Marine floating solar plants: an overview of potential, challenges and feasibility

Sara Oliveira-Pinto MScSenior Researcher, Equinor ASA (formerly designated Statoil), Stavanger, Norway (corresponding author: spin@equinor.com)**Jasper Stokkermans** BSc, MSc

Marine Engineer, Equinor ASA (formerly designated Statoil), Stavanger, Norway

The offshore environment represents a vast source of renewable energy, and marine renewable energy plants have the potential to contribute to the future energy mix significantly. Floating solar technology emerged nearly a decade ago, driven mainly by the lack of available land, loss of efficiency at high operating cell temperature, energy security and decarbonisation targets. The vast majority of the available technology and projects in operation are located in inland freshwater bodies. Currently there is momentum in the sector to develop floating solar systems to be deployed in marine environments. Experience from inland floating solar projects could open up possibilities to scale up and move to nearshore or even offshore conditions. Hence, it is relevant to explore the technical feasibility and challenges of designing floating photovoltaics (FPV) in marine environments, with a natural transition of FPV applications first to nearshore locations and then further exposed offshore environments. This research study provides a literature review of the potential of marine applications of floating solar plants, exploring the current available technologies, the technical challenges and the risks in designing and building these projects in the marine environment.

1. Introduction

Worldwide demand for energy is continuously rising and is projected to increase by 28% between 2015 and 2040 (IEA, 2017a), mainly propelled by developing countries, such as India or China, where strong economic growth drives increasing demand for energy (IEA, 2017b). Most of these developing economies are highly dependent on fossil fuels (oil, gas and coal) for electricity generation, which are well-known for having negative impact on the environment (Hussain *et al.*, 2017). Naturally, the growth in world's energy demand from fossil sources has had a key role in the rising levels of greenhouse gases in the atmosphere (Hussain *et al.*, 2017), but it is also linked to environmental pollution, which threatens public health. Therefore, finding alternative and more sustainable sources for electricity production is imperative. Currently, governments are investing significant efforts to seek more sustainable options to meet energy demands, rethinking their energy sector strategies and eagerly bringing renewable energy production into their country's energy mix. For that purpose, over the past years, governments have supported policies that support the penetration of renewables. This, combined with technological progress, has made it possible for alternative energy sources to become more cost-efficient and viable. The renewable sector is now into a positive loop marked by decreasing costs, rising investments and technology innovations. Therefore, unprecedented growth in renewable energy deployment is observed globally. By the end of 2018, the overall global renewable power capacity comprised of approximately 33% (2378 GW) of the world's power installed capacity (REN21, 2019). It is expected that by 2040 a large majority of

the worldwide renewable electricity generation will be from the hydropower sector, wind and solar photovoltaic systems (US EIA, 2016).

Currently, solar energy is one of the most attractive renewable energy sources. The most common way to harness solar energy is by using photovoltaic (PV) systems, which consist of electronic devices made of a material that exhibits the PV effect that converts sunlight directly into electricity (Hernández-Callejo *et al.*, 2019). PV systems are currently used in a variety of applications, from in-roof mounting systems to hundreds of megawatt ground-mounted plants to building integrated PVs. It is also common to find applications of solar modules in traffic lights, road signs, emergency telephones on motorways and even in coastal monitoring buoys. The recent developments and rapid cost reductions were the two main factors that enabled the sector to have the present steady growth (Reichelstein and Yorston, 2013). In fact, utility-scale PV systems have already achieved grid parity with conventional power plants. The levelised cost of energy (LCOE) of conventional energy generation projects such as coal range from 55 to 132 €/MWh (Lazard, 2016) or nuclear energy range between 89 and 125 €/MWh (Lazard, 2016), whereas the LCOE for utility-scale solar PV projects is between 45 and 56 €/MWh (Lazard, 2016).

In one decade, the growth of the solar PV sector was remarkable, reaching nearly 120 GW of the cumulative installed capacity in Europe by 2018 (Komusanac *et al.*, 2019), which corresponds to a more than tenfold increase. However, the

sector is expected to continue to have steep growth in the next upcoming years. By 2050, approximately 40% of global electricity generation will be provided by solar PVs, achieving an estimated cumulative installed capacity of nearly 19 TW globally (DNV GL, 2018). The installation of large-scale PV systems has large requirements on land usage, approximately 1.6 ha (0.016 km²) of land for each megawatt installed (Kabir *et al.*, 2018), for crystalline silicon (c-Si) technologies, which represent the large majority of PV installed capacity, representing *c.* 95% of the worldwide PV annual production in 2017 (Fise, 2019). Assuming that 70% of the aforementioned global cumulative installed capacity will be achieved by ground-mounted PV systems, that would translate to a land usage of nearly 212 800 km², a coverage of 88% of the UK (1.63 times the size of England). Lack of available land in some locations (especially in countries with a high population density and multi-purpose use of land) means that PV applications conflict with, for example, agricultural use or tourism (Liu *et al.*, 2018); this can lead to challenges in acquiring land for energy projects. Non-availability and/or competition for land will contribute to an increase in acquisition costs, impacting negatively the economic viability of solar projects. Additionally, the most attractive sites for deployment of ground-mounted PV systems have already been used, consequently leading to deployments in remote areas, far away from consumers. Lack of accessibility to transmission infrastructures and long distances to deliver power bring higher costs. There are thus still several challenges that limit the development of ground-mounted PV technology, mainly: (a) loss of efficiency at high operating cell temperatures as a consequence of the drifting effect (Cazzaniga *et al.*, 2018); (b) projects located in remote locations, which leads to high infrastructure costs (e.g. substations, transport, operation and maintenance (O&M)); (c) projects located in difficult areas (hilly or unstable terrains) leading to more site preparations (earthworks), hence increases in capital expenditure.

Given the above context, floating photovoltaics (FPV) have emerged as a solution to mitigate the above challenges, by providing optionality for the deployment of PV modules predominantly on man made reservoirs such as hydroelectric dams, small lakes, wastewater storage ponds and so on (Sahu *et al.*, 2016; Spencer *et al.*, 2019; Trapani and Santafé, 2015). The momentum gained by the sector in the last few years led to a total cumulative installed capacity of FPV of 1.1 GW by mid-2018 (against 132 MW in 2016), with Asia leading the wave of FPV projects followed by Europe (Boersma *et al.*, 2019). The World Bank report (Seris, WBG and IFC, 2018) conservatively estimates that the global potential of the FPV sector is nearly 400 GW.

Despite the higher costs, FPV systems are still considered a competitive technology, mainly due to two main advantages:

(a) the use of idle areas, being an attractive solution for densely populated countries, avoiding conflicts, for example, with agricultural use or tourism (Liu *et al.*, 2018) and (b) the potential for co-location of FPV systems on hydropower reservoirs. The latter has yielded multiple unique advantages, such as cost savings as a result of proximity to grid connections and existing infrastructures (Rosa-Clot *et al.*, 2017; Silvério *et al.*, 2018) and increased energy production. Co-location also enables a better ability to meet peak demand, especially in dry regions, where the two resources are highly complementary (Rosa-Clot *et al.*, 2017; Silvério *et al.*, 2018). Thus, installing FPV systems can reduce over-reliance on hydropower for electricity generation. Furthermore, it is argued that FPV systems will reduce the evaporation of the free surface of water bodies, by absorbing the solar radiation that the water would absorb and reducing airflow (Rosa-Clot *et al.*, 2017; Santafé *et al.*, 2014). In addition, it is expected that FPV systems will have a minimal impact on both fauna and flora at the site location; except for the often-desirable reduction in algae growth (Sacramento *et al.*, 2015; Sahu *et al.*, 2016). However, the environmental impacts are still poorly documented.

The different advantages of applications of FPV systems in freshwater environments have been highlighted in the literature by several authors – for example (Choi, 2014; Choi *et al.*, 2016; Rosa-Clot and Tina, 2011, 2018; Sahu *et al.*, 2016; Trapani and Millar, 2013). Another relevant advantage of FPV technologies is the expected increase in power production as a result of lower ambient temperatures underneath the panels, due to the natural cooling effect provided by the proximity to water, allied with the fact that the reflectivity of water increases irradiance in the PV array (Liu *et al.*, 2018; Sahu *et al.*, 2016; Seris, WBG and IFC, 2018). However, there are uncertainties regarding the magnitude of the enhanced power production, as energy production gains ranging from 1.5% to 22% have been documented in the literature (Lee *et al.*, 2014; Liu *et al.*, 2017; Rosa-Clot *et al.*, 2017).

As FPV applications in freshwater bodies are becoming more mainstream, there is already a focus from the sector to search for opportunities among marine applications. With offshore environments representing a vast source of renewable energy and with marine renewable energy (MRE) infrastructures having the potential to contribute significantly to the future energy mix, it is relevant to explore the technical feasibility and challenges of designing FPV in marine environments. The transition of floating solar applications to marine environments is a natural trend (Rosa-Clot and Tina, 2018). The motivation to explore marine applications of FPV is driven by the fact that most of the world's megacities are located along coasts and are currently facing strong population growth, stressing their land resources and challenging their ability to meet the increasing demand for energy. Despite

typically having busy coastal regions due to fishery activities, shipping lanes or even recreational areas, these regions still have unused areas, usually close to the shore, that can be used for energy generation. Most likely, offshore wind will not be the desirable MRE, due to its visual impact (a wind turbine has *c.* 200 m height). Proximity to consumers is also a relevant driver. In addition, the deployment of FPV systems in marine environments is an appealing alternative for cost reductions associated with the required land use (Sahu *et al.*, 2016). However, further research is required before commercial large-scale sustainable projects can be developed in marine locations.

It can be envisaged that the transition of FPV systems to marine environments will be carried out first for nearshore sheltered environments and then for further offshore locations.

Even though the first type of environments may be considered benign, depending on the location's characteristics, the local wave height can increase due to coastal processes – for example, reflection of the incoming waves. In addition, the existence of breaking waves may lead to excessive loads acting on the structure, thus implying increased costs associated with a more resilient design of the materials, the metallic frame and the mooring lines, as well as higher costs related to operating costs. Therefore, the current technologies available for freshwater environments will not be applicable for marine applications, hence the sector should focus on technology development for these environments. It is already possible to find literature on technologies for the aforementioned end (Grech *et al.*, 2016). Nonetheless, while offshore applications are several years out from reaching commercial status, it is already possible to find, among the sector initiatives, technologies to be implemented further away from the shore (Bellini, 2018), where the potential of co-location with offshore wind is being explored, taking advantage of the calmer water surface between wind turbines and the existing connection lines with power networks.

There are several opportunities for research and development within the sector, aiming for standardisation and optimisation of the technologies to enable commercialisation of the marine segment of FPV. However, due to the immaturity of the sector, there is a limited number of standards that can be directly used for designing these systems. Nevertheless, synergies can be drawn from several mature sectors such as offshore oil & gas (O&G), offshore wind and coastal engineering. Such synergies are key factors to ensure that the systems are designed to safely operate throughout their lifetime and to survive extreme weather events. This study aims to contribute to close the technical gap of design marine FPV systems, by providing a literature review and leveraging on the competence and knowledge from the before-mentioned industries, while transposing the relevant aspects that will have a major impact on the design of

marine FPV systems. Thus, the main objective of this paper is to address the potential of marine applications of floating solar plants, exploring the current technologies available, the technical challenges in designing and building these projects in the marine environment.

In addition, this paper also addresses the opportunities and synergies of co-location of marine FPV with offshore wind plants, due to the natural intra-annual complementarity of the solar and wind resources. In general, wind generates more energy in wintertime, whereas in summertime the opposite is the case. Finally, the co-location of marine FPV with offshore wind plants could be a niche market enabler to launch the commercial feasibility of marine FPV, despite the typical harsh environmental conditions of these locations.

The paper is organised as follows. Section 2 provides a brief description of the main components of an FPV system, based on the commercially available technologies. Thereafter, a literature review of the technologies for marine applications is presented. Section 3 aims to provide an overview of the key technical aspects of marine FPV systems, as well as a reflection on the risks and challenges of the sector. Finally, an overview of the most relevant design considerations regarding loads and load combinations is presented. Section 4 explores the opportunity of combining marine FPV and offshore wind farms at the same marine area, presenting the potential development synergies and issues associated with a combination of both renewable resources. Section 5 outlines the main conclusions.

2. Floating solar technologies

Currently, floating PV applications are still confined to inland water bodies such as lakes or hydroelectric dam reservoirs, which are characterised by having limited wave motions. A generic FPV plant, depicted in Figure 1, consists of the following elements (Sahu *et al.*, 2016; Seris, WBG and IFC, 2018): (a) the float, (b) the PV modules and their supporting system, which supports the weight of the modules and transmits the stresses on the float, (c) the electrical equipment, such as inverters and cabling, and (d) mooring and anchoring. A description of the main equipment in FPV plants is provided in Table 1.

The FPV sector lacks technology convergence with regards to floating structures. It is possible to find in the literature several concepts at different technology readiness levels (TRL) (Figure 2) ranging from individual rectangular-shaped floats made of high-density polyethylene (HDPE) connected with pins (Sahu *et al.*, 2016) to tubes supporting galvanised steel frames with fixed tilted-angle PV modules (Sahu *et al.*, 2016) or even innovative emerging solutions, such as the use of membranes (Bjørneklett, 2018).

Figure 1. Main components of FPV system (adapted from Seris, WBG and IFC (2018))

Table 1. Description of main equipment in FPV plants

Float	PV panels	Mooring system	Electrical equipment	
			Inverters	Electrical cabling
The floating structure provides buoyancy to the system, support to the PV panels and their supporting system. This structure can be constructed from various materials but often plastics (HDPE) are used for freshwater applications.	<p>The PV panels convert solar radiation directly into electricity through the PV effect (IFC, 2015).</p> <p>There are several PV technologies available on the market and several ways to classify them (Rosa-Clot and Tina, 2018). One classification is based on the thickness of the semiconductor: conventional silicon solar technologies or thin-film technologies.</p> <p>Mostly crystalline solar PV modules have been used for the floating solar systems. Multiple solar panels are mounted on the floating structure with a support system keeping the solar panels in place. For some solutions the solar panel support system is an integrate part of the floating structure.</p> <p>Glass–glass modules are often used on floating applications due to the lower permeability of water, protecting the solar panels of internal corrosion.</p> <p>PV panels are typically installed with a fixed tilt.</p>	<p>The mooring system fixes the floating structure's position to the bottom and/or to basin edge.</p> <p>The mooring system needs to account for the change in the water level of the basin. Its design also depends on the geotechnical conditions of the site.</p> <p>Mooring lines are generally formed of steel wires or synthetic ropes combined with steel chains (Sahu <i>et al.</i>, 2016), while anchor systems normally use concrete ballasts or helical piles.</p>	<p>Inverters are well-known solid electronic devices. Their main function is to convert the direct current (DC) output from the modules to grid-compatible alternating current (AC) electricity (IFC, 2015).</p> <p>There are two broad classes of inverters: central inverters and string inverters. The former are mainly used in medium and large-scale solar PV plants.</p> <p>Inverters can either be mounted on a floating platform or in land (Seris, WBG and IFC, 2018).</p>	<p>The power generated from the FPV system is transferred to land-based substation by way of an underwater cabling.</p> <p>Currently most of the projects installed do not have cables installed underwater. Regardless, a proper ingress protection rating needs to be guaranteed due to the high humidity environment and the mechanical cyclic motions of waves (Sahu <i>et al.</i>, 2016).</p>

Figure 2. (a) Individual float; (b) tubes supporting galvanised steel frames; (c) membranes (Seris, WBG and IFC (2018))

Currently, the most common type of floating structures in the sector are individual HDPE floats (Boersma *et al.*, 2019). In general, it is deemed that these individual floats with connecting pins are suitable for small waves, typically for wave heights up to 1 m (Ciel & Terre, 2018). The connection ears and pins are the weakest elements and determine the system strength. Hence, if these elements are exposed either to oblique waves or to slightly higher waves than the design limits there will be hot spots for stress concentration, which can compromise the reliability of the system. Moreover, as the FPV sector grows, the size of the projects will increase dramatically. Thus, in order to accommodate a multi-megawatt project, access to a larger water body will be required, hence the impact of the fetch on the wave generation process needs to be considered. Sites with great wind speeds allied to a longer fetch will contribute to the generation of higher waves. Therefore, this increases the vulnerability of these installations to adverse and extreme weather events, as it is expected for dynamic loads to occur, leading the floats to overturn, or the increase in motion could induce stresses at the connection points between floats, leading to failures and disintegration of the FPV system. FPV technologies such as membranes or tubes supporting galvanised steel frames could be a more reliable solution. However, further research needs to be carried out.

The above, allied with the upcoming transition of FPV applications to the ocean and its harsher wave conditions, make this type of float not suited to marine environments. It is already possible to find research activities focusing on the development of FPV concepts for ocean locations, targeting technology development and mainly focusing on finding the optimal

geometry for the float and addressing the challenges of the connections between the floats (e.g. Trapani and Millar, 2013, 2014).

Trapani and Millar (2014) developed a concept consisting of a thin-film flexible floating PV array. The inherent flexibility of concept allows it to damp incoming waves, thus minimising the forces on the structure and the mooring system (Trapani and Millar, 2014). Grech *et al.* (2016) built and tested four different prototypes of floating PV installations, which were deployed in a marine environment. Data were collected for more than a year and the results were compared with a similar installation constructed on land. The four technologies tested consisted of different floats, mounting techniques and PV module technologies. Grech *et al.* (2016) observed that the FPV technologies tested benefited from the cooler environment, increasing their electrical power output, while salt deposits on the PV modules did not appear to be an issue.

Commercial technologies are also emerging, with Swimsol (Figure 3(c)) being a pioneer. Together with Vienna University of Technology and the Fraunhofer Institute, Swimsol developed and launched, in the Maldives, one of the first commercial projects in a marine environment. The total project capacity is 96 kWp, comprising four platforms of 24 kWp each, moored independently (Rosa-Clot and Tina, 2018). The Swimsol concept Solar Sea 1500 can withstand waves up to 1.5–2 m high (Putschek, 2018) and consists of a semi-submersible type of floater, made from styrofoam with a frame of aluminium. The PV modules are installed with a 10° tilt (Rosa-Clot and Tina, 2018).

Figure 3. (a) SUNdy (DNV Kema, 2019; Sahu *et al.*, 2016). (b) Heliofloat (Eisl and Haider, 2016). (c) Swimsol (Swimsol, 2020)

DNV Kema (2019) developed a concept named SUNdy, targeting ocean applications consisting of a hexagonal array, which floats on the ocean's surface (Sahu *et al.*, 2016) (Figure 3(a)). Each array has an installed capacity of 2 MW and can either be deployed independently or linked to other production units to form a multi-megawatt FPV plant by means of marine-grade connectors (DNV Kema, 2019). The proposed float is made of a flexible foam mat where thin-film solar modules are attached (DNV Kema, 2019; Sahu *et al.*, 2016). This thin film is flexible and lighter than traditional rigid glass-based modules, thus enabling the overall system to follow the motion of the waves (DNV Kema, 2019), contributing to minimising wave-induced loads. The concept allows the electrical equipment, namely the inverter, to be installed in the centre of the float (Sahu *et al.*, 2016). The hexagonal shape minimises the number of anchor points, while also allowing the energy islands to be nested or grouped (DNV Kema, 2019). The overall system design enables the structure to deform to the incoming wave fronts while simultaneously being structurally robust. Nevertheless, such ability may lead to an increased complexity in terms of the design of the mooring cables for both the ultimate and fatigue limit state.

Heliofloat (Figure 3(b)), developed by the company of the same name, is a lightweight platform designed to hover above the water on air cushions (Eisl and Haider, 2016). A flat, open cylindrical skirt made of soft, flexible material is used as the

float, to increase buoyancy. PV modules are mounted on top of the platform's topside, which are then connected to the cylindric floats (Eisl and Haider, 2016). This concept was envisaged to have minimal impact on local fauna and flora as the platform is made partially of transparent material and therefore sunlight is not blocked from passing through the water (Eisl and Haider, 2016).

A consortium consisting of the Energy Research Center of the Netherlands, the Netherlands Organization for Applied Scientific Research, the Netherlands Maritime Research Institute, Abu Dhabi National Energy Co. and Oceans of Energy, a spin-off of Netherland's Delft University of Technology, worked together from 2018 to 2020 on the development, construction and operation of the world's first offshore floating PV plant for the North Sea (Bellini, 2018). A 8.5 kW modular PV system has been in operation since November 2019 and has successfully survived many storms (Bellini, 2019a). The goal of the pilot project is to be expanded shortly to 50 kWp, which will be tested for a year. The consortium is aiming to go even further and expects this demonstrator to reach megawatt-scale capacity (Bellini, 2019a). Although little is known about the floating system, it appears that PV modules were installed on a suboptimal horizontal configuration, which improves mechanical stability but is more prone to water inundation. Additionally, this project will test the viability of FPV projects at sea, in combination with wind power.

Following the lead of the above consortium, the marine engineering firm Jan De Nul Group has joined the race on technology development of marine application of FPV and a Belgian consortium has been formed to develop and construct another floating PV project in the North Sea (Bellini, 2019b). The pilot is expected to be launched during 2020 and will be located close to an aquaculture and offshore wind farm (Bellini, 2019b).

Recently, it was announced that Equinor and Moss Maritime are collaborating to develop a FPV concept for marine environments. The intention is to start a pilot project where the technology will be tested (ME, 2020).

2.1 Market and sector overview

The first FPV applications emerged in 2007 with one of the early constructions in Japan, the Aichi project, comprising an installed capacity of 20 kW (Sahu *et al.*, 2016; Seris, WBG and IFC, 2018). Subsequently, FPV applications expanded globally, with many installations located in Asia, namely in China, South Korea, India, Indonesia and Japan, among others (Ranjbaran *et al.*, 2019). The majority of the projects developed were small-scale systems aimed for research and demonstration purposes (Trapani and Santafé, 2015). In 2014,

the average plant size was 0.5 MW. The turning point for the sector was in 2015 with the first larger plant (7.55 MW) installed in Japan (Boersma *et al.*, 2019). FPV projects have been subsequently increasing in capacity, with the first multi-megawatt project installed in China in 2017 (40 MW) (Boersma *et al.*, 2019). Currently, China also has the largest FPV plant, with an installed capacity of 150 MW (Seris, WBG and IFC, 2018).

The cumulative installed capacity of FPV and the annual installed FPV capacity are presented in Figure 4. The growth in the sector has been impressive, with the cumulative installed capacity almost doubling in one year (2017–2018) enabling the sector to rapidly turn into a GWp industry. Asia is leading the current market for FPV applications, having a total installed capacity of *c.* 814 MWp. China hosts the largest projects, while Japan has the largest number of installed projects (Boersma *et al.*, 2019). The market in Europe is starting to develop, with the Netherlands being a very promising market for FPV, benefiting from a lot of inland water surfaces and enjoying favourable renewable energy policies. The potential of FPV has recently been mapped for Germany, and it was concluded that it could reach up to 3 GWp only in coal mine lakes (Enkhardt, 2020).

The growth of the sector contributed steeply to the improvement of its commercial pathway. The World Bank report (Seris, WBG and IFC, 2018) estimates that if the performance ratio of FPV projects is 10% higher than ground-mounted PV systems, the LCOE would be of the same order of magnitude of the LCOE of ground-mounted projects – that is, *c.* 53 €/MWh, while for ground-mounted projects, the LCOE ranges between 45 and 56 €/MWh (Lazard, 2016). It is expected that economies of scale and learning curves will contribute to cost reductions for the sector in upcoming years.

Economic assessments regarding applications of FPV in marine environments are scarce in the literature. Even though the marine FPV market is different from the offshore wind market, some similarities can be drawn: (a) both marine FPV and offshore wind can benefit from experience from the more established and conventional markets; (b) both meet additional challenges due to installation and operation with regards to being located in waters; (c) both have increased capital expenditure compared with their land-based options; (d) both seem in general to be able to obtain higher energy production than the land-based options.

Offshore wind is considered to be the most advanced case of offshore renewable energy, as it has been commercial since the early 1990s. Its LCOE in 2015 was *c.* 223 US\$/MWh (Irena, 2019), while in 2018 it was 115 €/MWh and is expected to lie between 57 and 100 €/MWh by 2035 (Kost *et al.*, 2013; Taveira-Pinto *et al.*, 2020). Similar evolution of costs for marine FPV projects can be expected. Additionally, the potential for near-future competitiveness of marine FPV projects associated with the need for climate change adaptation provide encouraging prospects for the increasing growth of solar energy exploitation, which in turn may also lead to an increase in investments and return-on-profit of FPV deployed in marine locations.

3. Design considerations of FPV plants in marine environments

3.1 Key technical aspects

The current low maturity of the sector contributes to a lack of standards that can be directly consulted when designing FPV systems, both for freshwater and marine environments. However, the sector can benefit from mature sectors such as offshore O&G or MRE (e.g. offshore wind). Therefore, in this section,

Figure 4. Global installed capacity of FPV in MWp (adapted from Seris, WBG and IFC (2018))

the fundamental aspects and the major issues related to the design of FPV plants for marine environments are outlined.

The design of FPV plants for marine environments is anticipated to be a complex process. These systems will be in a highly demanding environment. Thus, it is necessary to ensure safe operation throughout the lifetime of the system under all prescribed external conditions. It is foreseen that the impact of climate change will lead to an aggravation of extreme weather phenomena, bringing even greater challenges for marine FPV projects.

Marine FPV systems with a solid and long-term role in the energy mix need to meet the following requirements (Pecher and Kofoed, 2016; Petrini *et al.*, 2010), summarised in Figure 5.

- **Survivability.** Marine FPV systems are complex, with significant interactions between the individual subsystems and environmental loads. It is important to ensure that the system will survive under extreme conditions. Understanding the global response of the structure and the interactions between components, for example between the float and the mooring line connection points, are essential for a robust system. Additionally, experience from offshore technologies like O&G or offshore wind indicate that when floating structures are subjected to extreme environments, they can be damaged due to several phenomena such as green water slamming on the deck (Faltinsen, 2017).
- **Reliability and maintainability.** Marine FPV plants will be subjected to cyclic loads, consequently leading to fatigue of critical elements, typically at the connection points between the floats and the connection points of the mooring lines. Degradation due to saltwater corrosion will also affect the overall lifetime of the system. Ensuring easy access and inspection of the most essential parts of the system at location will be fundamental.
- **Overall power performance.** The dynamic nature of the movement of a FPV system needs to be considered, leading to uneven sunlight reaching modules on the same string, thus causing losses in energy production. These losses occur when interconnected PV cells of a string have different electrical characteristics at a certain instant (Lappalainen and Valkealahti, 2017). To benefit from

increased efficiency due to the cooling effect, the panels should be as close as possible to water, while avoiding possible damage due to (extreme) wave loads.

- **Scalability.** A marine FPV concept needs to have a higher DC/m² ratio in order to become economically viable – that is, it should accommodate as many modules as possible (higher installed capacity) per square metre for an individual floater. At the same time, the concept needs to enable the scalability of the plant by having multiple floaters connected, creating a multi-megawatt plant.
- **A positive environmental footprint.** These systems are expected to cover large areas of the ocean, potentially causing adverse effects on aquatic life. The environmental impact of these systems needs to be further assessed.

3.2 Risks and challenges

Even though momentum in marine FPV can be observed, there is no commercially available technology yet available that can be employed in open seas. Taking floating solar technology into rough offshore environments requires that the existing solar PV modules can resist salty water and withstand strong currents and wave and wind loads. Additionally, a cost competitive concept for the floating structure needs to be developed. Therefore, currently it can be envisaged that the main risks for marine FPV will be (a) TRL of marine FPV, (b) mooring and anchoring configurations, (c) logistics and marine operations, (d) reliability of the electrical power conversion equipment, (e) the efficiency, lifetime and reliability of solar modules, (f) materials and durability, (g) marine growth and aquatic life, (h) intermittency of the resource and (i) competition from other MRE (e.g. offshore wind and wave energy).

Currently, marine FPV presents a lower TRL. However, the positive momentum in research and development of concepts for marine applications (Bellini, 2019b; ME, 2020) will contribute to reduce this gap, and technologies with suitable TRL are expected to emerge in the upcoming years.

While permanent mooring systems are needed to keep the floating PV systems stationary under the combined effects of

Figure 5. Schematic representation of key technical aspects

wave, wind and current loads, balancing the requirements for robust mooring systems and reducing capital, installation and O&M costs is critical. Conventional mooring systems are proven successful for O&G applications as well as for MRE. Like in floating offshore wind or wave energy converters (WECs), it is expected that the mooring system will be a significant portion of the total FPV system cost (Myhr *et al.*, 2014). On average, for a WEC, the mooring system costs represent nearly 10% of the total capital expenditure (Ocean, 2015). Therefore, the lower revenue of marine FPV in comparison with O&G infrastructures, allied with the lower consequences of mooring system failures than O&G platforms or floating offshore wind turbines, should drive the sector to apply innovative systems and alternative materials for more cost-effective mooring systems, given the number of modules and high volumes of mooring lines. Additionally, optimal mooring spreads that share anchoring points, rather than traditional single mooring points, will most likely be preferable for marine FPV. Typical mooring systems can be either catenary or taut moorings (Figure 6) in shallow waters; FPV systems can be moored above the water to piles in the seabed. For small ponds, bank mooring can be a simple and cheap solution without the need for any submerged activities (WBG, Esmar and Seris, 2019).

The assembly and installation of structures in marine environments involve a set of complex operations, mainly due to the challenging character of the open sea environment challenging character, such as lifting, towing, manoeuvring and positioning of heavy structures (Bai and Bai, 2012). The challenging sea environment makes it crucial to plan ahead the lifecycle logistics of offshore structures and to use the best-fit equipment to perform such operations. Given the financial importance and the technical challenges associated with the logistics and marine operations, it is essential that the marine FPV sector finds a way to learn from the established offshore sector, while being able to define the most appropriate solutions for the industry, contributing to cost reductions and safe operations. For example, state-of-the-art offshore standards for planning and execution of marine operations are already available (e.g. DNV GL, 2011), which could easily be brought up into the industry. A proper review of these standards needs to be

considered as they were mainly developed for O&G industries, with more strict requirements.

Currently, the logistics and marine operations of marine FPV are poorly addressed by the research community and industry partners due to the low readiness of the technology. It can be expected that, for the first projects, the costs associated with installation and O&M will be at the higher end. However, a decrease in costs is foreseen as the sector gains experience. Additionally, it is expected that the installation of the first commercial projects would not bring many challenges as, typically, they will be installed close to the consumer (relatively close to the shore), avoiding the harsh environmental conditions of the open seas. In addition, the number of structures may be limited, which will allow the usage of non-specialised vessels. In cases where FPV structures can be towed to the site, most likely tugs can be used, whereas an anchor-handling vessel will be used for anchor installation.

The different materials of the different components in a marine FPV system need to be able to satisfy all the structural and functional requirements throughout the entire lifetime of the project – for example, exposure to water, salinity, humidity, environmental stress cracking, among others (George and Patel, 2019). For example, electrical equipment, such as the inverters and balance of plant components, will be exposed to high humidity environments, saltwater and to the effect of environmental loads, thus increasing the risk of corrosion and degradation and hence impacting their lifetime (George and Patel, 2019). There are currently many established electrical standards, codes and recommended practice for electrical applications in the marine offshore environment that are used by the O&G and offshore wind industries. However, preventive measures such as choosing a suitable ingress protection rating should not be disregarded during the design and installation stages (George and Patel, 2019). In addition, handling electrical equipment in these environments poses safety risks; additional safety measures thus need to be accounted for, both during installation and operation (George and Patel, 2019).

Cyclic loads from waves, wind and currents may cause deflections and stresses on the solar modules, which could cause microcracking of the modules leading to decreases in production and durability (Sahu *et al.*, 2016). Additionally, as highlighted by Sahu *et al.* (2016), the application of thin-film technologies in harsher environments needs further research studies, as the inherent light weight and flexibility of these PV technologies may enable them to better withstand the harsher environmental conditions of the ocean.

The tilt angle of the PV module is paramount, as incorrect positioning does not maximise the power output. There are different approaches to calculate the optimum tilt angle of a

Figure 6. Mooring line configurations: (a) taut spread; (b) catenary (adapted from Harris *et al.* (2004))

solar panel (e.g. Yadav and Chandel, 2013). Every location will have an optimal tilt angle that maximises the total annual irradiation. The theoretical optimum tilt angle is normally set to the latitude of the site, as a rule of thumb. However, other parameters such as soiling, shading and seasonal irradiation distribution can play a role in choosing the tilt angle. More highly tilted angles will result in less soiling but increased self-shading (IFC, 2015). However, if solar panels have a zero tilt, that will have a positive impact on the structural design of the floating structure. According to DNV GL-RP-C205 (DNV GL, 2010) wind forces on a structure are directionally proportional to the angle between the wind direction and the exposed area. In other words, wind loads will increase with the tilt of the panels, which may lead to an increase in the size of the floating system so it is able to withstand higher loads. Besides, standardised mass production is an important key factor for the development and the economy of marine FPV. Hence, having a standard equipment format is important, even though it would not be fully optimised for each location individually.

Salt water might also introduce additional degradation challenges – for example, in relation to corrosion and potential-induced degradation (Suzuki *et al.*, 2015). According to Sahu *et al.* (2016), the effect of saltwater on PV structures and module performance needs further research. The efficiency of FPV panels is expected to be higher than ground-mounted applications, increasing the performance of the solar farm. The cooling effect provided by close proximity to water will contribute to a reduction of the operating temperature of the PV modules (Sahu *et al.*, 2016). The design of the floating system influences the cooling effect, as shown by Liu *et al.* (2018) for freshwater applications.

Despite its simplicity, marine growth can cause many problems in offshore structures. If it exceeds the design value it will increase structural loading of the system, thus contributing to the likelihood of failure (El-Reedy, 2012). Marine growth consists of algae, marine invertebrates and other small organisms that adhere and accumulate on submerged members of offshore structures, causing an increase in their size and other physical properties (El-Reedy, 2012). It will thus increase the loads from waves and currents on the members and will result in higher self-weight of the member.

It is expected that marine FPV systems will create an artificial shelter for aquatic life in the surroundings and thus attract them. For example, the presence of birds will impact the maintenance activities of FPV plants: bird droppings are expected to happen, leading to locally shaded areas. Thus, O&M activities will need to be carried out more frequently in order to keep power production unaffected, while ensuring that water quality is not affected. For example, cleaning of the PV

modules needs to be carried out avoiding chemical products (Felix *et al.*, 2019). Colonisation of marine life on solar modules can also occur.

Intermittency of renewable energy sources (RES) is often identified as a challenge and their ability to meet demand is less predictable than conventional energy sources. Electricity grids are characterised by always requiring a balance between supply and demand. Higher penetration of RES will lead to challenges in the management of electricity grids, as RES are not dispatchable (IEA, 2011). Thus, a further significant increase in solar power generation will require substantial investments in battery storage capacity to shift production from peak production times and also to cope with cloudy days.

Marine FPV systems will compete with other MRE, so it is important that the technologies developed are cost competitive. The development of new technology is expensive and, due to the immaturity of the marine FPV sector, it is expected that LCOE estimates would be higher than those for MRE. It will be necessary to explore new methods of reducing the LCOE of marine FPV technologies as well as studying alternative applications that allow the commercial viability of projects to be reached. Competition for ocean space will occur between marine FPV and other MRE, but also with other different users – for example, fishing.

3.3 Loads and limit states for design

Like any other offshore structure, marine FPV plants are exposed to several type of loads throughout their lifetime. These loads can be classified as (Chakrabarti, 2005) permanent loads, operational loads, environmental loads, installation loads and accidental loads.

The environmental conditions at the site are the main source of external loading for FPV plants, both for marine and freshwater applications, and can be obtained either by site studies (e.g. bathymetry and geotechnical studies) or historical data (DNV GL, 2016a). The most relevant are wind conditions, wave climate, water depth, currents, solar irradiation and temperature.

Similar to ground-mounted solar systems, the site-specific wind condition is one of the prominent environmental conditions that govern the design of FPV systems. The effect of wind on FPV systems is threefold: it generates suction, pressure and drag forces on the system's components, it creates dynamic loads on the system and it influences the characteristics of the local wave climate.

There is a combination of a variety of disturbing and restoring forces that create waves on the ocean's surface. The effect of wind blowing perturbs the ocean surface by friction and

pressure variations, thus generating waves often designated as gravity waves (Massel, 2013). There is a strong correlation between the characteristics of the incident wind and the waves formed by its action, mainly the wave height and period. It is expected that regions with higher intensity winds will also have an energetic wave environment. The energy transferred from wind to the ocean surface can create waves and is subdivided into kinetic energy (movement of water particles) and potential energy (mass of water in the wave above sea level). It depends on factors such as the wind speed, the amount of time that the wind is blowing and the distance over which the wind excites the waves (i.e. the fetch) (Massel, 2013). Ocean waves will interact with FPV systems and the motion induced by waves will generate inertial forces on the system and dynamic loads on the structure due to the varying nature of waves. This is a phenomenon that has broadened studies in the offshore sector (Journée and Massie, 2001).

While FPV projects often consist of a large number of floaters that are all interconnected, the coupling between individual floaters is important. Theoretical linearisations give a good first estimate of what one might expect in certain environmental conditions and the FPV system response. Non-negligible non-linear effects make it hard to predict what will happen in an $N \times M$ array of moored floaters. The coupling effect will increase the system response complexity exponentially with the number of floaters. A typical megawatt FPV park consists of several thousand floaters, which are all elastically connected to one another; this has not been studied in detail earlier by the FPV industry or any other sector. The industry is trying to predict the behaviour of such systems with the currently available hydrodynamic packages, all of which have advantages and disadvantages. This adds to the possibility of non-linear wave effects, such as steep waves or even breaking waves. The latter are typically what might be expected at the design limit states and one ends up with a rather complex system (Journée and Massie, 2001).

It is expected that FPV will move gradually to larger water depths and, consequently, harsher environments. A similar development has been seen in the offshore wind industry, where first shallow-water locations close to the shore with low wave characteristics were occupied. Then, offshore wind projects started to move into deeper locations, leading to the development of floating offshore wind turbines. For FPV, larger water depths will lead to greater hydrodynamic loading on the system due to more energetic sea states at those locations. This often leads to exponential complexity in the system design as the system needs to resist larger external loads. Innovative designs, materials and methods will contribute for the industry to develop and provide access to new harsher environments.

The water depth will influence the type of mooring system that is applicable for the location. It will also affect the cost of the system as, typically, costs tend to increase for deep-water locations (Myhr *et al.*, 2014; Oh *et al.*, 2018). Current loads also have an impact on the design of the mooring system (Chen and Basu, 2018) as they are responsible for applying lateral loads or drag forces on offshore structures and can give rise to vortex-induced vibrations of slender structural elements and vortex-induced motions of large-volume structures (DNV GL, 2010).

Solar irradiation is a crucial parameter for estimating energy production at the location and is often classified into two major forms: global horizontal irradiation (GHI) and direct normal irradiance, being measured in kWh/m^2 (Právělie *et al.*, 2019). The GHI is considered relevant for assessing the energy production of PV technologies and consists of the total amount of direct and diffuse solar radiation incident falling on a horizontal surface.

The relevance of temperature is twofold. First, the ambient temperature has an effect on the heat loss transmissions between the solar module and the surrounding environment (Cornaro *et al.*, 2018). Second, it affects the materials chosen for constructing the floating system, as different materials have different thermal properties. The ambient temperature above the waterline and the surface water temperature will cause cyclical thermal expansion and contraction, potentially leading to fatigue at connecting points of the system and of the materials (George and Patel, 2019). Cyclic thermal loading is site specific.

In addition, it is noteworthy that in some locations other environmental loads are relevant for the design, such as earthquake loads and snow/ice loads.

Due to the stochastic nature of the environmental conditions, it is common to calculate the design value of these conditions in offshore structures by selecting an appropriate return period (T_R). This ensures that the design values of the environmental forces are neither too low nor too high, consequently leading to an underdesign or overdesign, respectively. High values of T_R are associated with extreme conditions. Selection of the relevant T_R will be a critical design activity. For offshore wind plants T_R is often set as 50 years (DNV GL, 2016b).

The design of marine FPV systems should be carried out in a manner that it will ensure that the structure performs adequately throughout its entire lifetime, under the worst-case scenario. This is achieved by designing the structures for a combination of loads to ensure serviceability, reliability and robustness. This can be achieved by analysing the design criteria in order to ensure that the relevant limit states are not exceeded. A limit state is defined as a condition beyond which

the structure no longer satisfies the design requirements (DNV GL, 2016b). Details on limit states can be found in several standards for the offshore industry (e.g. DNV GL, 2016b). However, a brief description of the relevant limit-state categories that may need to be checked for marine FPV systems are given below (DNV GL, 2016b):

- Fatigue limit state (FLS). Fatigue is extremely important in the design of marine FPV systems due to the cyclic nature of the loading exerted on the structure during its lifetime, which often is in the range of 20–25 years. FLS analysis is conducted to verify if the system has enough resistance to the accumulated and repeated loads to survive its design lifetime.
- Ultimate limit state (ULS). The aim of ULS analyses is to ensure that the overall strength of the system and its capacity are sufficient to withstand extreme load events.
- Serviceability limit state (SLS). SLS analyses are carried out to verify that the deflections, durability, temperature-induced deformations, excessive vibrations on the PV modules that may limit energy production are not exceeded.
- Accidental limit state (ALS). ALS analyses correspond to assessments to verify structural integrity or behaviour after an operational failure or accidental event.

4. Opportunities for co-location of marine floating solar with offshore wind

4.1 The potential synergies

The future of the marine FPV sector is intrinsically dependent on its commercial viability and on how it competes with other sources of energy (renewable or non-renewable) within the current market. Over time, cost reductions are expected to occur, mainly driven by economies of scale, technological progress and improvements in operations.

The topic of co-location MRE has been actively discussed in the research community, mainly the co-location of offshore wind and wave farms, as an alternative to accelerate the deployment of large-scale wave energy projects (Azzellino *et al.*, 2013; Pérez-Collazo *et al.*, 2015) and to solve some of the challenges that offshore wind farms face nowadays, especially the sensitivity of the O&M operations to weather conditions (Astariz *et al.*, 2015). Similar benefits can be achieved by combining marine FPV with offshore wind farms. The integration of marine FPV systems with offshore wind farms could be a niche market enabler to launch the commercial feasibility of marine FPV, despite the typical harsher environmental conditions seen at these sites. Synergies between both renewables can be achieved the co-location in the same maritime space, sharing common installations, logistics and

facilities, while ensuring efficient planning and use of the natural resources.

From a literature review of the synergies and positive impacts of combining wave and offshore wind (Pérez-Collazo and Iglesias, 2012; Pérez-Collazo *et al.*, 2014a, 2014b), it is expected that several of these synergies can be transposed to the co-location of marine FPV and offshore wind farms. They can be defined as follows.

- Increased energy production. The combination will increase the global energy yield per unit area of marine space used, contributing to a better use of natural resources and the maritime space (Pérez-Collazo *et al.*, 2015).
- Smooth power output. The combined exploitation will increase availability, thus decreasing the number of hours of non-activity, having a less negative impact on the grid (i.e. avoiding sudden disconnections and connections) (Pérez-Collazo *et al.*, 2015). Besides downtime reduction, a smoother power output profile will be achieved as different energy sources are unlikely to peak at the same times (e.g. sunny days usually have low winds and vice versa).
- Common grid infrastructure. According to Myhr *et al.* (2014), the electric grid infrastructure represents one of the most significant costs of an offshore wind farm project; depending on the technology, it can reach up to one third, with the cost of the export cable being one of the major contributors. The intermittent nature of the wind resource, which is largely impacted by irregular transitions between states of high and low power (Reikard *et al.*, 2015), leads to non-optimal usage of the export cable. Thus, combined energy production using a shared grid infrastructure would become an important factor for cost reduction and favour better utilisation of the export cable.
- Shared logistics. This is foreseen regarding the use of specialist marine equipment, installation vessels and facilities (e.g. port space). A considerable number of companies have diversified away from O&G and are now able to provide equipment and vessels for more diversified ocean-based activities, such as cable-handling equipment and trenching and burial tools. Making more productive use of vessels and port infrastructure will contribute to reducing costs.
- Shared O&M costs. Cost reductions on O&M activities are expected because vessels, equipment and specialised personnel will be shared for the maintenance tasks of the marine FPV and offshore wind farms.
- Environmental benefits. The co-location of both systems is expected to have a positive impact on the environment as they are a sustainable source for electricity production. However, the environmental impacts of marine FPV are still poorly documented. Especially the effect that these systems will have on aquatic environments, as it is

envisaged that marine FPV systems will cover large areas of the ocean surface.

- Potential for shadow effects. The benefits of the shadow effect have been previously discussed in the literature, mainly on the topic of the co-location of wave and offshore wind farms. The energy extraction from WECs modifies the local wave climate by reducing the mean wave height, creating the shadow effect (Perez-Collazo *et al.*, 2014a). Similar effects can be expected by installing FPV systems in the idle spaces between wind turbines. It is expected that these structures will dampen the waves, reducing the local wave climate, hence potentially leading to a wider window for O&M activities, which has an impact on O&M costs. In addition, with a reduction in the local wave climate, the loads on both offshore wind turbines and FPV systems will be lower.

4.2 Development challenges

Important steps are being taken to develop co-located offshore wind and marine FPV farms, with research projects emerging (Deme, 2019). At the moment, the focus relies on developing feasible and economic systems for harnessing the sun in the ocean. Being able to narrow the technical gap between offshore wind farms and marine FPV is a key aspect of making co-located farms become a reality.

Additionally, lack of experience in full-scale marine FPV plants co-located with offshore wind is a strong barrier. First, it may lead to increased risks during installation and operation. In an event of a mooring failure, the potential and consequences of a collision between the systems increase. For economically marginal industries like many MRE projects, this could lead to a financial risk for co-located projects. Design considerations and proper contingency plans need to be developed ahead to mitigate and minimise collision risks. Second, the lack of experience leads to additional economical risks associated with these projects, translating into higher insurance costs.

For a greenfield project development where offshore wind and marine FPV systems will be co-located, optimising the site selection may be challenging. A site that may be ideal from a wind resource perspective may not be ideal for harnessing the sun, and vice versa.

Co-locating marine FPV farms with offshore wind farms could also contribute to increasing the risk of accidents in the case of failure of the mooring lines of the FPV systems. Additionally, enough space needs to be guaranteed in order to ensure that O&M and inspection vessels can navigate without limitations. Finally, further studies to evaluate the impacts of covering large areas with marine FPV systems need to be carried out, as it is still unclear if the reduction of

sunlight entering the water surface will negatively affect aquatic life.

5. Conclusions

The strong development of FPV, primarily in freshwater bodies, has been propelled mainly by a lack of available land, loss of efficiency at high operating cell temperatures and decarbonisation targets. Despite several advantages and opportunities for further deployment of FPV systems, there are still challenges that need to be overcome, as there is a lack of track record among the sector and very little public available information about different technologies. Concurrently, there is a trend in initiatives to develop FPV systems for marine environments because the ocean represents a vast source of renewable energy and because the world's megacities located along coasts having challenges in meeting their increased demand for energy.

A concise literature review of existing FPV technologies for freshwater bodies has been presented. It was concluded that the most common type of floating structures used for inland waters (i.e. HDPE floats) are not suitable for deployment in marine locations as the connection ears and pins will face heavy loads, compromising the reliability of the system. Thus, research activities for marine FPV systems should focus on developing new concepts for FPV for the ocean instead of scaling up existing technologies. A literature review of the current available technologies for marine FPV applications is provided. Marine FPV applications are currently at a low technical maturity level; however, there is a focus in the research community to develop a cost competitive concept for a floating system that can withstand harsh marine environments.

The development of FPV systems for marine environments is a complex task due to the local environment, mainly due to the environmental cyclic loads and the proximity to saltwater. Finding a balance between a system that can withstand the cyclic loads of the environment and survive extreme conditions while simultaneously ensuring scalability for a multi-megawatt project is paramount. Meanwhile, minimising the mismatch losses seen by the solar modules as much as possible will be key for the development of a commercially viable marine FPV technology.

The lack of classification standards that can be directly used for designing these systems can be seen as a blocker for development of this kind of technology. Finding investments is harder when insurance companies cannot rely on industry-wide guidelines. However, synergies can be drawn from several mature sectors such as offshore O&G or offshore wind, in order to ensure that these systems are designed to safely operate throughout their lifetime and to survive under extreme weather conditions.

The opportunity of co-locating marine FPV and offshore wind farms was explored in this study. It is believed that it will be a niche market enabler to launch the commercial feasibility of marine FPV, bringing along several advantages to increase the success of project synergies, such as more efficient usage of the export cables to shore, which is a major cost on most MRE projects. Locally generated power reduces loss of energy in transport and reduces the investments for long infrastructures. Many of the world's biggest cities are located close to the ocean, providing excellent opportunities where clean, renewable, power production and power demand can meet.

REFERENCES

- Astariz S, Perez-Collazo C, Abanades J and Iglesias G (2015) Co-located wind-wave farm synergies (operation & maintenance): a case study. *Energy Conversion and Management* **91**: 63–75, <https://doi.org/10.1016/j.enconman.2014.11.060>.
- Azzellino A, Ferrante V, Kofoed JP, Lanfredi C and Vicinanza D (2013) Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach. *International Journal of Marine Energy* **3–4**: e11–e25, <https://doi.org/10.1016/j.ijome.2013.11.008>.
- Bai Y and Bai Q (2012) *Subsea Engineering Handbook*. Gulf Professional Publishing, Waltham, MA, USA.
- Bellini E (2018) Dutch consortium plans world's first "off-shore" floating pv plant for the north sea. *pv magazine*, 7 February. See <https://www.pv-magazine.com/2018/02/07/dutch-consortium-plans-worlds-first-off-shore-floating-pv-plant-for-the-north-sea/> (accessed 13/07/2020).
- Bellini E (2019a) Offshore pv system goes online in north sea. *pv magazine*, 12 December. See <https://www.pv-magazine.com/2019/12/12/offshore-pv-system-goes-online-in-north-sea/> (accessed 13/07/2020).
- Bellini E (2019b) First Off-Shore PV Project Launched in the North Sea. *pv magazine*, 19 July. See <https://www.pv-magazine.com/2019/07/19/first-off-shore-pv-project-launched-in-the-north-sea/> (accessed 13/07/2020).
- Bjørneklett G (2018) Offshore floating solar – a technical perspective. *PV Tech Power* **16(16)**: 6–9.
- Boersma T, van der Laan J, Noorduyn O and Mesbahi M (2019) *A Comprehensive Overview of 200+ Global Floating Solar Plants, SolarPlaza, the Netherlands*. See <https://www.solarplaza.com/channels/future-grid/12067/200-global-floating-solar-plants/> (accessed 13/07/2020).
- Cazzaniga R, Cicu M, Rosa-Clot M et al. (2018) Floating photovoltaic plants: performance analysis and design solutions. *Renewable and Sustainable Energy Reviews* **81**: 1730–1741, <https://doi.org/10.1016/j.rser.2017.05.269>.
- Chakrabarti SK (2005) *Handbook of Offshore Engineering*. Elsevier, Oxford, UK.
- Chen L and Basu B (2018) Fatigue load estimation of a spar-type floating offshore wind turbine considering wave-current interactions. *International Journal of Fatigue* **116**: 421–428, <https://doi.org/10.1016/j.ijfatigue.2018.06.002>.
- Choi YK (2014) A study on power generation analysis of floating PV system considering environmental impact. *International Journal of Software Engineering and Its Applications* **8(1)**: 75–84, <https://doi.org/10.14257/ijseia.2014.8.1.07>.
- Choi YK, Choi WS and Lee JH (2016) Empirical research on the efficiency of floating PV systems. *Science of Advanced Materials* **8(3)**: 681–685, <https://doi.org/10.1166/sam.2016.2529>.
- Ciel & Terre (2018) Hydrelío® Technology. See https://issuu.com/cieletterre/docs/c_t_catalog_hydrelio__technology_20 (accessed 13/07/2020).
- Cornaro C, Renzi L, Pierro M et al. (2018) Thermal and electrical characterization of a semi-transparent dye-sensitized photovoltaic module under real operating conditions. *Energies* **11(1)**: 155, <https://doi.org/10.3390/en11010155>.
- Deme (2019) *Expert Consortium Including DEME Explores Pioneering High-Wave Offshore Solar Technology*. See <https://www.deme-group.com/news/expert-consortium-including-deme-explores-pioneering-high-wave-offshore-solar-technology> (accessed 13/07/2020).
- DNV GL (2010) DNV-RP-C205: Environmental conditions and environmental loads. DNV GL, Oslo, Norway.
- DNV GL (2011) DNV-OS-H101: Marine operations. General. DNV GL, Oslo, Norway.
- DNV GL (2016a) DNVGL-ST-0437: Loads and site conditions for wind turbines. DNV GL, Oslo, Norway.
- DNV GL (2016b) DNVGL – ST-0126 Support Structures for Wind Turbines. DNVGL, Oslo, Norway.
- DNV GL (2018) DNV GL Energy Transition Outlook 2018 – A Global and Regional Forecast to 2050. DNV GL, Oslo, Norway. See <https://eto.dnvgl.com/2018/main-report> (accessed 13/07/2020).
- DNV Kema (2019) *SUNdy, A Floating Solar Field Concept*. DNV Kema, Arnhem, the Netherlands. See http://cdn.pes.eu.com/assets/misc_new/leaflet-sundy-deftcm4-529461pdf-477283816545.pdf (accessed 13/07/2020).
- Eisl R and Haider M (2016) *HELIOFLOAT – A Floating Lightweight Platform*. Austria. See https://www.tuwien.ac.at/fileadmin/t/tuwien/fotos/pa/2016/hm2016/HELIOFLOAT_platform_EN.pdf.
- El-Reedy MA (2012) Offshore structure platform design. In *Offshore Structures* (El-Reedy MA (ed.)). Gulf Professional Publishing, Waltham, MA, USA, pp. 93–211.
- Enkhardt S (2020) *German Coal Mines Could Host 3 GW of Floating PV*. Boston, USA. See <https://www.pv-magazine.com/2020/02/03/german-coal-mines-could-host-3-gw-of-floating-pv/> (accessed 13/07/2020).
- Faltinsen OM (2017) Slamming. In *Encyclopedia of Maritime and Offshore Engineering*. Wiley, Chichester, UK. pp. 1–12, <https://doi.org/10.1002/9781118476406.emoe041>.
- Felix AV, Hernández-Fontes J, Lithgow D et al. (2019) Wave energy in tropical regions: deployment challenges, environmental and social perspectives. *Journal of Marine Science and Engineering* **7(7)**: 219, <https://doi.org/10.3390/jmse7070219>.
- Fise (Fraunhofer Institute for Solar Energy Systems) (2019) *Photovoltaics Report*. Fise, Freiburg, Germany.
- George G and Patel P (2019) Floating PV systems – an overview design considerations. *PV Tech Power* **18(18)**: 3–6.
- Grech M, Stagno LM, Aquilina M, Cadamuro M and Witzke U (2016) Floating photovoltaic installations in Maltese sea waters. *32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany*, pp. 1965–1968.
- Harris RE, Johanning L and Wolfram J (2004) Mooring systems for wave energy converters: a review of design issues and choices. *Proceedings of the 3rd International Conference on Marine Renewable Energy, Blyth, UK*, pp. 180–189.
- Hernández-Callejo L, Gallardo-Saavedra S and Alonso-Gómez V (2019) A review of photovoltaic systems: design, operation and maintenance. *Solar Energy* **188**: 426–440, <https://doi.org/10.1016/j.solener.2019.06.017>.

- Hussain A, Arif SM and Aslam M (2017) Emerging renewable and sustainable energy technologies: state of the art. *Renewable and Sustainable Energy Reviews* **71**: 12–28, <https://doi.org/10.1016/j.rser.2016.12.033>.
- IEA (International Energy Agency) (2011) *Harnessing variable Renewables: A Guide to the Balancing Challenge*. IEA, Paris, France.
- IEA (2017a) *Independent Statistics & Analysis (International Energy Outlook 2017)*. IEA, Paris, France.
- IEA (2017b) *CO₂ Emissions From Fuel Combustion – Highlights*. IEA, Paris, France.
- IEO (International Energy Outlook) (2016) *IEO – International Energy Outlook*. U.S. Energy Information Administration, Washington, DC, USA.
- IFC (International Finance Corporation) (2015) *Utility-scale Solar Photovoltaic Power Plants – A Project Developers Guide*. World Bank Group, Washington, DC, USA. See https://www.ifc.org/wps/wcm/connect/f05d3e00498e0841bb6fbbe54d141794/IFC+Solar+Report_Web+_08+05.pdf?MODAJPERES (accessed 27/11/2019).
- Irena (International Renewable Energy Agency) (2019) *Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects*. Irena, Abu Dhabi, UAE. See https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf (accessed 13/07/2020).
- Journée J and Massie W (2001) *Offshore Hydrodynamics*, 1st edn. Delft University of Technology, Delft, the Netherlands.
- Kabir E, Kumar P, Kumar S, Adelodun AA and Kim KH (2018) Solar energy: potential and future prospects. *Renewable and Sustainable Energy Reviews* **82**: 894–900, <https://doi.org/10.1016/j.rser.2017.09.094>.
- Komusanac I, Fraile D and Brindley G (2019) *Wind Energy in Europe in 2018 – Trends and Statistics*. Wind Europe, Brussels, Belgium, Technical report, <https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf> (accessed 20/11/2019).
- Kost C, Shammugam V, Julch V, Nguyen HT and Schlegl T (2013) *Levelized Cost of Electricity Renewable Energy Technologies*. Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.
- Lappalainen K and Valkealahti S (2017) Photovoltaic mismatch losses caused by moving clouds. *Solar Energy* **158**: 455–461, <https://doi.org/10.1016/j.solener.2017.10.001>.
- Lazard (2016) *Lazard's Levelized Cost of Energy Analysis*, version 10.0. Lazard, New York, USA. See <https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf> (accessed 02/12/2019).
- Lee YG, Joo HJ and Yoon SJ (2014) Design and installation of floating type photovoltaic energy generation system using FRP members. *Solar Energy* **108**: 13–27, <https://doi.org/10.1016/j.solener.2014.06.033>.
- Liu L, Wang Q, Lin H et al. (2017) Power generation efficiency and prospects of floating photovoltaic systems. *Energy Procedia* **105**: 1136–1142, <https://doi.org/10.1016/j.egypro.2017.03.483>.
- Liu H, Krishna V, Lun Leung J, Reindl T and Zhao L (2018) Field experience and performance analysis of floating PV technologies in the tropics. *Progress in Photovoltaics* **26(12)**: 10, <https://doi.org/10.1002/pip.3039>.
- Massel SR (2013) *Ocean Surface Waves: Their Physics and Prediction*. World Scientific, Singapore.
- ME (Marine Energy) (2020) *Moss Maritime and Equinor Team Up on Floating Solar*. See <https://marineenergy.biz/2020/01/27/moss-maritime-and-equinor-team-up-on-floating-solar/> (accessed 13/07/2020).
- Myhr A, Bjerkseter C, Ågotnes A and Nygaard TA (2014) Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy* **66**: 714–728, <https://doi.org/10.1016/j.renene.2014.01.017>.
- Ocean ES (2015) Task 7: cost of energy assessment for wave, tidal and OTEC at an international level. *Ocean Energy Systems* 1–48.
- Oh KY, Nam W, Ryu MS, Kim JY and Epureanu BI (2018) A review of foundations of offshore wind energy converters: current status and future perspectives. *Renewable and Sustainable Energy Reviews* **88**: 16–36, <https://doi.org/10.1016/j.rser.2018.02.005>.
- Pecher A and Kofoed JP (2016) *Handbook of Ocean Wave*. Springer International, Cham, Switzerland.
- Perez-Collazo C and Iglesias G (2012) Integration of wave energy converters and offshore windmills. *Proceedings of the 4th International Conference on Ocean Energy (ICOE)*, Dublin, Ireland, pp. 1–6.
- Perez-Collazo C, Astariz S, Abanades J, Greaves D and Iglesias G (2014a) Co-located wave-wind farms: a preliminary approach to the shadow effect. *Proceedings of International Conference on Ocean Energy (ICOE)*, Halifax, NC, Canada.
- Perez-Collazo C, Astariz S, Abanades J, Greaves D and Iglesias G (2014b) Co-located wave and offshore wind farms: A preliminary case study of an hybrid array. *Coastal Engineering Proceedings* **1(34)**, <https://doi.org/10.9753/icce.v34.structures.33>.
- Pérez-Collazo C, Greaves D and Iglesias G (2015) A review of combined wave and offshore wind energy. *Renewable and Sustainable Energy Reviews* **42**: 141–153, <https://doi.org/10.1016/j.rser.2014.09.032>.
- Petrini F, Li H and Bontempi F (2010) Basis of design and numerical modeling of offshore wind turbines. *Structural Engineering and Mechanics* **36(5)**: 599–624, <https://doi.org/10.12989/sem.2010.36.5.599>.
- Prävälle R, Patriche C and Bandoc G (2019) Spatial assessment of solar energy potential at global scale. A geographical approach. *Journal of Cleaner Production* **209**: 692–721, <https://doi.org/10.1016/j.jclepro.2018.10.239>.
- Putschek M (2018) Experiences of marine floating PV projects. *Intersolar Conference 2018, Munich, Germany*.
- Ranjbaran P, Yousefi H, Gharehpetian GB and Astaraei FR (2019) A review on floating photovoltaic (FPV) power generation units. *Renewable and Sustainable Energy Reviews* **110**: 332–347, <https://doi.org/10.1016/j.rser.2019.05.015>.
- Reichelstein S and Yorston M (2013) The prospects for cost competitive solar PV power. *Energy Policy* **55**: 117–127, <https://doi.org/10.1016/j.enpol.2012.11.003>.
- Reikard G, Robertson B and Bidlot JR (2015) Combining wave energy with wind and solar: short-term forecasting. *Renewable Energy* **81**: 442–456, <https://doi.org/10.1016/j.renene.2015.03.032>.
- REN21 (2019) *Renewables 2019 – Global status Report*. REN – Renewable Energy Policy Network for the 21st Century, Paris, France. See https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf (accessed 07/01/2020).
- Rosa-Clot M and Tina GM (2011) Electrical behavior and optimization of panels and reflector of a photovoltaic floating plant. *26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany*, pp. 4371–4375, <https://doi.org/10.4229/26thEUPVSEC2011-5BV.2.54>.
- Rosa-Clot M and Tina GM (2018) *Submerged and Floating Photovoltaic Systems: Modelling, Design and Case Studies*. Academic Press, London, UK.
- Rosa-Clot M, Tina GM and Nizetic S (2017) Floating photovoltaic plants and wastewater basins: an Australian project. *Energy Procedia* **134**: 664–674, <https://doi.org/10.1016/j.egypro.2017.09.585>.

- Sacramento EMd, Carvalho PCM, Araújo JCd et al. (2015) Scenarios for use of floating photovoltaic plants in Brazilian reservoirs. *IET Renewable Power Generation* **9**(8): 1019–1024, <https://doi.org/10.1049/iet-rpg.2015.0120>.
- Sahu A, Yadav N and Sudhakar K (2016) Floating photovoltaic power plant: a review. *Renewable and Sustainable Energy Reviews* **66**: 815–824, <https://doi.org/10.1016/j.rser.2016.08.051>.
- Santafé MR, Ferrer G, Sánchez R et al. (2014) Implementation of a photovoltaic floating cover for irrigation reservoirs. *Journal of Cleaner Production* **66**: 568–570, <https://doi.org/10.1016/j.jclepro.2013.11.006>.
- Seris, WBG and IFC (Solar Energy Research Institute of Singapore, World Bank Group and International Finance Corporation) (2018) *Where Sun Meets Water: Floating Solar Market Report*. World Bank, Washington, DC, USA. See <http://documents.worldbank.org/curated/en/579941540407455831/pdf/131291-WP-REVISED-PI61277-PUBLIC.pdf> (accessed 13/07/2020).
- Silvério NM, Barros RM, Tiago Filho GL et al. (2018) Use of floating PV plants for coordinated operation with hydropower plants: case study of the hydroelectric plants of the São Francisco river basin. *Energy Conversion and Management* **171**: 339–349, <https://doi.org/10.1016/j.enconman.2018.05.095>.
- Spencer RS, Macknick J, Aznar A, Warren A and Reese MO (2019) Floating PV: assessing the technical potential of photovoltaic systems on man-made water bodies in the continental U.S. *Environmental Science & Technology* **53**: 1680–1689, <https://doi.org/10.1021/acs.est.8b04735>.
- Suzuki S, Nishiyama N, Yoshino S et al. (2015) Acceleration of potential-induced degradation by salt-mist preconditioning in crystalline silicon photovoltaic modules. *Japanese Journal of Applied Physics* **54**(8S1): 08KG08, <https://doi.org/10.7567/JJAP.54.08KG08>.
- SwimSol (2010) *SolarSea® 1500, Four Seasons Resort, Baa Atoll, Maldives*. SwimSol, Vienna, Austria. See <https://swimsol.com/solar-projects/floating-photovoltaic-offshore-solar-sea-power-pv-four-seasons/> (accessed 13/07/2020).
- Taveira-Pinto F, Rosa-Santos P and Fazerer-Ferradosa T (2020) Marine renewable energy. *Renewable Energy* **150**: 1160–1164, <https://doi.org/10.1016/j.renene.2019.10.014>.
- Trapani K and Millar DL (2013) Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. *Energy Conversion and Management* **67**: 18–26, <https://doi.org/10.1016/j.enconman.2012.10.022>.
- Trapani K and Millar DL (2014) The thin film flexible floating PV (T3F-PV) array: the concept and development of the prototype. *Renewable Energy* **71**: 43–50, <https://doi.org/10.1016/j.renene.2014.05.007>.
- Trapani K and Santafé MR (2015) A review of floating photovoltaic installations: 2007–2013. *Progress in Photovoltaics: Research and Applications* **23**(4): 524–532, <https://doi.org/10.1002/pip.2466>.
- WBG, Esmap and Seris (World Bank Group, Energy Sector Management Assistance Program and Solar Energy Research Institute of Singapore) (2019) *Where Sun Meets Water Floating Solar Handbook for Practitioners*. Esmap, Washington, DC, USA.
- Yadav AK and Chandel SS (2013) Tilt angle optimization to maximize incident solar radiation: a review. *Renewable and Sustainable Energy Reviews* **23**: 503–513, <https://doi.org/10.1016/j.rser.2013.02.027>.

How can you contribute?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions from the civil engineering profession (and allied disciplines). Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.