Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

Scientific and stakeholder evidence-based assessment: Ecosystem response to floating solar photovoltaics and implications for sustainability

G. Exley [a],[*], R.R. Hernandez [b],[c], T. Page [a], M. Chipps [d], S. Gambro [e], M. Hersey [f], R. Lake [g], K.-S. Zoannou [h], A. Armstrong [a],[i]

[a] Lancaster Environment Centre, Library Avenue, Lancaster University, Lancaster, LA1 4YQ, United Kingdom
[b] Department of Land, Air and Water Resources, UC Davis, Davis, CA, USA
[c] Wild Energy Initiative, John Muir Institute of the Environment, UC Davis, California, USA
[d] Thames Water Research, Development and Innovation, Kempton Park AWTW, Feltham Hill Road, Hanworth, TW13 6XH, United Kingdom
[e] Ennoviga Solar Ltd., 27 Old Gloucester Street, London, England, WC1N 3AX, United Kingdom
[f] South East Water, Rocfort Road, Snodland, Kent, ME6 5AH, United Kingdom
[g] Affinity Water, Tamblin Way, Hatfield, Hertfordshire, AL10 9EZ, United Kingdom
[h] Water Quality and Public Health Team, Water Quality and Compliance Directorate, Southern Water, Southern House, Yeoman Road, Worthing, BN13 3NX, United Kingdom
[i] Energy Lancaster, Science & Technology Building, Lancaster University, Lancaster, LA1 4YF, United Kingdom

ARTICLE INFO

ABSTRACT

Floating solar photovoltaic (FPV) installations are increasing globally. However, their interaction with the hosting water body and implications for ecosystem function is poorly understood. Understanding potential impacts is critical as water bodies provide many ecosystem services on which humans rely and are integral for delivering the United Nations Sustainable Development Goals (SDGs). Here, we used scientific evidence from a systematic review and stakeholder expertise, captured through an international survey and a workshop, alongside existing understanding of the role of water bodies in delivering ecosystem services and the SDGs. We found 22 evidence outcomes that indicated potential physical, chemical and biological impacts of FPV on water bodies. Assessment by stakeholders from across sectors indicated that reduced water evaporation is the greatest opportunity, whilst changes to water chemistry, including nitrification and deoxygenation, are the greatest threat. Despite these findings, FPV operators reported no observed water quality or ecosystem impacts. However, only 15% of respondents had performed water quality analysis; visual inspection alone cannot ascertain all water quality impacts. Based on the integration of these findings, we determined that FPV could impact nine ecosystem services. Furthermore, established linkages between ecosystem services and SDGs indicate the potential for impacts on eight SDGs, although whether the impact is positive or negative is likely to depend on FPV design and water body type. Our results further the understanding of the effects of FPVs on host water bodies and may help to ensure the anticipated growth in FPVs minimises threats and maximises opportunities, safeguarding overall sustainability.

1. Introduction

In the rush to mitigate the climate crisis, it is critical that new energy developments do not inadvertently hinder, but ideally enhance, other sustainable development goals. The deployment of low carbon,

renewable energy technologies is central to achieving the United Nations (UN) Sustainable Development Goal (SDG) adopted by UN member states in 2015 to ensure *access to affordable, reliable, sustainable and modern energy for all* (SDG7) [1,2]. Consequently, the increasing demand for low carbon energy has led to the rapid deployment of solar energy

infrastructure across the world [3], with technologies including solar photovoltaics (PV), concentrating solar power and solar thermal. PV technology dominates current solar energy infrastructure [4] due to its viability across climates [5] and scalability, permitting deployments ranging in capacity from residential-to utility-scale [6]. In comparison to other electricity generation methods, solar PV has a low energy density (~ 0.25 MW acre^{-1} [7]) and thus exerts a considerable land-use pressure [8–10], potentially impacting other SDGs, such as *life on land,* and the provision of ecosystem services on which society relies [11]. However, the flexible nature of PV has enabled innovative deployments that could be harnessed to incorporate co-benefits for other SDGs and the provision of ecosystem services [12]. For example, efforts to overcome land-use conflict between solar PV and agricultural production (SDG2 – *zero hunger*) led to the first commercial floating solar photovoltaic (FPV) energy installation in 2007 [10,13].

The rapid deployment of FPV coupled with the variations in FPV design provide opportunities for positive and negative impacts on the SDGs. FPVs are emerging worldwide as an alternative means of deploying PV [13]. To date, installed capacity has grown exponentially and is expected to continue [14], with estimates suggesting a minimum global potential of 400 GW-peak deployment [13]. Growth has been particularly strong in India and China, accounting for six of the ten largest FPV projects [15] (see Ref. [16] for details on global deployment locations). FPV arrays typically consist of five components: the floating support structure, a mooring and anchoring system, inverters, transmission cables and the PV modules [17]. Although FPVs vary considerably in their design, with manufacturers offering both bespoke and off-the-shelf systems, the majority employ an inter-locking floating pontoon comprised of high-density polyethylene, each supporting a fixed-tilt angle PV module [17]. Designs can be categorised by their surface coverage density, defined as the proportion of the installation in contact with the water body. In ascending order, 'Freestanding' designs (i.e. those mounted on poles) have the lowest coverage density, followed by 'small footprint' (i.e. where multiple PV panels are mounted on frames supported by floats), 'large footprint' (i.e. where a single PV panel is mounted on an individual float) and 'insulated' (i.e. those where PV panels are mounted on a continuous cover or membrane) designs (see Ref. [18] for full descriptions on FPV design and structure types and Figure S1). FPV systems rarely cover the whole water surface, and most are deployed at a distance from the edge of the water to prevent access or damage by theft and vandalism. Further, this permits variations in water level due to drought or maintenance, with some designs flexible enough to enable the installation to rest and operate on the water body bed if necessary [19]. In terms of water body selection, some locations enable a direct supply of power (e.g. to a water treatment works), while others export the power to a centralised electricity network.

FPVs offer several co-benefits, but there are also risks of unintended detrimental impacts, especially for water body function. One notable advantage of FPVs over building- and ground-mounted systems is the potential for greater PV panel efficiencies in response to the water body cooling effect [17,20–22]. They also spare land; regions with land-use conflicts have seen the greatest growth in FPV deployment [23]. Further, several schemes have been co-located with hydroelectric power generation. FPV-hydro systems take advantage of existing grid connections and infrastructure and improve the power output profile [24,25]. However, while the economic and technical feasibilities of FPVs are well established, indicating contributions to SDG7, scientific understanding of the water body opportunities and threats of FPVs is very limited. FPVs could benefit or disrupt water body function with implications for ecosystem services, natural capital and SDGs, including the provision of drinking water (SDG6 – *clean water and sanitation*) and carbon stores (SDG13 – *climate action*).

Given the dearth of understanding and the current rate of FPV deployment, there is an urgent need to accelerate understanding rapidly. The water body effects of FPVs will be primarily driven by their physical presence altering wind and solar radiation receipts, two fundamental

regulators of water body behaviour, with implications for surface meteorology, air-water fluxes and consequently water body physical, chemical and biological processes and properties [26]. Accordingly, the impacts of FPVs will vary with design, in particular the nature and extent of water surface use, with the response modulated by water body characteristics such as location, morphology and nutrient status [26]. Potential impacts can be determined by utilising emerging knowledge from FPV systems and inferring likely impacts from the established scientific understanding of natural water body covers, such as plants and ice, and artificial covers, such as evaporation suppression systems.

Given the multiple uses of water bodies, including FPV, it is critically important to capture the perspectives and expertise of stakeholders when resolving the potential implications of FPV on water body function [27–29]. As water bodies provide a large range of ecosystem services, the perspectives of a broad range of stakeholder groups and organisations (e.g. water body managers, recreational users, developers, environmentalists and local and national authorities) are required to develop a comprehensive FPV 'knowledge system'. Specifically, knowledge systems collate the expertise of actors (e.g. stakeholders who mobilise knowledge), organisations (e.g. intermediaries between actors), and objects (e.g. data or models) that perform knowledge-related functions [30,31]. Several studies have shown that the coordination and identification of priorities across knowledge systems have contributed towards the transition to low carbon energy [32–34]. Tapping into the FPV knowledge system helps bridge the knowledge gaps in this upcoming area of research.

The rapid deployment rate of FPV has outpaced understanding of the potential impacts on the host water body. Consequently, developing an understanding of the ecosystem impacts of FPVs is critical to ensure sustainable deployments that avoid concomitant detrimental impacts and maximise co-benefits. Therefore, the overarching aim of this paper is to determine the potential impacts of FPVs on the host ecosystem, the ecosystem services FPVs provide and the potential benefits and trade-offs with other SDGs. To achieve this, we (1) synthesise current evidence on the water body impacts of FPVs; (2) establish ecosystem service opportunities and threats presented by FPVs; and (3) discuss the overall sustainability of FPVs using a generalised framework by linking FPV impacts with SDGs. Finally, we prioritise further research needs and innovation to ensure the design and deployment of future FPVs promote co-benefits across the suite of SDGs, contributing to a sustainable low-carbon energy transition.

2. Methods

In order to address objectives one (evidence synthesis) and two (ecosystem opportunities and threats), we conducted an evidence review of the scientific literature, an international stakeholder survey and a stakeholder workshop (Fig. 1). Finally, outcomes from these were synthesised to address objective three (discuss the overall sustainability of FPVs).

2.1. Evidence review

The review of the scientific literature was conducted using the Defra Quick Scoping Review method, a methodology designed to assess the volume and characteristics of an evidence base prior to evidence synthesis [35]. The scope of the evidence search was constrained by the question; 'What are the potential impacts of FPV on water body function?' Search strings were formulated using the Population, Intervention, Comparison and Outcome (PICO) framework (see supplementary information for full details; section S2) and were developed by the authors and a steering group comprised of stakeholders from four United Kingdom (UK) water utility companies. The search was limited to studies published in English, while no restriction was imposed based on publication date. All literature returned was subject to pre-defined inclusion and exclusion criteria. Specifically, all literature needed
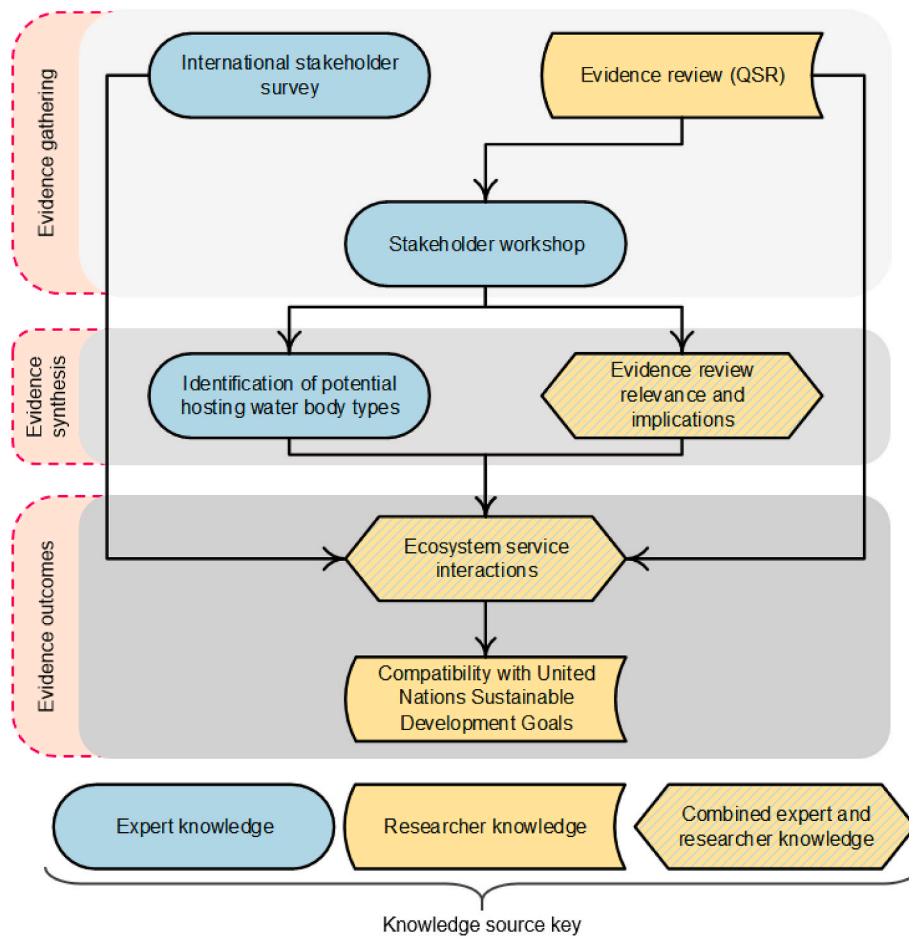
Fig. 1. Schematic of knowledge system components and the integration of connecting research activities.

geographical and climatic relevance to temperate regions and to contain evidence of an effect of water body coverage.

Returned articles underwent an initial title screen, followed by an abstract screen. If relevant or inconclusive, the whole article was read (see Figure S2 for an overview of the review process). Evidence (defined here as information and preferably numerical data) suggesting that surface covers impact water body function, was then extracted from each of the articles which passed the screening process. Each article was summarised and categorised by surface cover type: 'Ice', 'Plant' or 'Artificial'. An evidence outcome was allocated to indicate if the effect on water body function was 'negative', 'neutral' or 'positive' (see supplementary information for further details; section S2). Articles that speculated or hypothesised an effect were excluded from the review. Evidence strength was also assessed to indicate confidence. For example, if the articles were based on simulations of minor relevance to the temperate climatic region or if there were concerns regarding study design and applicability to FPV, the evidence was classified as weak. The remaining studies, which met the search criteria, were graded as strong.

2.2. International stakeholder survey

To gather contemporary understanding, which is especially important given the relative immaturity of FPVs and thus the limited studies in the scientific literature, we deployed an online international stakeholder survey. The survey targeted the knowledge system of FPV operators, actors with first-hand experience of FPV system functionality and potential water body impacts. Questions focussed on four categories; FPV characteristics (such as array size and type), water body characteristics (such as depth, surface area and use), sampling and data collection, and

FPV array management (such as bird deterrents and cleaning). The full list of questions and further methods, including ethical procedures, can be found in the supplementary information (section S3).

2.3. Stakeholder workshop

To gather further expert insight on FPVs, specifically on hosting water body types and the relevance and implications of the evidence review findings, we held a free to attend one-day *Floating solar: water quality impacts* workshop in London, UK, in November 2019. The workshop was attended by 27 stakeholders from different interest groups, specifically 11 participants from the water industry, six FPV developers, three from trade associations, four attendees from community-interest parties and three researchers (A.A., G.E. and T.P.). Attendees were predominantly UK-based, although global input was contributed by attendees based in Brazil, France and Norway.

2.3.1. Identification of different potential hosting water body types
Workshop attendees were asked to identify as many water body types as possible, including both natural and human-made systems that could conceivably host an FPV array. The ecosystem services provided by each water body type that could be affected by FPV deployment were qualitatively identified post-workshop using a conceptual framework for the integrated assessment of water-related services [36], with the list of freshwater provisioning, regulating, cultural and supporting ecosystem services compiled using a selection of established typologies [36–42].

2.3.2. Evidence review relevance and implications
To determine relevance and the implications of the evidence review

(section 2.1), attendees at the *Floating solar: water quality impacts* workshop assessed the findings. Divided into five groups, each comprising a mix of people from different interest groups, workshop attendees were asked to identify if each piece of evidence represented an opportunity or a threat to water quality (i.e. water body physical processes, chemistry, and biology). The opportunity and threat categories were partitioned into 'low', 'medium', 'high' and 'neutral' options, allowing attendees to choose both the direction and magnitude of the potential effect. The responses were pooled to create a stakeholder score to inform areas of greatest knowledge need, allocating positive or negative outcomes to each piece of presented evidence. Scores could range from −15, indicating stakeholders consider the evidence a 'high' level threat, to +15, indicating attendees consider the evidence to present a 'high' level of opportunity.

2.4. Overall sustainability of FPV

To address objective three (to contextualise the overall sustainability of FPVs using a generalised framework), evidence gathered during the evidence review, stakeholder survey and stakeholder workshop was combined with established knowledge in the scientific literature. First, we inferred FPV impacts on ecosystem services by identifying relationships between our gathered evidence and our typology of freshwater ecosystem services (section 2.3.1). For example, evidence that FPV reduces evaporation could be linked to the freshwater ecosystem service *provisioning of water for consumption*. This was original work and semi-qualitative in that it is based on evidence from stakeholders and scientific knowledge.

We subsequently identified linkages between the potentially impacted ecosystem services and the SDGs using the typology established in Wood et al. [41] and the dependencies across SDGs in Le Blanc [43]. Specifically, Wood et al. [41] selected 16 ecosystem services and used expert judgement to identify the magnitude of contributions of ecosystem services to specific SDGs and their targets. For example, Wood et al. [41] found a strong level of support for a contribution by the ecosystem service *water provision* to all Targets of SDG11 Sustainable Cities, except Target 11.7 (access to green spaces), where only a weak level of support exists between *water provision* and Sustainable Cities. In this study, we matched the freshwater ecosystem services we identified to be impacted by FPV to the terms used to describe ecosystem services in Wood et al. [41]. We then linked SDGs to individual SDG targets in Le Blanc [43], allowing us to build a generalised framework of FPV sustainability. Links defined as weak by Wood et al. [41] were not included.

3. Results & discussion

Below we provide a synthesis of the impacts of FPVs on water bodies, informed by scientific evidence and actors within the FPV knowledge system (objective 1). Subsequently, we determine the ecosystem service opportunities and threats presented by FPVs (objective 2) and discuss their overall sustainability (objective 3).

3.1. Synthesis of FPV impacts on water bodies evidence

Given the relative immaturity of FPV installations, there has been limited scientific study of their interactions with water bodies. Consequently, in the following sections, we share the outcomes of the scientific evidence review and the insight gained from the stakeholder survey. Finally, we discuss the potential beneficial and detrimental implications of FPVs on water body function and ecosystem services. Overall, there is limited evidence; thus, outcomes are indicative, and future research is urgently required.

3.1.1. Scientific evidence review

The evidence review of the scientific literature detailing the water body impacts of FPV covers, along with analogue natural and artificial covers as proxies, identified potential impacts on water body physical, chemical and biological behaviour. Over 7000 peer-reviewed scientific articles were initially identified. After evidence screening, 51 articles that detailed the impact of surface covers in temperate environments remained. In total, 29 (one categorised as weak) and 15 (one categorised as weak) pieces of evidence suggested that surface covers had positive and negative outcomes on water quality, respectively (see supplementary information; section S2; Figure S2). Out of these 51 articles, 45 articles described natural surface covers; 37 articles were studies of ice as a surface cover, and eight were studies of plants – the remaining six evaluated artificial surface covers, including FPVs, shade cloths and floating evaporation suppression devices. Although 14 articles on FPVs met the initial criteria to be read in full, 13 were subsequently rejected as they did not adequately consider, based on the protocol of this review, the effects of FPV coverage on water quality. Instead, these articles typically focussed on the technical or financial aspects of FPVs, often stating the effects on water quality are largely unknown and/or hypothesising impacts. The evidence, across surface cover types, were dominated by articles assessing biological impacts ($n = 27$), with equal numbers of articles ($n = 12$) for physical and chemical properties and processes (Table 1, Figure S2).

The impacts of surface covers are summarised below (the evidence is provided in the supplementary information; section S2). The appropriateness of each analogue cover as a proxy for FPV must be considered when inferring potential impacts of FPV. For example, in the instance of ice cover, the proxy with the most retained articles ($n = 37$), surface cover is likely to be spatially continuous, completely insulating the water body from the air during the winter months. However, FPVs do not extend fully across water surfaces. Moreover, the continuous nature of ice is a better representation of insulating FPV designs, rather than Freestanding and footprint designs (Figure S1). 'Small' and 'large' footprint designs (Figure S1) are better represented, particularly by plant cover ($n = 8$), where coverage may be spatially discontinuous across the water body and a lower density than ice. Only artificial covers ($n = 6$), such as shade cloths and floating evaporation suppression devices, provide a temporally representative proxy for FPVs, with coverage continually present throughout the year. Given these differences between the analogues and FPV, the potential beneficial and detrimental effects may differ from the evidence synthesised below.

3.1.1.1. The effect of surface covers on physical process & properties.
The evidence, across all surface cover types, detailed impacts on physical processes and properties, namely solar radiation receipts, water body temperatures, evaporation and mixing dynamics with implications for sediment suspension (Table 1). Surface covers promoted reductions in water temperature ($n = 3$). Whilst the evidence is limited, this trend is likely to pervade across FPV designs as they act as a physical barrier [44, 45], attenuating solar radiation and reducing the heating of surface waters, lowering water temperature [46–48]. We found that artificial covers tended to reduce the solar radiation reaching water bodies more than natural covers, due to their more extensive nature (typically deployed to cover the full water body surface) and lower transparency (e.g. a suspended shade cloth cover reduced light transmission by 99% [49] while ice cover reduced transmission by 53–82% [50]). For FPVs, the scale of impact will be highly dependent on FPV design. The surface cover colour, specifically black versus white, did not affect surface water temperatures even though black covers reached almost twice the temperature of white covers [51]. Instead, the cover's thermal properties control the transfer of absorbed thermal radiation to the water body [51]. Consequently, FPV design, including float construction material, should be considered when evaluating potential water body effects.

The water temperature impacts of FPVs will vary with incoming solar radiation, which can fluctuate dynamically across diel and seasonal scales depending on the location. For example, in Taiwan, a country with a tropical climate, temperature effects were quantified for a 'large

Table 1

Summarised outcomes of potential floating photovoltaic solar energy installations ('FPVs') effects on physical, chemical, and biological aspects of water quality from the scientific evidence review. Evidence outcome indicates if the article author ('s) identified the outcome as a negative (−), neutral (0) or positive (+) effect on water quality. The cover category refers to the type of natural (i.e. ice, plants) or artificial (i.e. other) surface cover studied. Stakeholder Workshop attendees were asked to identify if each outcome is either an opportunity or a threat to water quality. Opportunities and threats were further prioritised by stakeholders as 'low', 'medium', 'high' or they could choose 'indifferent'. A final stakeholder score was calculated for each evidenced effect. Low negative numbers indicate that the stakeholders considered the evidence as a 'high' level threat (i.e. −15). In contrast, a high positive number (i.e. 15) indicates the attendees considered the evidence to present a 'high' level of opportunity [109–113].

	Evidence Review								Stakeholder Workshop							
	Evidence from Quick Scoping Review	Evidence Outcome			Total Papers	Cover Category			Threat			Opportunity			Indifferent	Stakeholder Score
		−	0	+		Ice	Plants	Other	High	Medium	Low	Low	Medium	High		
Physical	Reduced evaporation			2	2			2			▪	▪		▪		9 [48, 53]
	Reduced water temperatures			3	3	2		1			▪	▪	▪	▪		8 [43, 49, 50]
	Reduced sedimentation and reduced sediment resuspension			2	2	2				▪			▪		▪	1	3 [57, 64]
	Horizontal mixing continues		1	4	5	4	1						▪	▪	2	7 [58-62]
Chemical	Anoxia (as water body isolated from the atmosphere)	2	1		3	3			▪	▪						−14 [69, 72, 73]
	Nitrification continues (substantial oxygen demand)	2	1		3	3			▪							−15 [78-80]
	Release of: • Methane (CH$_4$)	1			0	1			▪	▪						−14 [74]
	• Hydrogen sulfide (H$_2$S)	2			2	2			▪		▪					−13 [74, 75]
	• Ammonia (NH$_3$)				0	1			▪	▪						−14 [74]
	• Heavy metals from bed sediments	1			1	1			▪	▪						−14 [76]
	Reduced salinity			1	1			1			▪		▪		3	1 [46]
Biological	Reduced algae growth			4	4	1	2	1	▪		▪	▪		▪		7.5 [83-86]
	Delayed algal biomass peaks	1		2	3	3				▪	▪	▪			1	−6 [83, 87, 106]
	Modified algal community composition	2	2	3	7	7			▪	▪	▪	▪				−9 [44, 47, 89, 90, 93, 94, 107]
	Prolonged cover led to large algal blooms	2			2	2				▪					3	−4 [108, 109]
	Blue-green algae success is improved as competition from other species reduced due to lower light levels	1	1		2		2		▪	▪		▪				−12 [41, 95]
	Reduced mixing and turbidity allowed extensive growth of filamentous diatoms	2			2	2			▪	▪		▪			1	−7.5 [91, 92]
	Fish kills	1			1				▪		▪	▪	▪			−4.5 [73]
	Increased zooplankton numbers and enhanced survival		1	4	5	3	2				▪	▪				4 [42, 45, 101, 103, 105]
	Fish reduced their predator vigilance (birds)			1	1	1					▪					3 [104]
	Shading (i.e. darkness) reduced the feeding effectiveness of fish			1	1		1		▪							−3 [102]
	Reduced concentrations of faecal coliforms E. coli			1	1			1			▪	▪		▪	1	6.5 [110]

footprint' FPV array covering 40% of an irrigation pond's surface; it reduced winter water temperatures by 0.77 °C, and summer water temperatures by 1.4 °C [52]. Additionally, given that water bodies act as thermal stores, the reduction of solar radiation by FPVs will alter seasonal temperature dynamics. For example, with every 1% increase in winter-averaged ice cover on Lake Superior (MN, USA), average summer (July–September) surface water temperature decreased approximately 0.1 °C due to the impacts of ice thickness on solar radiation receipts and thereby temperature [53].

Water body surface covers change the thermal dynamics at the air-water interface [54], with significant impacts on evaporation ($n = 2$, Table 1). The multiple methods for estimating evaporative losses from water bodies with surface covers can present a challenge when comparing evidence qualitatively [55]. Experiments using palm fronds in an arid region suggest that the total area covered by a FPV may be approximately proportional to evaporative losses: palm fronds reduced evaporation by 55% when covering the full surface of a pool, and 26% when covering half [56]. However, given the importance of wind in determining evaporation rates, the proportional relationship may not hold, especially for larger water bodies [57,58]. Furthermore, FPV design (i.e. the change in roughness and impact on water-air connectivity), may also be an important factor in determining evaporative losses. For example, an evaporation suppression experiment in a laboratory setting found covering 91% of a tank's surface with free-floating spheres and free-floating disks reduced evaporation by 70% and 80%, respectively [51]. Given the large variation in FPV design, a better understanding is required to resolve the impacts of FPVs on evaporation.

Mixing dynamics are an important determinant of water quality, influencing sediment and water chemistry [59]; thus, the implications of FPVs on water body mixing must be resolved. Two studies found that surface covers reduced sedimentation and sediment resuspension, suggesting reductions in vertical mixing ($n = 2$, Table 1). For example, ice surface covers lowered gross sedimentation by over 20 times compared to the ice-free period [60]. Devoid of wind stress beneath the ice, resuspension rates fell to 50–78% of gross sedimentation, compared to a resuspension rate of 87–97% of gross sedimentation for an uncovered water body [60]. In contrast to vertical mixing, horizontal mixing has been observed under ice [61–64] and plant covers [65]. Consequently, resolving how FPVs alter mixing will be critical to understanding water quality impacts.

3.1.1.2. The effect of surface covers on chemistry. FPVs could impact several water chemistry properties and processes, including nutrient concentrations and gas exchange, with potential positive and negative consequences (Table 1). Reductions in nutrient and contaminant concentrations could occur in response to the reduced evaporation [51,56] caused by FPVs [66]. For example, surface covers have reduced the salinity of water bodies due to lower evaporative losses, with one example identifying an 8.2% reduction in soluble salt concentration [49]. Further, water nutrient and contaminant concentrations could be altered given the effect of surface covers on sedimentation and sediment resuspension [60]. For instance, water bodies with less extensive FPV covers, or comprised of lower footprint designs, are more likely to experience higher total phosphorus concentrations as the entrainment of suspended particulate matter can continue for a longer period or over a greater area of a water body's bed [67]. The responses are also likely to vary with water depth, with the effects of FPVs on sedimentation and sediment resuspension greater in shallower lakes [68,69]. For example, reduced vertical mixing in response to ice cover was associated with a reduction of phosphorus at the sediment-water interface [67].

However, FPVs may also negatively impact water chemistry ($n = 3$, Table 1). Surface covers, particularly ice cover (a proxy for 'insulated' FPV designs) due to its spatially continuous nature [70], isolates the water from the atmosphere, causing dissolved oxygen depletion [45]. A lack of dissolved oxygen can have multiple implications for water

quality, including the release of nutrients and contaminants from bed sediments [71]. Oxygen depletion increases over time as aerobic processes continually draw on the limited oxygen supply. Eventually, if insufficient oxygen enters the system, the water body becomes anoxic [72]. The rate of oxygen depletion will depend on FPV design and be highly water body-specific, depending on the rate of biological processes, stratification [73], forced aeration (such as reservoir agitation with mechanical mixers or bubblers), residence time [74] and degree of wind mixing [75]. For example, under ice cover, nitrification and the activation of anaerobic processes placed the greatest demands on dissolved oxygen supply, although fish contributed minimally to winter oxygen depletion ($n = 3$, Table 1). The rates of oxygen depletion also vary seasonally. For instance, sediment-water heating facilitates enhanced microbial respiration during winter [76], speeding up the development of anoxic conditions [77,78].

Oxygen depletion activates anaerobic processes that cause detrimental impacts; for example, ice cover on Russian, American and Canadian lakes caused a release of deoxidised gases such as methane, hydrogen sulphide, and ammonia [77]. As water bodies help regulate the climate, the release of methane, a potent greenhouse gas, is concerning. Released methane could increase the greenhouse gas intensity of electricity produced by FPVs. Moreover, oxygen-depleted bottom-waters can become enriched in reactive species of manganese, iron and phosphorus, with the concentrations increasing higher in the water column during prolonged periods of cover [79]. The release of metals such as manganese and iron is detrimental to water quality and constituent aquatic ecology, whereas increased phosphorus concentrations may facilitate phytoplankton growth, including problem blue-green algae, in phosphorus-limited water bodies [80].

Processes that consume oxygen can also impact water quality directly. For example, 1–25% of the dissolved oxygen depletion rate in seven temperate seasonally frozen lakes in Wisconsin, USA, was attributed to nitrifiers [81]. As well as consuming oxygen, nitrification leads to the accumulation of nitrate, which can be used by phytoplankton once the growing season commences [82], potentially leading to problematic blooms (see section 3.1.1.3). However, if dissolved oxygen is fully depleted, anaerobic conditions cause denitrification, the process that reduces nitrate to gaseous nitrogen, reducing eutrophication [59]. The likelihood and rate at which denitrification occurs under FPVs will also be linked to the temperature impacts as the rate at which heterotrophic denitrifying bacteria convert nitrate to nitrogen is controlled hierarchically, first by nitrate concentrations, then by temperature [83]. Consequently, depleted oxygen could lead to phytoplankton blooms, or, if anoxic conditions occur, lower water temperatures and depleted dissolved oxygen associated with FPVs may induce denitrification, potentially improving water quality by reducing eutrophication and phytoplankton recruitment.

Consequently, it is critical to understand the impacts of FPVs in light of the water body and design characteristics (including adaptive strategies for mitigating potential adverse effects; see section 5) when resolving potential water quality impacts. Furthermore, water body use informs the significance of the perturbations or enhancements. For example, an FPV installation could cause enhanced denitrification rates and improve water quality, while enhanced internal loading of phosphorus from anoxic bed sediments may promote phytoplankton growth, degrading water quality. Ensuing changes to water quality could require modified chemical water treatment to maintain drinking water quality, either reducing or increasing cost.

3.1.1.3. The effect of surface covers on biology. The evidence review identified biological effects of surface covers on three trophic levels; phytoplankton, zooplankton and fish (Table 1). Resolution of the impacts of FPVs on phytoplankton response is pivotal as they are the food source for all higher trophic levels and some exert considerable influence over water quality [e.g. 84,85]. All types of surface cover lowered

phytoplankton density, biomass and chlorophyll-*a* concentrations, attributable to lowered solar radiation curtailing photosynthesis [86–88] and potentially reduced vertical mixing limiting the release of phosphorus at the water-sediment interface [67]. The magnitude of impacts varied with water body type, surface cover and coverage extent, but were generally significant. For example, ice cover on a small lake in Poland reduced phytoplankton biomass by 51% [50]. Plant cover also reduced phytoplankton biomass, with an 88% reduction observed in an Argentinian mesocosm experiment [44]. Further, experiments using a dye that reduced light intensity to 1% of surface light in the photic zone reduced phytoplankton biomass by 60% [89].

As well as impacting overall biomass, light suppression caused by FPVs could cause shifts in the timing and occurrence of phytoplankton blooms. Lower phytoplankton growth, and therefore nutrient uptake, will allow the persistence of nutrients in the water column [64,86,90], increasing the chance of phytoplankton blooms later in the growing season. However, the complexity of phytoplankton and nutrient dynamics curtails the potential to offer universal predictions of timings and abundance [91]. However, overall, reductions in phytoplankton growth are likely to lead to enhanced water quality with improvements for recreational use and potentially reduced water treatment costs.

Reductions in phytoplankton biomass and shifts in the timing and occurrence of phytoplankton blooms are also likely to be accompanied by changes in phytoplankton species composition, given the different physical and chemical conditions imposed by FPVs [50,92,93]. For example, filamentous diatoms that are adapted to darker conditions may increase due to improvements in water clarity and reduced sediment resuspension in very sediment-rich waters [94,95]. The characteristics, or functional traits, of phytoplankton determine if they will increase or decrease under FPVs, for example, the motility, nutritional mode, ability to form resting stages, organisation, cell shape, and size class were found to be significant predictors of phytoplankton species under ice [47]. Generally, reduced light availability and the associated cooler water temperatures under surface covers eliminates large and drifting types of phytoplankton, favouring smaller motile forms capable of mechanical movement [96]. Drifting types are also impacted by the lower vertical mixing rates under surface covers, with populations decreasing if the water movement is less than the species' sinking rate [97].

Competition with other species will influence the abundance of each phytoplankton species. For example, as FPVs shift water column irradiance from high-intensity to low-intensity, there is the potential for blue-green algae populations with low critical light intensity to increase, utilising their low light tolerance and the reduced turbulence under FPVs to outcompete other phytoplankton species [44]. For example, plant cover resulted in blue-green algae dominating the overall species composition when 50–75% of the water's surface was covered but was less abundant when the surface cover was lower [98]. Resolving the impacts of FPVs on blue-green algae will be of key importance for water body managers given increased bloom prevalence with climate change [99], implications for recreational activities and aesthetic values [100], and the need for enhanced raw water processing and treatment due to the production of muddy odour metabolites geosmin and 2-methyliso-borneol (resulting in taste and odour issues) if FPVs are deployed on reservoirs used for drinking water [101,102].

Although solar radiation and nutrient concentrations are the primary drivers of phytoplankton response, resolving the oxygen and temperature impacts is critical for understanding impacts at higher trophic levels. In ice-covered lakes, oxygen depletion is the most important factor determining the onset of fish mortality [45,76], while non-covered lakes may see fish die-offs during extreme summer conditions which cause a temperature-oxygen squeeze [103]. However, the impact of FPVs on oxygen content is poorly resolved, with both increased and decreased risk of anoxia possible (see section 3.1.1.2 [26]). Temperature, as a regulator of metabolic rate, has significant impacts on higher trophic levels. For example, one study found a 9% decrease in zooplankton abundance with a 1 °C decrease in water

temperature in autumn, while in spring, a 1 °C rise in water temperature increased zooplankton abundance by 27% [48]. In addition to temperature regulation of metabolic rates, temperature thresholds exist that cause step changes in biological processes. For example, a shift from cold water to warm water zooplankton species occurred at a critical threshold of 10 °C in the spring, with a less conspicuous change occurring in the autumn [48]. Comparison of FPV induced temperature changes to those caused by other water body covers suggest that the impacts are likely to be less extreme. However, FPV studies are very limited [24,52].

In addition to the direct impacts of FPVs on species, the indirect effects through altered predator-prey relationships are critical to determining the overall impacts on water body biology. Surface covers, such as emergent and floating-leaved macrophytes, may enhance the survival of zooplankton by providing a refuge from predation. For example, the overall density of cladocerans ('water fleas') was, on average, over 60 times greater in the presence of plants than in open water [104]. Further, zooplankton have been observed to increase their horizontal and vertical migration under surface covers as shading from plants offers a mechanism to avoid predation from fish [105]. However, such impacts do not always occur; evidence from a different study found no significant difference in zooplankton abundance or diversity along a horizontal gradient from the macrophyte-covered littoral to the open pelagic zone of temperate lakes [106]. Fish may also change their behaviour, including by reducing their predator vigilance in the presence of FPVs. For instance, brown trout increased their swimming activity under ice cover, swimming 38% of the time, compared to 21% in the absence of cover [107].

A further indirect impact on lower trophic levels is the consequences of fish kills due to anoxia. For example, in a study of 13 European lakes with winter ice cover, summer zooplankton communities were comprised of a significantly greater proportion of larger-bodied taxa, as smaller planktivorous fish populations reduced the predation pressure on zooplankton [108]. In turn, these larger-bodied and more abundant zooplankton had stronger grazing impacts on phytoplankton, having a positive cascading effect on water quality [76,108]. Such changes in species composition between trophic levels can impact overall ecosystem resilience and may have consequential impacts on the provision of food for human consumption for some water bodies.

3.1.2. Stakeholder insight

Stakeholder expertise is crucial to capture the potential impacts of FPVs and contextualise findings from the scientific literature. Our stakeholder survey captured responses for approximately 6% (*n* = 13) of FPV installations globally (based on the total number of FPV systems, *n* = 229 [16]). All of the FPV installations surveyed were deployed on
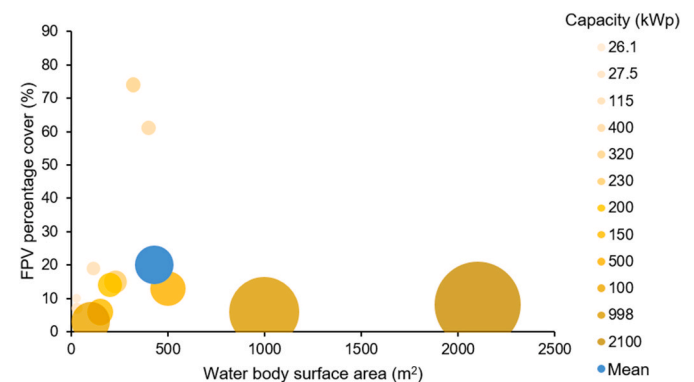
Fig. 2. Global stakeholder reported FPV surface coverage as a percentage of water body surface area. Each 'bubble' is proportional in size to the capacity (kWp) of the individual FPV array. The blue bubble indicates the mean FPV percentage coverage, host water body surface area and array capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Water body type and potential ecosystem service delivery. Water body types gathered from attendees at the Floating solar: water quality impacts workshop. Ecosystem service typology based on Grizzetti et al. [36], Kumar [37], Maltby et al. [38], Chopra et al. [39], Costanza et al. [40], Wood et al. [41], de Groot et al. [42]. A ● indicates an ecosystem service delivered by the water body. ■service and treated water reservoirs store fully treated potable water in a drinking water network, ◆raw water reservoirs store untreated water, ✧bankside storage holds water abstracted from a river prior to water treatment and treatment reservoirs.

		Natural										Human-made												Total services
		Ponds	Tarns	Lakes/Lochs (freshwater)	Rivers	Fjords/sea lochs	Seasonally dry water beds	Marshes and wetlands	Lagoons	Estuaries/tidal areas	Open ocean/sea	Service and treated water reservoirs■	Raw water reservoirs◆	Bankside storage✧	Agricultural ponds	Canals	Aqueducts	Harbours, marinas, docks	Filter beds	Sewage ponds	Contaminated water area	Settlement ponds for mining	Fish farms or aquaculture	
Provisioning	Aquatic organisms for food and medicines			●	●	●				●	●												●	6
	Water (quantity and quality) for consumptive use (for drinking, domestic use, and agriculture and industrial use)	●	●	●	●				●			●	●	●	●									9
	Water for non-consumptive use (e.g. generating power or navigation)	●		●	●	●				●	●	●	●			●	●	●						11
Regulating	Buffering of flood flows, erosion control through water/ land interactions and flood control infrastructure	●	●	●	●		●	●	●				●	●	●	●	●				●	●		14
	Maintenance of water quality (natural filtration and water treatment)	●	●	●	●			●	●	●			●	●		●	●		●	●	●	●	●	16
	Climate regulation	●	●	●				●																4
Cultural	Tourism & Recreation (kayaking, hiking, etc.)	●	●	●	●	●		●	●				●	●		●		●					●	11
	Existence values (e.g. personal satisfaction from seeing water bodies)	●	●	●	●	●		●	●				●	●	●									10
Supporting	Role in nutrient cycling (role in maintenance of floodplain fertility), primary production	●	●	●	●	●		●	●	●	●												●	10
	Predator/prey relationships and ecosystem resilience	●	●	●	●	●		●	●	●	●		●	●									●	11
Total by water body		9	8	10	9	6	1	7	7	5	4	2	7	6	3	4	3	2	1	1	2	2	5	
Total by water body type		Total = 66										Mean = 6.6				Total = 38							Mean = 3.2	

human-made water bodies (although FPVs have been deployed on natural water bodies); 11 FPV arrays were deployed on irrigation reservoirs, and one each on a reservoir supplying raw water to a water treatment works, storm water pond and a sand extraction pit. These deployment locations may reflect the co-benefits of locating FPVs near to energy demand (e.g. water treatment works) and the relative challenge of obtaining permission to deploy FPVs on natural water bodies.

At present, FPV capacity is often limited by water body size and the desire to deploy systems to meet specific power needs. For example, the three largest systems deployed in the UK are on raw water reservoirs and were designed to meet the electrical needs of the adjacent water treatment works. Consequently, the capacities tend to be smaller than ground-mounted systems, with the surveyed FPV's capacities ranging from 26 to 2100 kWp (Fig. 2), although, globally, systems up to 70 MW have been deployed [16].

Given the implications for solar radiation and wind energy inputs and thus water body response [24], percentage cover is the most important determinant for resolving impacts on the hosting water body [114]. Percentage cover has been shown to impact physical, chemical and biological water body properties and processes ([11,114]; section 3.1.1), and ranged from 3% to 74% in the survey (Fig. 2). The optimum FPV percentage coverage needs to balance power demands with potential water quality impacts in light of other water body uses [115].

Scientific evidence of the effects of surface covers on water bodies infers some negative impacts (see section 3.1.1), for example, a switch to problematic phytoplankton species. However, the survey respondents did not detail any adverse water body impacts; the negative impacts were predominantly technical, such as issues with operation and maintenance (see supplementary information for further details; section S3). Nevertheless, water body impacts may have been overlooked as specific monitoring was only undertaken at two of the sites post-deployment, the survey was completed by FPV operators who may have limited environmental expertise, and many impacts may not be identifiable visually. For example, all survey respondents reported birds perching and/or nesting on the PV panels or infrastructure supporting the panels as solely a technical issue, as bird fouling reduces PV performance [116,117]. However, results from our evidence review suggest that bird fouling increases the nutrient loading of phosphorus [118,119] and bacterial pathogens, including campylobacters [120–122], both of which have detrimental impacts on water quality. For example, bird droppings have been found to account for 25–34% of external phosphorus loading to an urban lake [123], with other studies identifying even greater loading [e.g. 119]. Unlike other perching features, bird droppings will be washed off during panel cleaning, in addition to heavy rainfall [124], releasing pulses of nutrients into the host water body (see supplementary information for further details; section S3). Moreover, there may be numerous other unseen impacts on water quality, such as changes to thermal stratification [114], phytoplankton populations and lake productivity.

3.1.3. Evidence synthesis

The limited scientific evidence and FPV operator knowledge demonstrates a critical need to rapidly develop a more detailed understanding of FPV impacts on water bodies, including the effect of FPV design and water body characteristics (see section 3.1.1). Whilst scientific evidence of the water body impacts of FPV is very limited, the consequences of other water body covers suggests significant physical, chemical and biological impacts could occur. The limited stakeholder evidence is underpinned by limited monitoring of existing FPV installations and that many of the potential water body impacts are not visible. Consequently, there is an urgent need to generate FPV specific evidence of water quality impacts through both scientific assessments and by extending stakeholder monitoring beyond minimum statutory obligations (see section 5), encapsulating different water body types and FPV designs, along with modelling capabilities.

3.2. Potential ecosystem service impacts

Perturbations to ecosystem properties and processes caused by FPVs will influence the provision of ecosystem goods and services upon which society relies. Water bodies provide a range of essential ecosystem services and store vital natural capital [125]. For example, water bodies are critical for providing drinking water, regulating water quality through natural filtration and supporting essential nutrient cycling [36,126]. However, one of the challenges of assessing the impact of interventions, such as FPVs, on ecosystem services is correlating beneficial and detrimental changes in properties and processes, which are measurable, to ecosystem services which are commonly estimated using a range of measures [127,128]. Here we use our scientific understanding and stakeholder expertise to infer the potential of FPVs to impact ecosystem services and natural capital.

Water body type is central to estimating the ecosystem services delivered and their associated value [126], and thus the impacts of FPV deployment. Despite only four types of FPV hosting water body being identified in the stakeholder survey (see section 3.1.2), stakeholders at the workshop identified an extensive range of potential recipient water bodies, suggesting that as FPV deployments accelerate, hosting water body types may expand. All water body types identified offer additional ecosystem services beyond the supply of low carbon energy. However, there was variation in the number of services, and likely value, between water body types (Table 2). FPVs could affect every ecosystem service provided by water bodies except 'buffering of flood flows, erosion control through water/land interactions and flood control infrastructure' (Table 2). Of all the ecosystem services, the regulation of water quality is provided by nearly all the human-made water bodies that may host FPVs (Table 2). Moreover, even if the delivery of additional ecosystem services were unnecessary, such as food provisioning, many would need to be maintained by default given their synergistic relationship with water quality and the complex dynamic interactions between individual ecosystem services [11,129–131].

Whilst most ecosystem services could be impacted by FPVs, the direction and magnitude of impacts are often unclear due to limited evidence and the complexity of water body function [26]. For example, in terms of the provisioning of water for consumptive use, FPVs could enhance the quantity of water available and potentially the quality: reduced phytoplankton biomass (influenced primarily by temperature and light), evaporation (primarily influenced by wind and water temperature) and sediment resuspension rates (primarily influenced by wind mixing) are potential positive consequences of FPVs (see section 3.1.1). However, there is a chance that FPV could enhance ecosystem disservices, impacting the quality and quantity of water available for consumptive use. For example, changes in phytoplankton species dynamics to taxa which are suited to the low-light, non-turbulent conditions under FPVs including problematic blue-green algae and filamentous diatoms (see section 3.1.1.3). Predicting the consequences of FPVs across the full suite of ecosystem services water bodies provide is particularly challenging given the range of ecosystem processes and properties that will influence the outcomes [132].

On average, natural water bodies identified by workshop attendees as potentially suitable for FPV deployment support double the number of ecosystem services compared to those identified for human-made water bodies. The difference suggests that, on average, deployments of FPVs on human-made water bodies may have fewer adverse impacts on ecosystem service provision (Table 2) and ultimately on the SDGs. Unsurprisingly, this reflects the motivation to create water bodies that deliver a specific ecosystem service [133] compared to natural water bodies that have existed for millennia and provide a range of ecosystem services [38]. Given that all the FPV deployments reported in the stakeholder survey were on human-made water bodies, reflecting a global trend [115], suggests current FPV deployments may have relatively limited impacts on ecosystem service provision. However, water body ecosystem services and their value are likely to change over time in

response to climate change [134,135] and changes in water body use and ecosystem service demand [133]. Consequently, enhancing knowledge of the impacts of FPVs on all water bodies is important.

3.3. Critical implications for water bodies

Once FPV ecosystem service effects are understood, prioritising particular ecosystem services and trading potential positive and negative impacts of FPVs for specific water bodies will be imperative. Given the common underpinning importance of water quality regardless of water body type or use, and lack of understanding of FPV impacts, we focus on the impacts of FPVs on the physical, chemical and biological properties of water bodies highlighted in the evidence review (section 3.1.1).

Overall, stakeholders perceived the enhancement of water body physical processes by FPVs as offering the greatest opportunity in terms of water quality, specifically the potential to reduce evaporation (score +9) – which strongly aligns with the evidence gathered during the review (Table 1). Conversely, stakeholders perceived changes to water body chemical properties and processes as representing the greatest potential threat of FPVs in terms of water quality impacts, identifying nitrification and the consequent deoxygenation of the water in particular (score −14, Table 1). The scientific evidence mirrored these stakeholder concerns, with the majority of evidence suggesting that water body covers adversely impact water chemical properties and processes (Table 1). In terms of biological impacts, the likelihood of reduced phytoplankton growth was perceived as the greatest opportunity of FPV deployment on water bodies (score +7.5, Table 1). However, the uncertainty in response, particularly the potential for blue-green algae proliferation (as competition from other species reduces due to lower light levels), was seen as the greatest threat (score −12, Table 1). Concern that prolonged periods of cover could lead to large phytoplankton blooms was also highlighted (score −4, Table 1). The broad range in stakeholder response for biological impacts emulates the mixed evidence outcomes gathered during the evidence review (Table 1).

The diversity of actors in the knowledge system (i.e. stakeholders), and the associated implications for their primary interests, led to variation in assessments of opportunities and threats. For example, reduced planktivorous fish stocks may enhance water quality by lowering nutrient concentrations and improving water clarity [136], a benefit to raw water reservoir managers. However, fish kills suggest poor ecological condition and many water body managers are required to replenish fish stocks for recreational purposes. The largest variation in responses (i.e. responses were spread over four or more threat or opportunity categories) were for the potential of FPVs to reduce water temperatures, lead to fish kills, modify phytoplankton community composition and reduce phytoplankton growth (Table 1). In contrast, stakeholders unanimously viewed all chemical responses as a threat, except for salinity impacts (Table 1).

The differences in stakeholder-identified relative opportunities and threats of FPVs for water bodies indicates the complexity in resolving deployments for specific water body types and integrating ecosystem service impact with management and design decisions [137]. For example, balancing the delivery of ecosystem services beyond the provision of drinking water from a water supply reservoir, such as recreational and leisure opportunities [133,138] and disservices such as greenhouse gas emissions, which increase the rate of global warming [139,140]. Moreover, understanding the impacts in light of FPV designs, host water body characteristics, and management goals will be critical to maximise the opportunities and minimise the threats posed by FPVs [115]. For example, minimising water quality impacts on raw water reservoirs will be a priority, but potentially of little consequence for irrigation reservoirs; evidence for this can be seen in the survey results, where stakeholders routinely monitored water quality for raw water reservoirs but not for irrigation reservoirs (see section 3.1.2). Moreover, if FPVs are deployed on a reservoir supplying drinking water with no public access, a lack of recreation opportunity cannot be considered an ecosystem disservice. Consequently, identifying the full suite of ecosystem services opportunities and threats posed by FPVs is complex and should be resolved for individual water bodies prior to deployment.

4. The overall sustainability of FPV

To determine the overall sustainability of FPVs, the impacts of FPVs on ecosystem services (Table 2) and the links between ecosystem services and the SDGs, including dependencies across SDGs [43], can be placed into a generalised framework based on the UN SDGs. We found FPVs have opportunities and trade-offs with nine water body ecosystem services and may beneficially or detrimentally affect progress towards reaching eight out of the 17 SDGs. Based on the ecosystem service links determined by Wood et al. [41], we found the SDGs most linked to water bodies (i.e. by seven ecosystem services), and thus potentially most influenced by FPV deployment, are *zero hunger* (SDG2), *sustainable cities and communities* (SDG11) and *climate action* (SDG13) [41] (Fig. 3). *Clean water and sanitation* (SDG6) is linked to six water body ecosystem services; *no poverty* (SDG1) to four; *good health and wellbeing* (SDG3) to three; and *industry, innovation and infrastructure* (SDG9) and *responsible consumption and production* (SDG12) to two [41] (Fig. 3). Out of the ten water body ecosystem services, FPVs are most likely to impact on *water quality provisioning* (Table 2), therefore, likely making opportunities and trade-offs with SDGs 1, 3, 6, 11 and 13 the most widespread (Fig. 3).

Moreover, four of the SDGs, *affordable and clean energy* (SDG7), *decent work and economic growth* (SDG8), *life below water* (SDG14) and *life on land* (SDG15), are partially linked to several other SDGs [43]. Thus, FPV deployment could beneficially or detrimentally affect SDGs indirectly (Fig. 3).

Synthesising multiple components of the knowledge system highlights the complexities and potential extent of the opportunities and trade-offs in FPV sustainability, underscoring the need to accelerate understanding rapidly. To ensure relevance among the wide range of FPV installations identified in our international survey and potential recipient water body types identified by workshop attendees, our framework provides a generalised overview that is non-specific to FPV design or deployment characteristics (e.g. location, water body usage, lake size metrics etc.). Given the compelling evidence gathered, some ecosystem service interactions are more certain than others, regardless of FPV design or deployment characteristics, but this is not universal (see section 3.2). As knowledge of the beneficial and detrimental impacts of FPVs evolve, our framework can be populated with evidence beyond our current understanding, improving specificity and strengthening the overall knowledge system. As such, it will be critical to establish the variation in impacts between different FPV designs, host water body characteristics and water body management goals through open sharing of installation-specific data and collaboration between all knowledge system actors and entities.

5. Future research and innovation

The previous sections highlight notable knowledge gaps that impede the sustainable deployment of FPVs. Consequently, we suggest essential priorities for future research and innovation.

The international stakeholder survey and evidence review demonstrated the critical need for more monitoring of FPV installations to resolve impacts. As stakeholders perceived changes to water chemistry as the greatest threat, work in this area should be prioritised. A concerted research effort is required to enhance fundamental understanding of the processes by which FPVs affect the water body. Moreover, stakeholder sampling protocols must be extended beyond minimum statutory obligations to enable better resolution of impacts. The knowledge generated should be synthesised across FPV deployments to elucidate the influence of FPV design and water body characteristics. Bayesian and fuzzy systems could provide a useful

means to synthesise quantitative (e.g. from monitoring and simulations) and qualitative (e.g. expert insight) information from across the FPV knowledge system [26]. The outcomes should be collated and made available to inform industry best-practices and guide future innovations. Moreover, enhanced knowledge will permit the implementation of standards for deployment, ensuring environmental compliance throughout the FPV's life cycle, including manufacturing, deployment, operation and decommissioning.

FPV design is adaptable and versatile (see Figure S1 for examples), so using a techno-ecological approach should be considered when innovating future systems [141]. Incorporating engineering that is mutually beneficial for technological and ecological systems offers an opportunity

to enhance the overall sustainability of FPVs. For example, one respondent of the international stakeholder survey used glass-glass PV modules, enabling light to reach the water's surface to minimise ecological impacts. Other adaptations include the addition of an aeration system to manage deoxygenation risks. Such FPV design adaptations must reflect the specific deployment location and anticipated impacts.

Finally, means to produce urgently required low carbon electricity should be compared to the counterfactual in order to maximise the overarching sustainability of the energy system. If not FPV here, then where? If not FPV, then what? To make such decisions improved knowledge and better integration of ecosystem services with

Fig. 3. Generalised framework linking outcomes gathered from the knowledge system (e.g. international survey, evidence review and stakeholder workshop) with the ecosystem services delivered by freshwaters (based on Wood et al. [41]) and the United Nation's Sustainable Development Goals (SDG). Links between Tier 1 (light grey box) and Tier 2 (dark grey box) SDGs are based on Le Blanc [43].

management practices is required [137]. Mapping of ecosystem service and SDG impacts is currently generic, but FPVs are likely to interact with nine ecosystem services and eight SDGs. Resolving the impacts is critical to ensure FPVs are appropriately designed and located.

6. Conclusions

FPV deployments are increasing rapidly worldwide, but there is minimal scientific evidence of water body impacts. This is a critical knowledge gap given the potential implications for ecosystem services and ultimately sustainability with this emerging form of low carbon electricity. Here, by drawing on an FPV knowledge system underpinned by scientific evidence and stakeholder expertise, we elucidated the possible impacts. The evidence showed a range of physical, chemical, and biological water body properties and processes could be impacted, predominately driven by changes in light attenuation, water temperature, and water movement. However, the available evidence was limited and shows there is an urgent need for further research. Without this understanding, ecosystem service provision could be at risk, or opportunities for co-benefits missed, with implications for eight SDGs unknown. Ultimately, advancing the state of knowledge on FPVs will provide the framework to maximise environmental benefits, ensuring the preservation or enhancement of water body processes, function, and service delivery.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111639.

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