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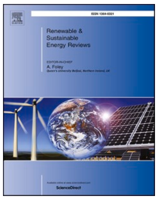

Potential environmental impacts of floating solar photovoltaic systems

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ABSTRACT

The use of floating photovoltaic systems in freshwater and marine environments is forecast to increase dramatically worldwide within the next decade in response to demands for accelerated decarbonisation of the global economy whilst avoiding competition for land, particularly near population centres. The potential environmental impacts of this expanding, novel technology are gradually becoming apparent and warrant consideration. This study reviews and evaluates the various potential environmental impacts of introducing floating photovoltaic arrays into aquatic (freshwater and marine) ecosystems based on the current state of floating photovoltaic technology and known impacts of similar industries. Environmental impacts of floating photovoltaic systems fall into several categories including shading, impacts on hydrodynamics and water-atmosphere exchange, energy emissions, impacts on benthic communities, and impacts on mobile species. The social acceptability of floating photovoltaic systems and the ability for long-term coexistence with other activities and interests are also discussed. Floating photovoltaic systems have an important role to play in global decarbonisation, but close collaboration between stakeholders will be required to better understand potential environmental and social impacts of this new technology. Development and validation of appropriate monitoring methods at scale, and consideration of long-term, equitable solutions to identified impacts, is important to enable sustainable expansion of this industry.

1. Introduction

As the urgency to decarbonise global energy supplies accelerates, photovoltaic (PV) arrays, which rely on panels of photovoltaic cells ("solar panels") to convert solar irradiation into electricity, have become increasingly important for "green" utility-scale power generation in the face of changes in global energy markets [1–5]. Nonetheless, PV arrays require extensive areas for effective deployment, especially close to concentrations of high human population density where demand for land is already high. Deployment of floating photovoltaic (FPV) arrays on top of water bodies provides a logical solution to this problem and is therefore expected to increase dramatically worldwide within the next decade [6,7]. Global FPV capacity has accelerated exponentially since 2007 when the first functional system (with a 20-kW capacity) was installed in Aichi, Japan, reaching 2.4 GW in 2019; this rapid growth looks set to continue into the foreseeable future [8–13]. Table 1 summarises current significant FPV projects, predominantly located in freshwater and estuarine systems in East and Southeast Asia. However, FPV capacity is also being developed in many other countries, including Brazil, Egypt, Nigeria, South Africa, the United States, Portugal, the Netherlands, and the UK among many others [9,11,14–22].

Most FPV research to date has focused on freshwater applications, notably in tropical areas where solar irradiation is plentiful throughout the year and conventional sources of power may be unreliable or absent (as evidenced in Table 1; [37]). Given increasing demand for electricity in coastal and island communities, efforts are also increasing to expand this technology into marine environments [38].

Before any novel technology is deployed at scale, it is important to identify potential environmental impacts so that they can be minimised to societally acceptable levels before they cause irreversible damage. Many countries require Environmental Impact Assessments (EIA) to be

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Abbreviations

CAPEX	Capital expenditure
CECEP	China Energy Conservation and Environmental Protection Group Corporation
DVM	Diel Vertical Migration
EIA	Environmental Impact Assessment
EM	Electromagnetic
EMF	Electromagnetic field
FAD	Fish aggregating device
FPV	Floating photovoltaic
GW	Gigawatt (AC output)
HDPE	High-density polyethylene
kW	Kilowatt (AC output)
MW	Megawatt (AC output)
MWp	Peak megawatt DC output capacity of solar array produced under standard test conditions
NIMBY	Not in my back yard
NTPC	National Thermal Power Corporation
O&M	Operations and Maintenance
ORE	Offshore renewable energy
PV	Photovoltaic
STS	Solar tracking system
VLFS	Very large floating structure
WEC	Wave energy converter
3D	Three-dimensional

conducted for such projects, but effective EIA relies on having information on the potential impacts [39]. Varying by country, social impacts are not always included when undertaking EIA. Some jurisdictions require a separate Social Impact Assessment while in others these are combined in an Environmental and Social Impacts Assessment (ESIA). Social impacts are also normally included in Strategic Environmental Assessments (SEA) which cover plans and programs including energy [40]. Due to the infancy of FPV technology, very little information is available regarding the environmental and social impacts of FPV projects, particularly in marine environments. Given the urgency of tackling the global climate crisis and upscaling of renewable energy globally, early identification of potential environmental and social impacts of FPV systems is critical to aid planning authorities in licensing of future, and up-scaling of existing, FPV farms. Early consideration of knowledge gaps can also help guide the research required for informing assessments more widely [41]. For new technologies such as FPV, such research may be best concentrated in dedicated test sites, as has happened for tidal and wave offshore renewables [41,42].

This review intends to address the following broad questions in relation to FPV projects:

- What environmental impacts are known to occur, or can be anticipated, in relation to FPV project deployment and operation?
- How significant (in terms of spatiotemporal footprint, severity of impact, etc.) are these environmental impacts known or likely to be, and what factors might influence this significance?
- How different are impacts anticipated to be, in terms of scope and significance, when comparing marine environments to freshwater environments?
- What data gaps currently exist, in relation to these environmental impacts, and how might these be addressed?

While the main focus of the review is on environmental impacts of FPV projects, these often lead to or underpin societal concerns towards this and other renewable energy technologies [43]. The aim of this review, therefore, is to also provide a brief overview of the potential social interactions as well as a comprehensive evaluation of potential environmental impacts of FPV projects, with a particular focus on marine ecosystems. The study commences with a summary of the design and operation of FPV systems from an engineering perspective, followed by a review of environmental impacts based on broad impact categories. The review builds upon existing information on impacts of FPV arrays [38,44,45] and explores current data gaps, with a specific focus on comparing impacts in marine ecosystems with those in more widely studied freshwater systems. The intent is to provide an overarching framework for evaluation of environmental impacts of FPV systems irrespective of whether they are deployed in freshwater or marine

Table 1
The ten current largest FPV solar farms, ranked by capacity (MW). Two even larger projects under development at time of writing are also included for comparative purposes [23].

Project name	Country	Location	Rated capacity (MW)	Approx. area	Approx. cost (US$)	Status at time of writing
Saemangeum floating solar energy project [23,24]	South Korea	Reclaimed estuarine tidal flat near Saemangeum	2100 MW	30 km^2	$3.96 bn	Under development
Omkareshwar Dam floating solar farm [25]	India	Narmada river, Madhya Pradesh	600 MW	20 km^2	$409 m	Under development
Wenzhou Taihan Solar PV Park [26]	P.R. China	Zhejiang province	550 MW	4.9 km^2	N/A	Completed
Hangzhou Fengling Electricity Science Technology's solar farm [23,27]	P.R. China	Changhe and Zhouxiang reservoirs, Zhejiang province	320 MW	3 km^2	$260 m	Completed
Three Gorges New Energy's floating solar farm [23,28]	P.R. China	Artificial lake near Huainan City, Anhui province	150 MW	3 km^2	$151 m	Completed
Cirata Reservoir floating photovoltaic (PV) power project [23,29,30]	Indonesia	Cirata reservoir, West Java	145 MW	2.5 km^2	$95 m	Completed
NTPC Ramagundam solar power plant [23,31]	India	Ramagundam reservoir, Telangana	100 MW	1.8 km^2	$56 m	Completed
NTPC Kayamkulam floating solar project [23,32]	India	Kayamkulam reservoir, Kerala	92 MW	4 km^2	$58 m	Completed
CECEP Floating Solar Farm project [23,33]	P.R. China	Artificial lake near Shuzou city, Anhui province	70 MW	1.4 km^2	N/A	Completed
Sembcorp Tengeh Reservoir Floating Solar Farm [23,34]	Singapore	Tengeh reservoir, Tuas district	60 MW	0.5 km^2	N/A	Completed
Sirindhorn Dam Floating Solar Farm [35]	Thailand	Lam Dom Noi River, Ubon Ratchatani province	45 MW	0.5 km^2	$34 m	Completed
Hapcheon Dam floating PV power plant [23,36]	South Korea	Hapcheon Dam artificial lake, South Gyeongsang province	41 MW	2.5 km^2	$65 m	Completed

environments. It is important to note that this review does not intend to provide a full life cycle analysis of FPV structures; therefore, the environmental impacts related to extraction of raw materials, manufacturing, transport, etc. prior to FPV installation are not considered.

2. Engineering aspects of FPV design

In the following section, current approaches to FPV design are briefly reviewed to provide context for subsequent discussion of environmental and social impacts. This approach is deliberately broad, seeking to capture the diversity of existing FPV designs.

2.1. Diversity of structures

FPV technologies have yet to coalesce into a standard design, but all systems essentially comprise horizontal or tilted photovoltaic solar panels mounted on floating support structures, enabling deployment atop water bodies [38,46,47]. These support structures can be flexible or rigid; in some designs, PV panels track the changing position of the sun through solar tracking systems (STS), while in others the panels can remain operational whilst submerged [48,49].

An important benefit of FPV, compared with land-based PV, is the potential for higher operational efficiency due to the cooling effect of the surrounding water, which conducts heat significantly more efficiently than air. This beneficial cooling effect is particularly relevant in warm climates [50–52]. Design considerations for FPV are, however, fundamentally different from land-based PV in that FPV must cope with waves and water movements, particularly in larger lakes and the sea. Continuous impacts from waves can pose a significant challenge [53], and structural reinforcements may be required to increase resilience and avoid device failure [54]. Several solutions to this problem have been considered:

- Enlargement and reinforcing of the buoyancy system and support structures, comparable to semi-submerged oil and gas platforms or floating wind turbine foundations, so that PV panels can be installed on frames above the main wave impact zone. However, this solution is unlikely to be commercially viable given the large surface area required and high material, manufacturing and operation and maintenance (O&M) costs.
- Modular designs, where floating pontoon units supporting the PV panels are connected by hinges allowing flexibility under wave motion. Such designs possess gaps in between modules, allowing some light penetration and water-atmosphere exchange with the water below. Nevertheless, wave slamming can still lead to structural damage [55].
- Flexible, thin-layer structures, where the PV modules rest directly on the water. In this design, the air gap, which can initiate wave slamming, is eliminated; continuous cooling of PV panels by the water represents an additional advantage [17]. By following the surface topography, such structures transmit most of the wave energy downstream, reducing mechanical stresses on the structure itself [47].

Offshore structures are typically designed for an economically viable service life exceeding twenty years [56]. FPV systems must not only survive extreme conditions, but also maintain their integrity and ability to function over this extended period. It is imperative, therefore, that the materials used are suited to prolonged exposure to aquatic environments [57]. This particularly applies to joints and hinges used in modular designs.

FPV structures also need to be held in place by anchoring systems, which are likely to be more extensive than those employed for offshore hydrocarbon and floating offshore wind [58]. Examples from other sectors, such as aquaculture of macroalgae or shellfish which use extensive moorings, may offer fruitful lessons for design. Although aquaculture cages may be subject to higher drag forces compared with FPV [59,60]. colonisation of FPV by biofouling organisms may increase drag over time [61–63].

2.2. Size

FPV farms can be considered another specialised type of very large floating structure (VLFS), which includes floating airfields, bridges, piers, fuel storage facilities, as well as offshore hydrocarbon drilling platforms and other forms of renewable energy infrastructure [64,65]. There are also parallels with different types of commercial aquaculture in terms of its spatial footprint [66]. However, FPV farms have increased in size to the point where individual developments cover areas of tens of square kilometres (as highlighted in Table 1) so that their spatial footprint exceeds that of most other floating artificial structures. Most of these larger FPV systems are presently installed in freshwater environments where environmental conditions are more benign. In the open ocean, the surface area of individual FPV farms may well be smaller, at least initially, to cope with more extreme conditions. For example, FPV systems being tested or proposed for integration into wind farms in the southern North Sea are projected to be on the order of 0.5–1 km^2 in area (Oceans of Energy, 2022, pers. comm.). On the other hand, because many FPV designs are modular, they can theoretically be expanded to much larger sizes in the future, although this itself raises new challenges both in terms of design (e.g. anchorage) and of potential impacts.

2.3. Connectivity

Although some projects utilise the power produced locally, for example to power an adjacent fish farm, larger FPV farms will require a secure connection to a power grid. The development of underwater electricity transmission is well advanced in the offshore wind industry and FPV will likely employ similar technology, especially if co-located with existing energy infrastructure [6,67]. Despite considerable amounts of offshore wind-related cabling already installed, some areas of environmental uncertainty remain, for example around the possible effects of electromagnetic fields (EMF) on marine organisms.

2.4. Locations

In inland locations, FPV systems are usually deployed in larger bodies of open water (e.g. lakes and reservoirs), or anywhere where the panels are not subject to shading. FPV systems are also increasingly being considered for marine applications to address increasing demands among coastal populations for sustainable energy sources, to resolve conflicts over usage of scarce land, and to reduce project costs [6]. FPV infrastructure can also be integrated, or co-located, with offshore applications such as wind energy generation, hydrogen production and aquaculture [68–70].

2.5. Material composition

Compared to land-based PV, FPV systems will likely have a higher capital expenditure (CAPEX). To reduce the CAPEX, one potential strategy is to use low-cost and low-maintenance materials, such as high-density polyethylene (HDPE). The exposure properties of HDPE are well known, and such plastic materials are usually lighter and cheaper compared with the metallic materials that have been widely used in older offshore industries. If a modular design is adopted, the manufacturing process can be streamlined while such designs can reduce transportation, installation, and decommissioning costs. However, if novel materials are used, their durability under long-term immersion in (salt) water would need to be evaluated through accelerated ageing tests in conditions of high humidity and UV radiation levels.

2.6. Operation & maintenance options

FPV panels need to be kept clean from salt, biofouling, sediment, and other debris to maintain their operational efficiency. Manual cleaning may not be economically viable, especially offshore, and self-cleaning systems are likely to be required for large-scale FPV arrays [71,72]. Alternatively, flexible, thin-layer FPV designs will be self-cleaning to some extent through surface water action. This interaction between waves and panels may not only ensure cleaning, but the resulting cooling may also improve efficiency [52]. However, more research is required to determine the optimal freeboard that balances the stresses from wave slamming with maximum cleaning efficiency.

Solar tracking systems (STS) are widely used in terrestrial PV, where the panel orientation is automatically adjusted to take maximum advantage of the insolation angle [73]. Tilting panels around the horizontal axis have been implemented in some freshwater settings [74], while rotation around the vertical axis has also been proposed [75]. Feasibility of such dynamic control in marine applications presently remains unclear and could lead to considerable mechanical stresses caused by panels acting like sails when turned in down-wind orientations. Unless the supporting flotation substructure is extremely large, panel orientation will fluctuate due to passing waves, which may also reduce efficiency gains from dynamic positioning.

3. Environmental impacts of FPV in aquatic ecosystems

The operational lifetime of FPV infrastructure to be deployed in freshwater and marine settings is expected to be on scales of 10–20 years [76], which is sufficiently long to result in environmental impacts at various scales. The following section seeks to address these impacts, organised along broad themes: 1) shading, 2) impacts on hydrodynamics and water-atmosphere interchange, 3) energy emissions, 4) impacts on benthic communities, and 5) impacts on mobile species. Some impacts are a result of the physical presence of the FPV structure, moorings etc. whereas other impacts only occur due to the structure intercepting sunlight (i.e. their severity is reduced or absent at night). Potential societal effects of widespread FPV development are discussed separately. A graphical summary of potential impacts is provided for freshwater and marine systems in Fig. 1A and B.

3.1. Shading effects

FPV systems significantly reduce underwater irradiance (shading, as illustrated in Fig. 1; [38,77]), which may negatively impact organisms reliant on photosynthesis, including phytoplankton, benthic species such as seagrasses and macroalgae and even coral reefs [44,45,78]. The effect of shading caused by FPV systems will vary by latitude, time of day and water column properties. Near the equator, the sun is generally high in the sky (close to a 90° angle relative to the horizon), whereas at higher latitudes, lower solar angles mean that the incoming light is more diffuse. The resultant impact on underwater light levels ranges from a well-defined shadow immediately adjacent to the FPV at low latitudes, to a more extensive, slanted area of shading at higher latitudes.

Shading provided by FPV can be beneficial in enclosed freshwater systems such as reservoirs by reducing harmful algal blooms [48]. However, significant reductions in photosynthetic activity in water bodies that are fully covered by FPV systems can lead to reduced dissolved oxygen levels [78–80]. Covering large stretches of (semi-) enclosed water bodies such as lakes, reservoirs or coastal lagoons may thus result in overall depletion of phytoplankton biomass, changes to timing and occurrence of phytoplankton blooms, persistence of unused nutrients in the water column, and changes in phytoplankton community composition [45,81]. Such effects can cascade through food webs reducing overall system productivity [82]. The significance of any such effects will vary depending on whether, and to what extent, gaps between FPV units allow sunlight to penetrate [63,77].

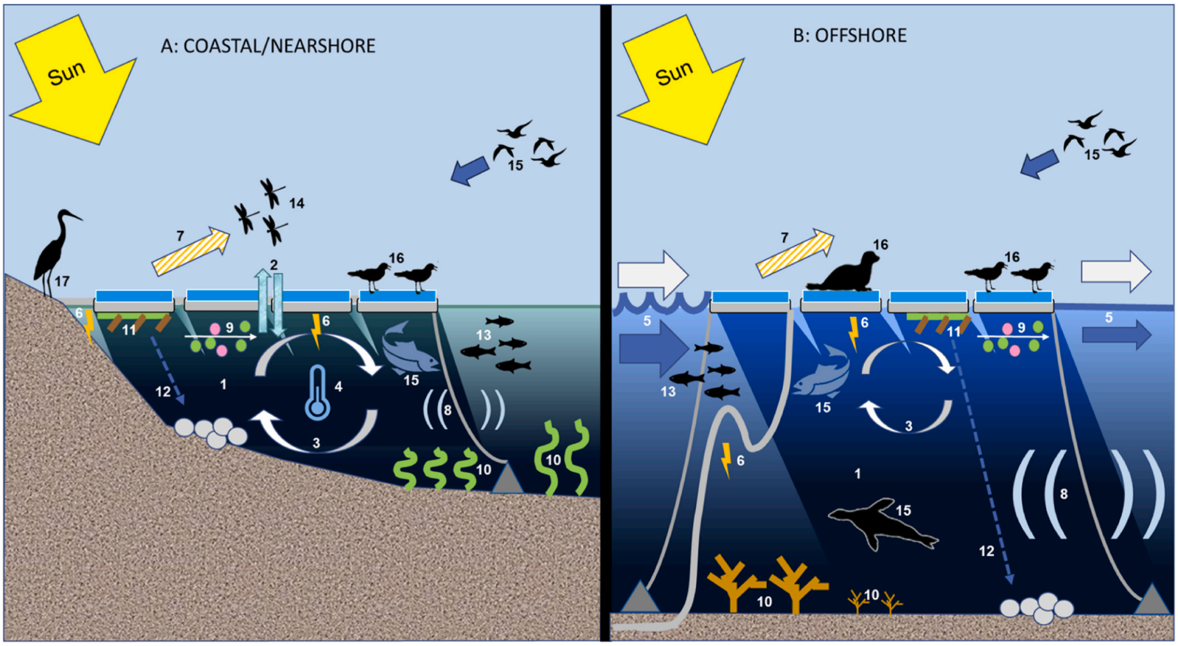

Fig. 1. A and B. Schematic overview of the various potential impacts by FPV on the surrounding environment in A) coastal/nearshore (mainly freshwater) and B) offshore (mainly marine) environments. FPV systems are indicated by the horizontal blue/grey panels, and moorings, power cables etc. are included in grey. Only the main impacts are illustrated. 1 = Shadow underneath FPV (can be continuous or disjunct); 2 = Altered water-atmosphere exchanges; 3 = Changes to vertical circulation patterns; 4 = Changes to water temperature; 5 = Changes to wave exposure through wind shielding (wind = white; waves = blue); 6 = Electromagnetic field (EMF) emissions; 7 = Reflection of (polarised) light; 8 = Underwater sound emissions; 9 = Impacts on phytoplankton (green) and zooplankton (pink); 10 = Impacts on benthic light-dependent organisms; 11 = Development of epibenthic fouling communities (incl. invasive species); 12 = Benthic biodeposition effects; 13 = Attraction of fish etc. (artificial reef effects); 14 = Impacts on polarotactic species (e.g. insects); 15 = Attraction of top predators; 16 = Use of FPV module infrastructure for resting by mobile species; 17 = Restriction of access to water surface (from land or underwater).

Potential effects of shading by FPV on photosynthesis by marine phytoplankton were modelled by Karpouzoglou et al. [44]. This study used various assumptions regarding the spatial distribution of FPV coverage, but nonetheless suggested strong dependence of photosynthesis on both local conditions and the amount of sea surface which was obscured. Modelled primary production declined by <10 %, when up to 20 % of the sea surface was covered, but declined rapidly once cover was increased further. Karpouzoglou et al. [44] concluded that FPV-driven shading effects on marine phytoplankton communities were potentially important, at least at local scales, and widespread deployment could have significant effects. However, currents in large water bodies are likely to transport phytoplankton out from underneath FPV structures before light deprivation becomes a serious problem, although spatially resolved models and appropriate parameterisation experiments are required to better understand this potential impact.

Reductions in underwater irradiance by FPV systems may also impact benthic photosynthesisers (as illustrated in Fig. 1A and B). This would generally be limited to water depths of <30 m, where light levels are sufficient to sustain submerged communities of macrophytes and algae. Whilst many freshwater ecosystems depend on diverse and flourishing macrophyte communities [83], comparable communities in shallow marine environments include seagrasses (e.g. *Zostera* sp.) and macroalgae such as stoneworts (Characeae), kelps (Laminariales) and maerl (*Lithothamnion* sp.) [84]. Various animal species, most notably reef-building corals (class Hexacorallia) also rely on photosynthesis by symbiotic algae (zooxanthellae) living inside their tissues [85]. These communities are often highly biodiverse [86] and widespread reductions in light levels due to FPV development could have negative impacts on their long-term persistence; this aspect requires careful consideration when siting potential FPV farms [87–90].

Zooplankton also respond to light [91], with illumination being a major driver of Diel Vertical Migration (DVM). DVM sees both marine and freshwater zooplankton migrate to the surface at dusk to feed on phytoplankton in the safety of darkness and return to depth at sunrise to avoid the threat of visual predators [92]. Changes in the light field are known to impact zooplankton DVM behaviour [93]. Being advected underneath FPV farms (as illustrated in Fig. 1) can be likened to the light environment experienced by zooplankton during a solar eclipse, with sudden darkness experienced for a short period of time (several minutes, based on observed flow speeds [93,94]). Zooplankton are known to respond to eclipses by shallowing their vertical position [95], while lunar eclipses delay swimming behaviours usually observed at moonrise [96]. Both kinds of behavioural responses could be expected for zooplankton transported under FPV farms, which would result in zooplankton moving towards the surface while underneath the FPV, at additional energetic cost. As zooplankton are subsequently advected out of the shadow underneath the FPV, sudden exposure to high ambient light levels will significantly increase their vulnerability to predation [97]. The impact of shading on zooplankton behaviour may only become significant under larger FPV installations, where individual zooplankton might spend significant periods in shaded waters and initiate DVM.

To fish, the presence of shade can be desirable, presumably because it makes them more difficult to spot compared with adjacent sunlit parts of the water column or from above [98–100] (as illustrated in Fig. 1A and B). Helfman [98] also proposed that the relative visual advantage to fishes of remaining in shade would increase with increasing water clarity. More recent studies noted an increase in the encounter rate of large predatory fish along the edges of similar large floating structures (floating piers), but a decline in overall fish abundance and diversity in more deeply shaded areas beneath the piers [101,102]. These observations suggest that areas of deep shade beneath large floating structures may be suboptimal habitat for many fish species [101,102]. Given the potential for FPV systems, particularly those in enclosed freshwater systems, to reduce intensity of phytoplankton blooms and thereby increase water clarity over time, the indirect effects of shade produced by FPV may become an increasingly significant driver of fish distribution in such systems.

In summary, shading is likely to negatively impact local plant and algal communities (and other organisms that require light, such as scleractinian corals) beneath FPV farms, and lead to increased environmental heterogeneity due to spatially discrete, semi-stationary, abrupt changes in ambient light levels. The wider significance of this heterogeneity, particularly to plankton and fish, remains poorly understood at present. These impacts can be at least partially mitigated by FPV design, e.g. by arranging FPV panels in a different shape, and/or ensuring that sunlight continues to reach the water column below through gaps in the FPV cover [102]. The effectiveness of any such measures will need to be established experimentally.

3.2. Impacts on hydrodynamics and water-atmosphere interactions

3.2.1. Water-atmosphere exchanges

In freshwater settings, FPV systems can reduce water loss through evaporation by 1) reducing the temperature of the water body below and 2) restricting exchanges at the water-atmosphere interface ([45]; as illustrated in Fig. 1A). This may be a significant secondary benefit of FPV systems in areas where rainfall is scarce and human populations rely on reservoirs and/or irrigation channels for domestic, agricultural, and industrial water [103,104]. In most marine settings, the massive discrepancies in scale between FPV systems and the surrounding ocean make changes to evaporation rates largely irrelevant, except potentially in sheltered sites such as coastal lagoons [105]. Such sites are by definition coastal, limited in size, and may display reduced tidal ranges, all of which could encourage future FPV development. As coastal lagoon communities often contain species of conservation concern [106], potential impacts of FPV on local hydrological cycles and evaporation rates should be considered to mitigate impacts on these sites. Complete coverage of waterbodies with FPV could also inadvertently restrict access to surface waters for a wide range of terrestrial and aquatic species (waterbirds, amphibians, aquatic insects etc. as illustrated in Fig. 1A).

3.2.2. Changes to water temperature

FPV systems are expected to result in localised cooling of the water below the panels by reduced exposure to heating by solar irradiation [17,45] (as illustrated conceptually in Fig. 1A). As most aquatic species' physiological processes are closely linked to ambient water temperatures, a sufficiently large change in temperature could influence the physiological states and/or behaviours of organisms [107]. Depending on the extent of coverage and the degree of vertical mixing and horizontal water transport in the area, FPV-induced reductions in surface temperature may be noticeable at local scales, especially if water exchange rates are limited (e.g. lakes, reservoirs, coastal lagoons [108]). Reductions in irradiation levels may also result in changes to seasonal temperature dynamics due to reduced storage of heat in the water body [45]). Recent observations of FPV systems in the Netherlands confirm both the occurrence of temperature reductions and reduced levels of temperature variability beneath FPV structures, although overall effects in these cases appeared limited [63,77]. In general, impacts of FPV-induced reductions to ambient temperatures on biological communities are likely to be minor.

3.2.3. Changes to vertical mixing

FPV systems may change the extent of vertical mixing of the water column beneath and downstream of the structure, analogous to effects observed under sea ice or adjacent to wave energy converters as illustrated conceptually in Fig. 1A and B (e.g. Refs. [109,110]). This effect is partly caused by wind shielding from the structures, resulting in reduced mean wave heights and reductions in turbulence and vertical mixing. For flexible thin-layer structures floating at the sea surface, hydrodynamic drag will increase, thereby also reducing turbulence and vertical mixing to the extent that increased stratification could result. Such changes to local hydrodynamics may impact the replenishment of dissolved nutrients essential for phytoplankton growth, with potential knock-on effects for pelagic communities [111,112]. Similar concerns have been expressed in relation to offshore wind farms [113] and aquaculture infrastructure [114], but the larger spatial extent of FPV farms may make it an important consideration for this industry as well. This effect is likely to be most noticeable when deploying FPV systems in areas that naturally experience strong seasonal stratification, such as sheltered freshwater lakes, reservoirs and coastal embayments, but also in deeper waters further offshore [115,116]. Understanding the relative magnitude of such impacts, in relation to FPV, will require focused hydrodynamic modelling studies.

3.3. *Emissions and pollution*

3.3.1. *Energy emissions*

Solar PV panels do not absorb all incoming sunlight, instead reflecting some of the incident radiation back into their environment (as illustrated conceptually in Fig. 1A and B [117]). In terrestrial settings, concerns have been raised that expanses of reflective PV arrays can be perceived as water bodies by migratory waterbirds, which then collide with the structures as they attempt to land (known as the ‘lake effect’). Such collisions may cause injury whilst uninjured birds may face significant difficulties taking off again [118,119]. FPV structures would intuitively be expected to pose less of a problem to aquatic birds, assuming they are able to distinguish these structures from water surfaces when attempting to land. Further work is needed to clarify different bird species’ ability to identify and avoid collisions with such structures under varying environmental conditions.

The surfaces of PV panels cause reflected sunlight to become partially linearly polarised [120] (as illustrated conceptually in Fig. 1A and B). Many animal groups, including insects, birds, amphibians, and others, are polarotactic, or sensitive to polarised light, which they use as an environmental cue to locate open water [121,122]. Aquatic insects (dragonflies [Odonata], mayflies [Ephemeroptera], caddisflies [Trichoptera] etc.) are often attracted to PV panel surfaces in large numbers, attempting to deposit eggs which then desiccate and die, creating ecological traps unless corrective mitigation measures are taken [121,123]. While FPV structures deployed in freshwater settings could attract polarotactic aquatic insects, it is unclear whether these insects would then continue to seek out the FPV in preference to the surrounding water, unless most of the water surface were covered with FPV. This problem is unlikely to be a significant concern in marine settings, given the significant discrepancies in scale between FPV systems and the surrounding ocean, and the apparent absence of large numbers of flying polarotactic species (other than seabirds that use polarised light for navigation [124]).

Moorings associated with FPV structures may emit underwater noise, particularly in currents or during storm events (illustrated conceptually in Fig. 1A and B, with sound intensities more likely to be elevated in larger, offshore arrays). Similar concerns about persistent long-term noise production have been raised in relation to fixed and floating offshore wind [125–127]. Characterisation of this noise amplitude and frequency spectrum will be important to ensure that FPV systems do not present a significant additional source of anthropogenic underwater noise, particularly when considering the cumulative effect of multiple renewable energy developments [127].

Apart from small systems providing electricity to local users such as adjacent fish farms, larger FPV arrays will export electricity via transmission cable systems [128] Such cables generate local electrical and magnetic fields (illustrated conceptually in Fig. 1A and B) and understanding potential impacts of EMF has long been a concern for the renewables industry and regulators. Many species (e.g. crustaceans, elasmobranchs, marine turtles) are sensitive to local variations in the Earth’s electromagnetic field (EMF) and use electromagnetic-based cues to orient, navigate or forage [129,130]). Accordingly, concerns have long been expressed about potential effects of artificial EMF on EM-sensitive species [131]).

Despite several studies into EMF associated with offshore wind farms (e.g. Refs. [132–134], its effects on behaviour and physiology of most marine and freshwater species remain poorly understood. Several recent studies have suggested that EMF can impact the distribution and movements of benthic invertebrates such as crustaceans, at least at local scales [130,133,135]. EMF sensitivity in elasmobranchs (sharks and rays), where electrodetection has been long established as a primary sensory system, is better understood [136]. Behavioural responses to EMF, potentially associated with foraging behaviour, have been observed in various elasmobranchs [133,137]. Numerous migratory fish species (e.g. eels, salmonids) are also known or suspected to use the Earth’s geomagnetic field to navigate, and these species could potentially be affected by artificial EMF generation, but observations are again limited [138,139]. Further work is needed to understand any potential impacts of EMF modifications around FPV structures, including the solar panels and the power take-off cables, on EMF-sensitive species such as elasmobranchs.

3.3.2. *Chemical pollution*

Risks of chemical pollution are limited in well-maintained FPV systems. Unlike terrestrial PV arrays, where chemical dust suppressants are often used to maintain panel efficiency with various negative environmental impacts [140], the presence of water will generally reduce the requirement for such substances. However, the use of antifoulants on submerged surfaces can result in pollution, and the ramifications of their use should be carefully considered; recent advances in this field also offer potential for non-chemical antifoulant alternatives [141].

3.4. *Impacts on benthic ecosystems*

3.4.1. *Impacts on surrounding sediments*

Anchors are required to hold the FPV system in position and these can result in localised scouring of the seabed [142]. If the FPV is located over sensitive benthic habitats, anchors are likely to cause direct disturbance during installation. Anchors may also move as the FPV responds to waves and currents, potentially exacerbating impacts on adjacent benthic habitats. Modern anchor designs have, however, benefitted from experience in the aquaculture and offshore renewables industries and are designed to minimise such effects [143]. Risks from resuspension of sediments during both installation and operation are likely to be trivial in comparison with other sectors (e.g. commercial fishing using mobile benthic gears such as trawls, aggregate dredging; [142,144,145]).

Studies beneath floating structures, such as wave energy converters and aquaculture facilities, have illustrated how the composition of the seabed underneath FPV systems may change over time due to deposition of biogenic material from epibenthic communities [146–148] (illustrated in Fig. 1A and B). Decomposition of large volumes of such material deposited onto the sediment can lead to reductions in oxygen levels and ultimately to reductions in overall biomass and diversity of benthic fauna [149], particularly in locations with limited circulation. On the other hand, falling debris (e.g. shells from epibenthic bivalves) may stabilise sediments, creating increased habitat complexity which may increase local biodiversity [150–152].

The significance of impacts of FPV systems on surrounding sediments, and the spatiotemporal scales over which such impacts are detectable, will vary according to local conditions. Considerable expertise in assessing and monitoring the dimensions of benthic footprints around other maritime industries already exists [153–155] and such approaches could be utilised here as well.

3.4.2. *Artificial reef effects*

Once deployed, FPV systems will be rapidly colonised by ‘fouling’ epibenthic organisms, with complete coverage anticipated within a year of installation [156,157] as illustrated in Fig. 1A and B. Epibenthic communities often contain suspension feeders, which through their collective foraging activities may reduce water turbidity, further enhancing the contrast between shaded and lit parts of the water column [158–160]. The presence of mature epibenthic communities may offer opportunities for shelter and/or foraging for a wide range of mobile species, ranging from crustaceans to fish to birds.

Biofouling is generally considered undesirable in FPV and offshore renewable energy (ORE) more generally as it adds mass [161], roughens the subsea surface of the structure leading to increased drag [38], enhances corrosion [162], and can affect the amount of light received by the PV panels (by fouling algae; [163]. FPV-associated artificial structures could also act as 'stepping stones' for invasive non-native species [157,164,165]. For example, coastal specialists that would otherwise be unable to survive in offshore marine environments, such as the marine midge (*Telmatogeton japonicus*) and skeleton shrimp (*Caprella mutica*), have colonised aquaculture installations and wind farms across the world and would likely do the same with FPV structures [166–169].

The precise composition of the resulting epibiotic community will depend on the time the structures have been deployed, their shape, 3D complexity, chemical composition, average and peak flow speeds, temperature, salinity, depth (with wave action and light levels being important drivers), structural stability, and likelihood of scouring by turbulence and suspended sediment [156]. The potential artificial reef effects of widespread FPV deployment should, therefore, be viewed as one element of a broader expansion of very large floating structures into marine environments, where cumulative spatiotemporal effects on epibenthic communities are still only partially understood but are likely to be significant.

3.5. *Impacts on mobile species*

3.5.1. *Fish*

Mobile species such as fish often congregate around artificial infrastructure (as illustrated conceptually in Fig. 1A and B; [170–172]), although whether such structures increase available fish biomass by improving habitat quality or aggregate existing fish biomass from across a wider area, continues to be debated [173–175]. Similarly, floating objects have been long known to attract a wide range of fish [176]. In some commercial fisheries this behaviour is exploited by deploying floating fish aggregation devices (FADs), which are then targeted by fishers once enough fish have been attracted [177–179]. Floating objects may provide different benefits depending on the objects' size, composition, complexity, and longevity, including shelter from predators, epibiotic feeding opportunities, concealment from prey, a means to encounter conspecifics or a substrate on which to deposit eggs [98,176, 180–184]. Colonisation of floating objects appears rapid, although individual fishes' residency time may be limited [185]. FPV systems may encourage aggregative and associative behaviours among pelagic fish, and the potential for this type of stationary, floating offshore infrastructure to act as a fish attractor has been previously noted [186,187]. However, as mentioned previously, intense shading has been found to reduce attractiveness to various fish species, especially those reliant on vision for foraging, at least in coastal environments [101,102]. Future expansion of offshore infrastructure, including arrays of FPV systems, floating offshore wind turbines, and wave energy converters, could thus lead to changes in fish distribution [3,188,189].

Aggregative and associative behaviours of different fish species around FPV infrastructure can be anticipated, analogous to fish aggregations observed among wind farms, oil & gas platforms, etc. [160,190, 191]. If fish become preferentially associated with FPV infrastructure, among which fishing is likely to be impractical, such sites could start to act as miniature Marine Protected Areas, potentially resulting in increases in abundance and reproductive outputs for local fish populations [192–194]. The potential wider environmental impacts of such changes to fish distribution and movement patterns deserve careful consideration when planning FPV deployments.

3.5.2. *Megafauna*

Large mobile species ("megafauna", here referring to e.g. mammals, birds) may be attracted to FPV systems if they provide perceived benefits such as shelter, a place to rest, or access to concentrated or otherwise unavailable food resources (as illustrated in Fig. 1A and B). Birds are likely to be among the earliest to discover and make use of artificial floating structures as a place on which to rest and/or from which to forage, analogous to their interactions with natural floating objects or fixed structures [195]. Stationary offshore infrastructure, such as oil & gas platforms and wind turbines, is commonly used by seabirds to rest upon and may even allow birds to make use of previously inaccessible resources (e.g. great cormorants [*Phalacrocorax carbo*] foraging among offshore wind farms located well outside their traditional foraging ranges; [196,197]). Diving species such as the black guillemot (*Cepphus grylle*) have also been observed to use floating wave energy converter (WEC) systems to rest on and forage in the sheltered area on their lee side (although birds' use of the WECs declined as wind speeds increased; [198]). As well as providing foraging and roosting opportunities, some bird species may breed on aquatic infrastructure, including offshore oil rigs [199,200]. FPV structures are, therefore, likely to be used by various aquatic and marine bird species, potentially resulting in deposition of bird guano on the panels and support structures that can negatively impact FPV productivity [55]. Automated or self-cleaning mechanisms for the PV panels may need to be considered to avoid this problem. Nevertheless, FPV projects should remain alert for the possibility of inadvertently creating ecological traps (whereby attraction results in reduced fitness; [201]). Conversely, some sensitive species may avoid the vicinity of FPV farms in a manner similar to offshore wind infrastructure, which could have long-term negative consequences if widespread FPV deployment led to abandonment of important foraging or resting areas [202,203].

Aquatic mammals (notably pinnipeds i.e., seals, sea lions and walrus) may also seek out accessible floating structures, such as pontoons or boats at anchor, on which to rest [204]. All pinnipeds haul out regularly onto land or sea ice to rest, avoid predators, moult and breed [205–207]. Many pinnipeds are central place foragers, repeatedly returning to the same areas between foraging trips [208]. Widespread deployment of FPV offshore could, therefore, provide novel opportunities for pinniped species to remain at sea for longer and/or exploit previously inaccessible areas, as has already been observed anecdotally in at least one marine FPV test site in the southern North Sea (Prof. K. Camphuysen, Netherlands Institute for Sea Research, Pers. Comm., 2022).

Similar to seabirds, scats left behind by hauled-out pinnipeds could potentially reduce FPV panels' electrical generation capacity; robust automated cleaning systems may be required. Given their considerable strength and body weight, the regular presence of pinnipeds hauled out onto FPV structures could lead to physical damage or even partial submergence [209]. In freshwater and coastal settings, other species of aquatic mammals such as otters may also make use of FPV infrastructure. FPV systems in (sub)tropical freshwater and inshore marine environments could be used by aquatic reptiles, including turtles, crocodilians, and aquatic snakes [210], as a platform on which to rest and, importantly, bask in the sun, as well as a central point from which to forage. It may prove difficult to discourage such behaviour without fencing off FPV structures.

As previously mentioned, the recent and ongoing expansion of ORE infrastructure across marine ecosystems may modulate the distribution and abundance of fish through artificial reef effects. This, in turn, could drive changes in the distribution of marine top predators. Evidence that individual animals may seek to associate with ORE infrastructure is accumulating [211], but wider population-level effects are still poorly understood. Further work is needed to clarify the wider importance of FPV and other ORE infrastructure in driving long-term changes in distribution of marine mammals, seabirds and other top predators, with as-yet poorly understood consequences.

Entanglement in fishing gear and marine debris is a common cause of injury or death of large mobile species, such as marine mammals, elasmobranchs, seabirds and marine turtles [212–216]. Entanglement risks posed by ORE-related mooring systems and transmission cables are thought to be low, with the possible exception of the largest whales, due to the dimensions and flexibility of the structures involved [217,218]. There are, however, ongoing concerns about abandoned, lost or discarded fishing gears [219] becoming snagged onto ORE devices, where these can continue to entangle, and cause injury and mortality of, a wide range of marine species in an uncontrolled fashion [219]. Further work is required to understand the true significance of this problem, especially considering the potential for fishing effort redistribution around these developments.

4. Social impacts of FPV in aquatic ecosystems

Development and commercial scale operation of any renewable energy technology in the marine environment can have significant societal impacts [220]. In literature from the European Economic Area, where FPV systems are still in early stages of development [38], there is recognition by engineers and ecologists that successful adoption of this technology is dependent on “acceptable” ecosystem effects, as well as technological and economic viability [43,221]. The social acceptability of different renewable energy technologies has been widely studied over the past two decades. The literature includes exploration of people’s opinions on renewable energy projects (see for example [222,223]) to the development and application of different social and psychological theories, from place attachment [224–226] to NIMBYism and rejection of it [227–229]. Current research has focused on understanding renewable energy technology interactions through an energy justice lens, a systems approach that includes equality, fairness, and access within the nexus of biodiversity loss, the climate emergency, and the need to transition to a low carbon economy [230,231].

Much of the limited research on people-technology complexities around FPV comes from land-based lake and reservoir arrays [232]. This literature describes societal challenges around access to livelihood activities, such as fishing [221], and concern over the health and safety of workers on-site and in FPV factories [233,234]. One of the few social studies of FPV in the EU was conducted on a pilot reservoir-based system in the Netherlands; the findings showed a mixed view of the project [235]. Perceptions were based on interactions with livelihood activities, leisure accessibility and visual impact, and lack of trust in the legal, planning, technological and environmental management processes and procedures. Opinions varied according to stakeholder type: business owners were more likely to assess the project through perceptions of economic impact, while recreationalists viewed access and visual impact as the decisive components, and NGOs focused on ecological ramifications and unknowns. The authors highlight the challenge of researching the social interactions of a technology where there are still many uncertainties relating to environmental impact, socio-economic benefits, and technological performance [235].

The research on the social interactions of FPV is sparse, particularly for marine-based systems. However, available evidence echoes the wider renewable energy literature, in that technological and economic viability does not automatically equate to social acceptability [236] or energy justice [237]. Specific social considerations and appropriate mitigation measures for any impacts are dependent on the location and scale of an FPV operation [233], as well as its environmental and economic interactions, and the cultural, political and policy contexts of the area. From a broad perspective however, coastal environments are used for multiple human purposes which may interact with deployment of FPV technology. These can include fishing, tourism, shipping and transportation, security and military activities, recreation, and protection of environmental characteristics. Landside uses should also be included in social interactions to incorporate housing, recreation, industry, transportation, and protection of environmental characteristics (including vistas).

Key considerations that are found in social literature on renewable energy, but are not presently covered in sufficient depth by social studies on FPV, include: community and public opinions on FPV [235]; policy and planning interactions [235]; visual impact assessments (see [238] as an example from onshore solar energy systems); the socio-cultural, socio-economic and wellbeing effects of displacement of livelihood activities (e.g. fishing and tourism operations); and appropriate mitigation measures (see[236] as an example from offshore wind), contextually appropriate stakeholder identification and engagement and community benefits mechanisms (see [239] as an example from offshore wind); and the interlinkages between all these in the development of a ‘social licence to operate’ for FPV (see [240] as an example from multi-use offshore platforms). Further, as FPV is still in its infancy from a global perspective, there is the opportunity for transdisciplinary research to contribute to the development of decision-making tools that take an energy justice approach – including inequalities in benefits/disbenefits and human well-being, and non-Western approaches to knowledge production

FPV technology may lend itself well to spatiotemporal co-location with other, more mature offshore infrastructure such as oil & gas platforms, fixed offshore wind turbines, WECs, aquaculture fish cages and/or floating breakwaters. Such co-location could lead to a shared infrastructure and reduced O&M cost, ultimately reducing levelized cost of energy. For an FPV-wind or FPV-WEC system, the benefits will also include an increased and smoother power output [241], since the FPV systems would supplement power output during the summer months, when there is typically less wind. Integration of FPV and offshore wind may represent a further step towards the development of offshore energy hubs, which may assume increased economic and strategic significance over time [242,243] but may result in synergistic environmental and social impacts which will likely increase in line with the forecast expansion of this and other floating infrastructure [244]. Co-location with nature conservation (e.g. by locating the FPV inside a Marine Protected Area) may be practical if the environmental impacts do not negatively affect the species or habitats for which the protected area was originally established. Fishing activities are likely to be curtailed in the vicinity of a FPV and may result in displacement and reallocation of fishing effort, similar to what has already occurred with offshore wind farms [245,246].

5. Anticipated monitoring needs

Like other renewable energy developments, future FPV developments will likely be required to undertake some form of environmental impact assessment (EIA) as part of their licensing conditions. Where applicable, FPV should also be considered in SEA for energy plans and programs. Given that FPV is still a very new industry, it is important to consider what monitoring approaches might be appropriate. This especially pertains to questions about water quality below the structures, condition of light-dependent species (phytoplankton, macrophytes, macroalgae, corals etc.), presence of invasive species as part of the biofouling community, light and noise emissions, and use of FPV structures by mobile species (fish, birds, mammals etc.). Any monitoring scheme for FPV will need to conform to national regulatory standards, but aspects that could be considered include:

- Ensuring that water quality sampling (e.g. dissolved oxygen, temperature) is undertaken at a range of depths and locations below the FPV structure, where the FPV design allows, to understand small-scale heterogeneity.
- Developing regular biofouling sampling schemes to enable monitoring for invasive non-native species.

- Understanding scale and distribution of emitted polarised light levels, and likely attractiveness (and conservation risk) to flying polarotactic species.
- Incorporating passive acoustic monitoring for FPV sites to ensure that full-scale FPV installations do not contribute significantly to anthropogenic noise levels.
- Monitoring presence and usage of FPV structures by mobile species, which could involve a combination of remotely operated in-air cameras, periodic visual surveys, underwater active acoustic surveys (for fish), passive acoustic monitoring (for cetaceans), eDNA surveys (for benthic and pelagic communities), etc., as appropriate.

Any monitoring scheme should consider not only the FPV structures themselves, but also wider activities surrounding installation (including power cables) and maintenance vessels. Given the costs of monitoring, testing and refining monitoring tools should be considered a priority, preferably at designated FPV testing sites where the performance of different FPV systems can be evaluated [77].

6. Conclusions

Floating photovoltaic (FPV) technology is emerging as an important component in ongoing efforts to decarbonise global energy generation systems. This is, therefore, an opportune time to reflect upon the various potential environmental impacts that might be observed following widespread deployment of this novel kind of infrastructure. In summary:

- Various broad categories of environmental impact are known or expected to occur across different aquatic environments.
- Environmental impacts of FPV systems are expected to scale with the fraction of the water body's surface area that they occupy.
- Environmental impacts from FPV should be considered cumulatively in combination with impacts from other industries.
- Cross-sectoral collaboration is needed to ensure data gaps are addressed and appropriate solutions implemented.

FPV systems are expected to have their strongest impacts in situations where the FPV covers most, or all of, the available water surface, particularly on freshwater ecosystems. Significant impacts may also be anticipated where FPV projects are installed in sheltered coastal locations, especially those with restricted water exchange with the open sea such as coastal lagoons. Although impacts from offshore FPV deployment may be reduced given differences in scale with the open ocean, cumulative impacts could still occur, especially in combination with other projects such as offshore wind farms or aquaculture.

Known or potential environmental impacts of FPV will vary by location, but are expected to primarily involve 1) abrupt changes to light levels in the water column below the FPV structures, 2) impacts on hydrodynamics and water-atmosphere interchange, 3) energy emissions, 4) impacts on benthic communities, including artificial reef effects and accommodation of invasive non-native species, and 5) impacts on mobile species (fish, marine mammals etc.).

As the FPV industry expands, close collaboration between researchers, developers, regulators and other stakeholders will be necessary to understand the nature and severity of environmental and social impacts that may occur, and to consider sustainable and equitable solutions. These may involve changes to FPV array design, mooring systems, antifouling approaches etc., as well as greater co-location with other sea users. The use of FPV test sites will be crucial to developing appropriate environmental mitigation and monitoring approaches for the benefit of the industry, society and nature.

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.

Data availability

No data were used for the research described in the article.

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