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A global study of freshwater coverage by floating photovoltaics

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ABSTRACT

Floating Photovoltaic (FPV) deployments are accelerating worldwide and FPV coverage on water surface can strongly influence their ecological impacts. Yet, a global assessment of their characteristics is still lacking. We identified 643 FPV power plants constructed across the globe. We found that FPV power plants currently exist in 28 countries, predominantly concentrated in Asia. FPV coverage was highly variable between lakes, ranging from 0.004 % to 89.9 % of lake surface area. Overall, FPV coverage averaged 34.2 % (±22 SD, n = 494), varying significantly across continents. FPV coverage was significantly driven by lake size and morphological complexity, with smaller lakes and lakes with simplified morphology having higher FPV coverage. The high variability in FPV coverage worldwide suggests a high context-dependency of their ecological impacts that will likely be stronger in small lakes with higher FPV coverage.

1. Introduction

Renewable energy deployment is important for decarbonizing the energy sector. Photovoltaics, despite their potential, often require 20 times more land than fossil fuels for equivalent power production [1]. A recent advancement in the photovoltaics sector, known as floating photovoltaics (FPV), involves arrays of photovoltaic panels attached to a floating plastic structure and secured on the water body using a mooring system [2]. FPV deployments are accelerating globally due to their increased efficiency (owing to lower operational temperatures) and land-saving benefits [3,2]. It is estimated that covering 10 % of world's existing hydropower reservoirs with FPV might be enough to decarbonize the electricity sector by 2050 [4]. However, FPV plants are installed on a variety of water bodies across the world, including smaller freshwater ecosystems such as water treatment and water storage ponds and gravel pit lakes [5,6]. Freshwater ecosystems provide countless services including utilitarian values (e.g. drinking water, irrigation), but also intrinsic and cultural values, such as climate regulation, biodiversity maintenance, scenic appreciation and well-being [7,8]. FPV is listed as one of the main potential issues likely to impact biodiversity conservation [9], and a major issue associated with the deployment of FPV is the absence of empirical studies assessing their ecological consequences on freshwater biodiversity and lake ecosystems.

Several characteristics of freshwater ecosystems (e.g. size, trophic status, residence times, and geographical location) can modulate FPV impacts but FPV coverage, i.e. the proportion of the ecosystem that is covered by solar panels, is predicted to be the main driver prevailing across all ecosystem types in driving the ecological impacts of FPV on freshwaters, and thereby, affecting critical ecosystem services society relies on [10,5,11]. FPV alters solar radiation receipts and wind mixing, the two dominant forms of energy inputs into water bodies, resulting in a variety of ecological consequences [12,5]. Shading of water surface and reduction of wind speed can alter biological and hydrodynamic properties such as water temperature, primary production, having reverberating effects on freshwater biodiversity [13,11]. Using modelling approaches, recent investigations have predicted, for instance, strong reductions in chlorophyll-a biomass with increasing FPV coverage, with certain scenarios (FPV coverage >60 % or >70 %, depending on the array sitting location) leading to highly-reduced chlorophyll-a concentrations ($<1\ \mu gL^{-1}$) [13]. FPV coverage higher than 40 % could impact fundamental parameters of lake ecosystems such as microalgal growth, physicochemical and water quality parameters [14,11,15].

Despite the rapid and recent growth of FPV, there is, to date, a lack of a global quantitative assessment of their characteristics in term of water body coverage and associated water body characteristics (but see [16]). Given the importance of FPV coverage, the lack of knowledge hampers

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modeling and empirical studies that quantify potential ecological impacts. The aim of this study was therefore to provide a quantitative assessment of the extent of FPV coverage on lake ecosystems worldwide and identify its main drivers. Specifically, we predicted that FPV coverage would be highly variable among lakes across the globe due to different industrial and water body contexts and driven by geographical location and water body characteristics such as size and morphology.

2. Methods

We performed a survey of existing FPV power plants derived from a variety of external sources, including market and industry reports, manufacturers' websites, publicly released media, and published articles in scientific journals. The survey was conducted until April 2023. The first step of our survey was to identify FPV plants. Once a FPV plant was identified, available information on lake morphometry, FPV coverage and FPV power plant capacity were gathered. Where possible, the power plants were located using Google Earth Pro (7.3.4.8248 version). Once the project location was accurately identified, latitude and longitude coordinates were recorded. The Google Earth Pro polygon tool was then used on the most recent satellite image to measure the size of the lake (area, m^2), the perimeter of the lake (m) and the FPV area (m^2). Where FPV coverage (%) was not provided by the original source, it was calculated as the ratio between FPV area and lake size. Importantly, FPV plants identified that were listed as under construction or pilot projects were not included in our database. Shoreline development was used to estimate lake morphological complexity and was calculated as $DL = L/2\sqrt{\pi A}$ [17], where L and A represent lake perimeter and lake area. High shoreline development values indicate a higher deviation from a circular shape or a more complex morphology.

643 FPV plants were identified across the globe during our survey and were used to characterize the spatial distribution and installed capacity of FPV plants worldwide. Lake area, FPV area and lake perimeter were obtained for 77 % of them (n = 494). Indeed, some FPV plants were not identifiable using the satellite images due to their recent date compared to the images available in the Google Earth database. The final dataset used for statistical analysis consisted of the 494 lakes with data on FPV coverage, lake area and lake perimeter (allowing shoreline development calculation). A general linear model (GLM) with a quasibinomial family was used to identify the drivers of FPV coverage. The choice of the quasibinomial family was motivated by the nature of our response variable, which represents percentages. The explanatory variables included in our model were geographical location of lakes, categorized by continent (Asia, Europe and America, with other continents excluded due to insufficient data; $n < 3$), lake area and lake morphological complexity (shoreline development). All predictor variables were $\log_{10}$ transformed. The full model with all interactions was run and subsequently simplified by removing non-significant interactions ($p < 0.05$). Significance of explanatory variables was tested using the Anova function (car package; Fox and Weisberg, 2019). The final model did not include any interactions, and linear fits were used to visualize the relationships between predictor variables and FPV coverage. For the categorical predictor continent, a post-hoc pairwise comparison was conducted to identify statistical differences between continents. All variables in the final model had variance inflation factor (VIF) < 2, indicating low collinearity among variables. Statistical analyses were performed in R 4.1.1 (R Core Team, 2021) using the packages car (Fox and Weisberg, 2019), ggplot2 (Wickham, 2016) and emmeans (Lenth, 2023).

3. Results and discussion

A total of 643 FPV power plants installed in inland water bodies were identified across the globe (Supplementary Material 1). They were all installed on artificial lentic ecosystems such ponds, gravel pit lakes and reservoirs and were located in 28 countries (Fig. 1). A large majority of FPV plants were located in Asia (n = 545, 84.7 %), with 38.8 % located in Japan (n = 250), followed by Taiwan (12.1 %, n = 78) and China (9.5 %, n = 61). In Europe, 70 plants were identified, with the majority being located in Netherlands (n = 20), followed by Spain (n = 11), France, United Kingdom and Italy (n = 9 each). In North America, 18 plants were identified, 17 located in the United States and 1 in Panama. In South America, 7 plants were identified. We also found existing FPV plants in Israel (n = 56), Africa (n = 1) and Oceania (n = 2).

The mean installed capacity for the FPV plants identified worldwide is 7320 kWp ± 23761 (n = 351), with capacities ranging from 5.2 kWp in South Korea to 320,000 kWp in China (Table 1). Indeed, this FPV plant, located at the Shandong Province in China, is currently considered the largest FPV plant in the world [18]. The total installed capacity of these 351 FPV power plants was 2.55 GWp.

The mean FPV coverage of the plants identified worldwide was 34.2 % (±22.0 SD, median = 35.0, n = 494, Fig. 2a, Table 1) and ranged from 0.004 % on a water reservoir in China to 89.9 % on a fish pond, also in China. FPV coverage was significantly affected by lake area, lake morphology and by the geographical location (GLM, pseudo-$R^2 = 0.22$). FPV coverage significantly decreased with lake size ($X^2 = 65.5$, df = 1, $p < 0.001$). 66.2 % (n = 327) of the lakes identified in this study were smaller than 0.1 km^2 (mean = 0.28 km^2 ± 0.85 SD, median = 0.05 km^2, Table 1), with an estimated mean FPV coverage of 35 % for lakes of 0.05 km^2 (Fig. 2c). Lake morphological complexity was highly variable among recipient lakes, with shoreline development ranging from 1.4 (i.e., lakes with a virtually circular shape) to 4.22 (i.e., lakes with very dendritic contours) (Table 1). Morphological complexity significantly influenced FPV coverage ($X^2 = 20.9$, df = 1, $p < 0.001$), with lower FPV coverage observed in lakes with higher morphological complexity (Fig. 2d). FPV coverage significantly differed between continents ($X^2 = 18.32$, df = 2, $p < 0.001$), with significantly higher FPV coverage in Asia (35.1 % ± 21.5 %) than in Europe (28.1 % ± 24.5 %) and North America (28.4 % ± 24.8 %), respectively (post-hoc pairwise comparisons, $p < 0.001$, Fig. 2b, Table 1).

Our findings revealed lake size and morphology to be key drivers of FPV coverage with significant variations across continents, suggesting a high context-dependency of the potential ecological impacts of FPV on freshwaters. FPV plants are spread worldwide with a high concentration in eastern Asia and particularly in Japan, potentially attributed to the necessity of diversifying the renewable energy matrix linked to the limited land availability for expanding other traditional ground-mounted systems and other competing land uses [19]. FPV plants are also emerging in Europe and North America. Differences in FPV coverage between continents could be caused by potential differences in the development of a legal framework regulating FPV installation and the characteristics of recipient ecosystems (e.g., size and shape of the systems, type of system and use). It can also be related to local social acceptance of a new technology development. A study on the social feasibility of FPV on a recreational lake at the Netherlands found that public acceptance was influence by the scale of the projects, with aesthetics impact being a main variable decreasing FPV support [20]. Furthermore, effects of lake size and morphological complexity can be expected as smaller lakes may require higher coverage for cost-effective installations, while more complex shorelines can impose physical and technical restrictions limiting the installation of feasible FPV designs [21].

Lake ecosystems are highly valuable [22,8] and FPV installations can represent a new source of pressure regulating processes within these systems [9]. Larger FPV proportions will likely alter their biodiversity, functioning and provisioning of ecosystem services, also having societal implications as it can compromise navigation, angling and recreation activities. Given the higher FPV coverage on smaller water bodies, impacts are likely to be greater in these systems as they are reaching the threshold predicted by models to start having negative effects on water quality (40 %) [11]. Small lakes represent a major fraction of global

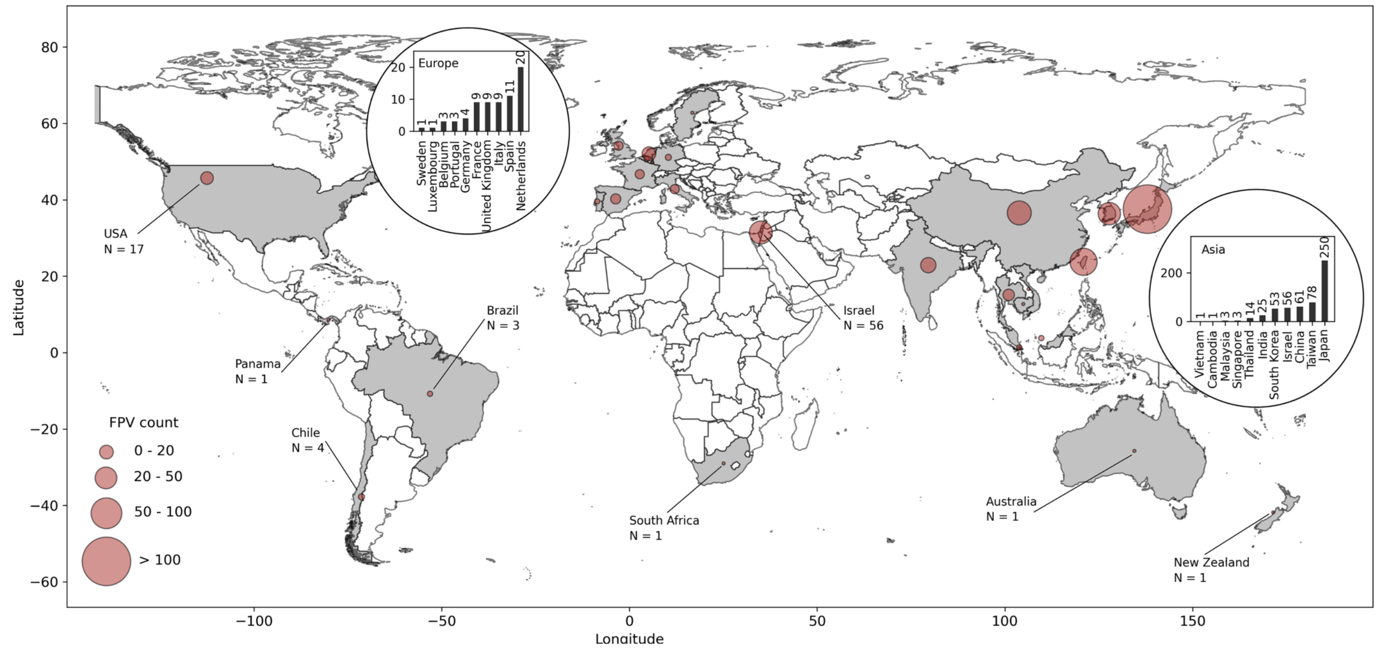

Fig. 1. Global distribution of FPV plants (n = 643). The number of FPV plants in each country is represented by the size of the red circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Descriptive statistics (average, standard deviation, median, minimum and maximum) of FPV coverage in power plants identified worldwide. Morphometric characteristics of the recipient lakes and power plant installed capacity are also displayed.

Parameter	Location		n	Mean	SD	Median	Data range (min - max)
FPV coverage (%)	Continent	Asia	431	35.06	21.54	36.4	0.004–89.91
		Europe	48	28.12	24.47	24.9	0.48–88.17
		North America	15	28.41	24.84	20.6	2–68.24
	Global		***494***	***34.19***	***22.01***	***35.03***	***0.004–89.91***
Lake area (km^2)	Continent	Asia	431	0.30	0.9	0.05	0.001–8.45
		Europe	48	0.16	0.25	0.05	0.001–1.28
		North America	15	0.11	0.29	0.03	0.001–1.13
	Global		***494***	***0.28***	***0.85***	***0.05***	***0.001–8.45***
Shoreline development	Continent	Asia	431	1.43	0.46	1.27	1.03–4.22
		Europe	48	1.33	0.27	1.22	1.05–2.16
		North America	15	1.24	0.17	1.19	1.03–1.67
	Global		***494***	***1.41***	***0.44***		***1.03–4.22***
Installed Capacity (kWp)	Continent	Asia	273	8191	25,293	1714	5.2–320000
		Europe	55	5797	20,359	471	11–147000
		North America	16	823.5	1293	212	10–4402
		South America	4	430	522	218	85–1200
		Oceania	2	570	664	570	100–1039
		Africa	1	59	–	–	–
	Global		***351***	***7320***	***23,761***	***1330***	***5.2–320000***

lentic systems, hosting a great proportion of freshwater biodiversity [23] and regulating multiple ecosystem scale processes [22,8]. However, these small water bodies often go unnoticed by governmental institutions, which have yet to develop comprehensive policies or legislations aimed at their protection [22]. This lack of attention is reflected on the incipient legal framework regarding the installation of FPV. In large lakes, FPV coverage was, overall, much lower than in small lakes and often below the values identified to induce important ecological impacts.

4. Conclusion

In conclusion this study represents a novel effort to quantify the FPV coverage in inland water bodies globally. Our findings highlight that FPV coverage is significantly influenced by lake size, morphological complexity, and geographical location, potentially influenced by economic considerations and technical constraints. Given that the potential ecological effects of FPV plants on the recipient water bodies are expected to be mainly driven by the level of FPV coverage, our results indicate that smaller lakes with less complex shorelines will be more likely to have higher FPV coverage and potentially more intense ecological impacts [6] caused by high levels of reduction in light penetration and changes in water temperature [13,24]. As FPV installations continue to expand globally, our study underscores the need for empirical investigations of varying FPV coverages across different lake sizes and ecological contexts. Bridging the gap between technological development and freshwater conservation is crucial, and future research efforts should focus on elucidating the ecological consequences of FPV, to better guide management agencies and regulation of future projects. This will allow to find a compromise between development of this new renewable technology and freshwater conservation.

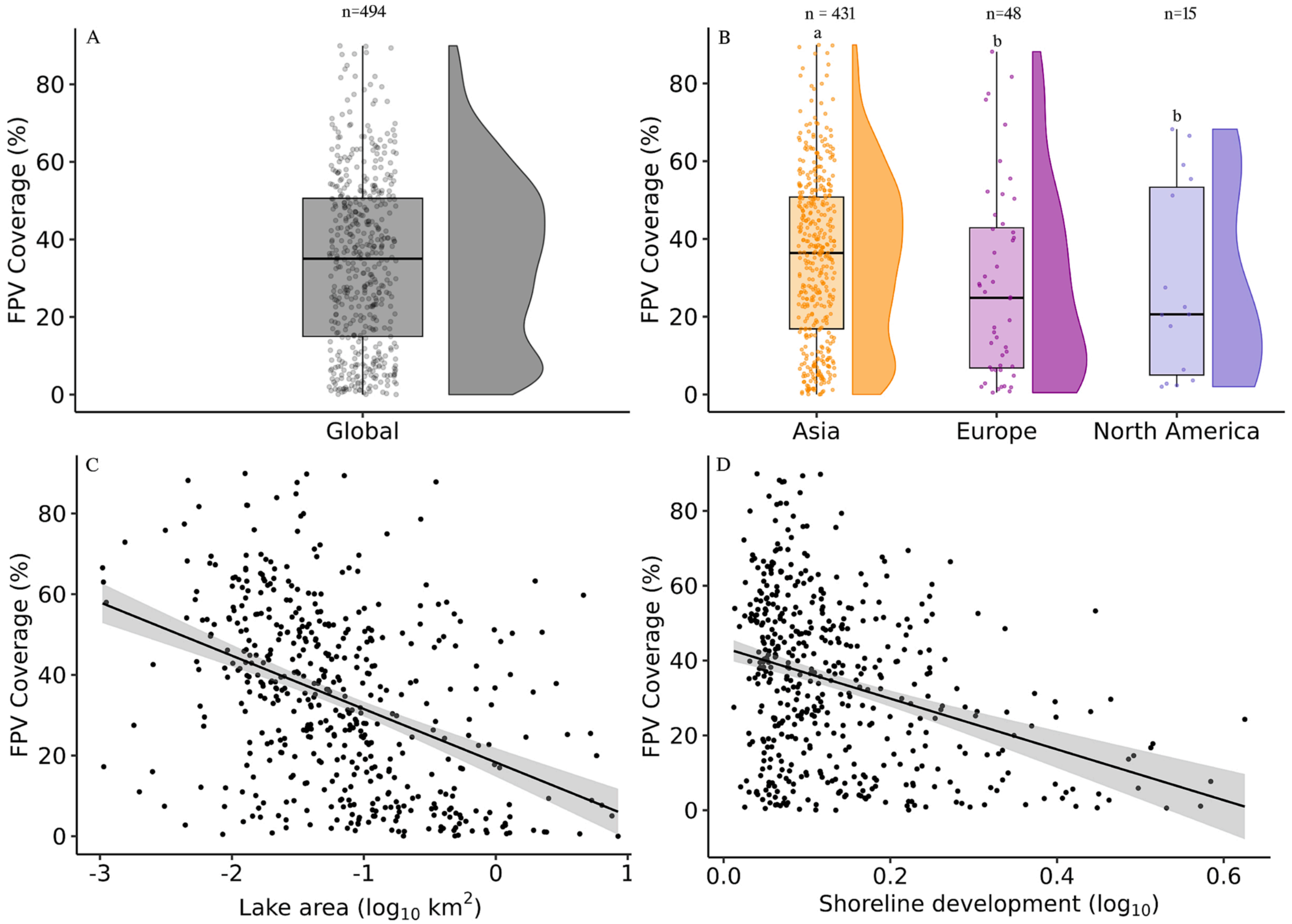

Fig. 2. (A) Global FPV coverage (n = 494), (B) FPV coverage in each continent and effects of (C) lake area and (D) lake morphological complexity (shoreline development) on FPV coverage. Different letters indicate significant differences. The black lines represent significant relationships.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2023.112244.

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