shoreline. They run parallel to shore and can be relevant in nearshore FPV plants. Since restricting the natural flow of a current can result in sediment accumulation and environmental impacts on estuaries and shorelines, the impact of a floating plant on natural currents should be studied when installed in susceptible locations.

The consequences of these loads on the floating structures can be drift motions, drag and lift forces, and vortex-induced oscillations of the submerged slender members. Currents can also erode the seabed, exposing the foundation of the mooring system of the plant.

Since current speeds are inferior than those of wind, dynamic pressure effects are less important than viscous boundary layer forces [239]. Estimating the current loads on the structure is analogous to the wind loads and can also benefit from experimental and CFD numerical models [240]. Current load estimation may also be combined with waves by adding the corresponding flow velocities or by advanced CFD methods that solve the wave-current interaction [213].

There are barely any publications that address water current loading on FPV structures. Nonetheless, this matter has been tackled in more mature offshore sectors, like aquaculture [241], offshore wind [242] and, of course, tidal/stream energy converters [243]. These loads are generally estimated via experimental tests, static approaches or CFD models.

5.3.4. Tides

The water level is an important parameter for the design of an FPV plant [48]. These water level variations are a combination of astronomical tides (driven by the gravitational forces exerted by the Moon and the Sun) and meteorological tides (driven by storm surges and other atmospheric phenomena) [244]. Both tide types should be combined to obtain the water level boundary conditions in the load assessment of an FPV structure. While astronomical tides follow a predictable regular pattern [245,246], storm surge events are commonly forecasted through numerical models [247]. For a precise definition of water level variations, tide gauges (also known as mareographs) can be deployed on site.

Water level variations mostly influence the design of the mooring system. Taut moorings could be unsuitable since they may slack in low water levels and/or sink the structure in high water levels. Rigid moorings should allow the vertical movement of the floating structure through the full range of water level variations. Catenary moorings should be long enough to maintain an appropriate shape during both extreme water levels. Buoys and weights can be used to maintain this shape. Flexible mooring systems, like Seaflex®, respond adequately to water level fluctuations [68].

The tidal variations also influence the local wave conditions. Wave breaking depends on the local water depth and restricts the maximum possible wave height. The wave celerity, which also depends on the water depth, governs the wave propagation onshore, which includes phenomena such as refraction and shoaling [146]. Therefore, the full range of water levels should be considered to set the boundary conditions of the FPV. In offshore projects, the mean high and low water spring levels are commonly considered, while in near-shore projects the highest and the lowest astronomical tides may be applied instead [49].

There are scarce publications that consider the water level variations in the calculation of an FPV structure [46]. However, some freshwater systems were designed for reservoirs with strong water level variations [248,249], and some even contemplated the possibility of reservoirs drying up [48]. Not much is yet known regarding marine applications. However, the world's largest offshore plant is meant to have the full installation seat on the seabed during low tides [143].

6. Conclusions

To gather the key issues in the design of marine FPV systems, a comprehensive review of the existing technology was performed with a focus on structural design aspects. The main elements of FPV systems were described and, for each one, the design implications of transitioning to the marine environment were identified. Subsequently, a thorough classification of the existing FPV technologies was presented, along with an assessment of their suitability for the marine environment. The synergies of marine FPV plants with MRE and other proposed combinations were also disclosed. Finally, general rules and approaches for the estimation of environmental loads on marine FPV systems as well as the structural design of the plant were introduced. Recommendations and conclusions of major interest are summarized hereinafter.

In contrast to freshwater FPV systems, marine designs are required to endure extreme environmental loads and resist saltwater corrosion and biofouling. In pontoon-type solutions, plastic materials such as HDPE may be applied to floats. Antifouling coatings and sustainable materials should be considered to prevent the degradation of their mechanical properties and to avoid microplastic pollution, respectively. To withstand the extreme marine loads (mainly wind, waves and currents), FRP may be used in structural members instead of metallic materials, which are heavier and prone to corrosion. The supporting structure may also play a significant role in keeping the panels at a safe height from the sea level. The mooring system would make up a large share of the total structural costs of an FPV system. Mooring systems for marine FPV systems are still far from being resolved, but a good starting point is conventional offshore mooring designs, such as catenary, taut, compliant and rigid. Typical anchoring systems, like dead weights, drag anchors, embedded anchors, or suction foundations may also be applied. In the marine environment, the PV modules will be required to resist higher mechanical tension and withstand saltwater corrosion. Rigid modules may be enhanced through external coatings and proper encapsulants. Alternatively, a flexible approach may be adapted through thin-film technology. Tracking, cooling, cleaning, and storage systems, which are intended to maximize yields, can be incorporated into the FPV designs.

The analysis of the different FPV technologies revealed that pontoon type plants will probably play a major role in the transition to the marine environment. Class 1 systems could adopt flexible joints, rescale their floating systems and consider a higher truss structure to keep the modules safe. The very conception of Class 2 plants relies on cost savings rather than structural performance. As a result, these systems are not suitable *per se* for offshore conditions and require strong design adaptations. Class 3 systems are essentially floating islands. They are technically feasible by means of rescaling, but costs will escalate as well. Superficial plants played an experimental role in the current FPV market but show great potential for offshore applications, especially thin-film based designs. These systems minimize stress by allowing deformation and could be cheaper than pontoons, at the cost of harvesting less resource.

Synergies between marine FPV and other sectors were gathered and discussed. A great synergy was found when co-locating FPV plants with other MRE, especially with OWTs. FPV plants can also synergize with marine sectors that require the supply of electricity, such as aquaculture, seawater desalination, offshore oil & gas and seaports. The potential of the synergies that this technology presents were found to be as vast as untapped.

Key aspects of the design of marine FPV plants were disclosed in this article. Since there are no specific design standards for marine FPV plants, standards meant for freshwater applications and other marine structures were provided as general design guidance. Environmental actions are the main loading source for marine FPV plants. Different methodologies can be applied to assess the structural response of FPV systems to environmental loading. However, since the dynamic response of FPV plants cannot be ignored in the marine environment, rigid solid dynamics or hydroelastic methods should be applied.

As for the estimation of environmental loads, a statistical approach is required, bearing in mind the 25-year lifespan of FPV structures and the acceptable risks. Wind loads on the PV modules and floater freeboard may be assessed through analytical formulations. Nonetheless, a realistic analysis would require CFD models or/and wind tunnel testing. Estimating the current loads on the marine FPV structures is, for the most part, analogous to the wind loads. Although wind was the major environmental concern in freshwater FPV designs, wave action could be the major forcing factor in exposed coastal areas. For an accurate design, irregular sea states should be analysed by considering wave theories different from linear theory. Loads way be estimated through the Morison formulation, CFD models, or a combination of thereof, depending on the relative size of the floating bodies and the importance of non-linear phenomena. Water level is of paramount importance for the design of the mooring system. Thus, different tide scenarios must be considered during the analysis of the plant. Both tides and currents will affect wave conditions, and that must be addressed as well.

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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