Resources, Conservation & Recycling 207 (2024) 107689

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Floating solar power as an alternative to hydropower expansion along China's Yellow River

Kai Chen [a], Yubin Jin [b], Yueyang Feng [a], Wen Song [a], Yingjie Li [c], Yanxi Zhou [d], Xiaona Guo [a], Yinshuai Li [a], Xiaomei Kou [e], Annah Lake Zhu [f], Ruishan Chen [a,*]

[a] School of Design, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China
[c] Natural Capital Project, Woods Institute for the Environment, Stanford University, Stanford, CA, 94305, USA
[d] Power China Kunming Engineering Corporation Limited, Kunming, 650051, China
[e] Power China Northwest Engineering Corporation Limited, Xi'an, 710065, China
[f] Environmental Policy Group, Wageningen University, Wageningen, 6706KN, Netherlands

ARTICLE INFO

Keywords:
Renewable energy transition
Hydropower
Solar power
Dam construction
Floating photovoltaics
Ecological impacts

ABSTRACT

Hydropower provides a growing renewable energy source, yet remains controversial due to its environmental impacts. We demonstrate a potential solution to hydropower growth that integrates solar power and hydropower by installing floating photovoltaic (PV) infrastructure at existing hydropower reservoirs. This solution circumvents new hydro-dam construction by supplying the same amount of energy from new floating solar power installations. We simulated this solution in the upper main stream of China's Yellow River, where 15 new hydro-dams are planned. We find that installing floating PV on 25.3 % of the existing hydropower reservoirs would provide enough energy to replace all new hydro-dam construction and save 497.1 km^2 of land compared to land-based PV replacement. Although floating PV as an alternative to hydropower expansion could slightly increase the initial investment (up to 9.0 %), it would avoid the adverse impacts hydropower poses to the Yellow River basin and alleviate land pressure for PV development.

1. Introduction

Hydropower is a leading component of current and future renewable energy portfolios in many countries. Globally, hydro-dam construction is on the rise, especially in emerging economies (Winemiller et al., 2016; Zarfl et al., 2015). Hydropower expansion in the upper main stream of the Yellow River – known as the "mother river" of China – provides clear evidence (Huang and Li, 2024; Li et al., 2018; Tang et al., 2013). Although 23 hydro-dams have already been built on the river's upper main tributary, there still remains a large untapped hydropower potential in this reach, with plans for future construction to meet electricity demand. In 2022, the total installed capacity of all commissioned dams was 15.6 GW (Fig. 1, Table 1), including some dams with an installed capacity of more than 1000 MW (e.g., Laxiwa: 4200 MW, Longyangxia: 1280 MW). The ecological impacts of these dams are far-reaching, including: (i) altered hydrological characteristics (Ouyang et al., 2011; Zhang et al., 2018), (ii) obstruction of natural fish migration (Xie et al., 2018; Yi et al., 2022), (iii) trapping of sediment and nutrients (Ouyang et al., 2011; Ran et al., 2013), and (iv) increased risk of Reservoir Induced Seismicity (Jackson, 2012). Also, with a high density of dams, the risk of a disaster from dam breaking is heightened. If hydropower expansion in the upper main stream of the Yellow River continues business as usual, another 10.3 GW will be deployed in the coming decades (Fig. 1, Table 2), increasing the cumulative environmental impacts and heightening the risk of a large-scale disaster. Hence, developing viable non-hydro renewables to offset hydro-dam construction is essential for expanding energy production in the Upper Yellow River basin while avoiding adverse impacts.

Solar energy provides an emerging alternative to hydropower expansion in river basins with broad ecological and environmental benefits (Schmitt et al., 2019; Siala et al., 2021). Replacing hydropower, however, requires the construction of large utility-scale PV plants, whose typical fluctuations in power output can compromise the reliability of the power system (Omran et al., 2011). Substantial spinning reserves are required to cope with the uncertainty of PV power output, resulting in an extended power system with higher operating costs and

* Corresponding author.
E-mail address: rschen@sjtu.edu.cn (R. Chen).

https://doi.org/10.1016/j.resconrec.2024.107689
Received 12 January 2024; Received in revised form 15 April 2024; Accepted 3 May 2024
Available online 15 May 2024

risks. In the upper main stream of the Yellow River, for example, a total capacity of 5.4 GW of hydropower is currently under construction and another 4.9 GW is planned (Table 2). Replacing these hydropower with utility-scale PV would substantially impact power system operations, compromising overall reliability. Yet, combining hydro and solar power can offset hydropower expansion while also ameliorating the impacts of utility-scale PV integration on the power system.

Combining hydro and solar requires the coordinated operation of a hydropower plant and a PV plant – i.e., both are integrated into the power system through the same substation (An et al., 2015). The advent of this coordinated "hydro+PV" operation provides new opportunities for synergistically combining the unique features of each renewable energy source. Specifically, as a promptly adjustable power source, hydropower can improve overall power quality by acting as a real-time power compensator for highly variable solar PV (An et al., 2015; Fang et al., 2017; Ming et al., 2017). Meanwhile, solar PV can supplement hydropower in dry periods and can also reserve water to further buffer future power shortages (Gonzalez Sanchez et al., 2021). Generally speaking, PV plants should be physically close to hydropower plants to make the "hydro+PV" coordinated operation feasible and cost-efficient (An et al., 2015). Given this proximity, the existing electrical lines used to transmit the hydropower can also be used to transmit the solar PV electricity, circumventing the need to install new potentially expensive and difficult-to-permit power lines.

Currently, the implementation of "hydro+PV" coordinated operation includes two approaches: land-based PV connected to hydropower and floating PV connected to hydropower (Silvério et al., 2018). The latter approach demonstrates unique advantages that may make it a more attractive alternative to hydropower expansion on a river basin scale. These unique advantages are well documented, including: (i) saving land surface (Essak and Ghosh, 2022; Lee et al., 2020); (ii) improving PV power conversion efficiency resulting from the cooling effect of water (Dörenkämper et al., 2021; Essak and Ghosh, 2022); (iii) easing deployment by limiting site preparation and civil works (Essak and Ghosh, 2022); (iv) saving water by limiting evaporation by covering water surfaces (Agrawal et al., 2022; Essak and Ghosh, 2022; Lee et al., 2020); (v) mitigating climate change impacts on water bodies by

Table 1
Characterization of hydropower plants operational today in the upper main stream of the Yellow River (above Qingtong Gorge).

Name	Latitude (°)	Longitude (°)	Capacity (MW)	Generation (TWh/year)	Reservoir area (km^2)
Banduo	35.31	100.27	360	1.41	0.73
Longyangxia	36.12	100.92	1280	6.00	383.00
Laxiwa	36.07	101.19	4200	10.22	13.94
Ni' na	36.06	101.27	160	0.76	2.40
Lijiaxia	36.12	101.81	2000	5.90	31.58
Zhiganglaka	36.11	101.87	190	0.76	1.60
Kangyang	36.06	101.95	284	0.99	5.36
Gongboxia	35.88	102.23	1500	5.14	22.00
Suzhi	35.87	102.34	225	0.88	6.72
Huangfeng	35.87	102.43	225	0.87	8.87
Jishixia	35.83	102.71	1020	3.36	13.61
Dahejia	35.84	102.75	142	0.56	0.98
Bingling	35.81	103.01	240	0.97	7.85
Liujiaxia	35.93	103.34	1700	5.79	131.00
Yanguoxia	36.06	103.27	509.6	2.28	16.10
Bapanxia	36.14	103.41	220	1.11	11.00
Hekou	36.17	103.47	74	0.39	2.20
Chaijiaxia	36.12	103.54	96	0.49	2.54
Xiaoxia	36.15	104.01	230	0.96	3.90
Daxia	36.31	104.16	330	1.48	7.00
Wujinxia	36.40	104.40	140	0.68	2.06
Shapotou	37.45	105.02	120.30	0.61	3.92
Qingtongxia	37.88	105.99	327	1.18	75.00
Total	–	–	15,572.9	52.8	753.4

Note: The order of hydropower plants is consistent with their location order in Fig. 1. Huangheyuan is about to be dismantled, therefore excluded. A dash indicates 'not available'. Data was sourced from the Ministry of Water Resources, China and its commissioned institution – POWERCHINA.

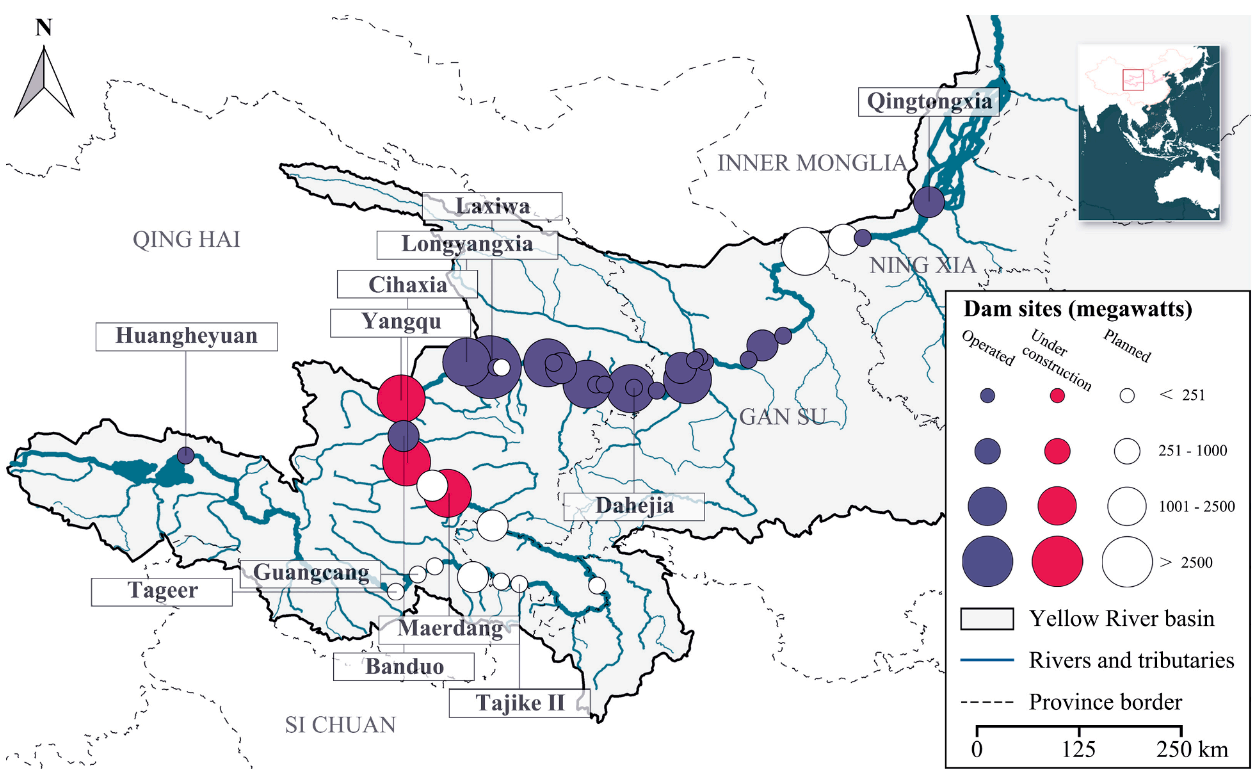

Fig. 1. Study area. The upper main stream of the Yellow River and the location and size of dams operated in 2022 (bluish-purple circles), under construction (red circles), and planned (white circles).

reducing water temperatures and shortening the duration of water stratification (Exley et al., 2021); and (vi) limiting algae growth, thereby improving water quality (Essak and Ghosh, 2022; Naganathini et al., 2020). The operational feasibility of floating PV connected to hydropower has already been demonstrated. In 2019, for instance, 47.5 MW peak floating solar PV power generation panels were installed on the reservoir of the existing Da Mi hydropower plant in Vietnam, enabling electricity generation in a coordinated “hydro+floating PV” operation (Nguyen et al., 2023).

Despite the potential advantages of floating versus land-based PV connections with hydropower, the technical feasibility, economic feasibility, energy, and non-energy co-benefits (such as land savings and algal reductions, etc.) remain underexplored. Previous research on floating PV connected to hydropower has primarily focused on engineering feasibility, technical potential, and non-energy co-benefits related to evaporation savings and CO2 savings (Gonzalez Sanchez et al., 2021; Kakoulaki et al., 2023; Lee et al., 2020; Mamatha and Kulkarni, 2021). These focused studies have been systematically assessed mainly from the perspective of supplementing hydropower or replacing thermal power generation. To our knowledge, no comprehensive studies have evaluated floating PV connected to hydropower as an alternative to hydropower expansion, especially involving the non-energy benefits related to land savings. Given that hydropower expansion is planned in many emerging economies with potentially significant environmental impacts, this blind spot in understanding the synergies between “hydro+floating PV” requires attention.

To close this critical knowledge gap, we quantified the technical potential and financial costs for floating PV connected to existing hydropower to offset new hydro-dam construction using accurate hydropower plant data and a technically rigorous PV system performance model (PV_LIB, Sandia National Laboratories) (Andrews et al., 2014). We also quantified the land savings floating PV provides compared to land-based PV with equivalent potential. Our spatially explicit simulations focus on the upper main stream of the Yellow River (Fig. 1), which is a reach with a high concentration of hydropower development and a great potential for future expansion, providing a powerful case for investigating the benefits of combined hydro and floating PV installations. Our analysis is based on two “thought experiments”. The first estimated how much reservoir area would be required to fully replace hydropower expansion with floating PV connected to existing hydropower and compared the initial investment costs between the two approaches. The second estimated the land-saving potential of floating PV by calculating how much land area would be required to generate the same amount of energy using land-based PV (also connected to existing hydropower). In these two thought experiments, we also examined how much reservoir coverage would be required to replace each future hydropower plant with floating PV, the financial performance of the needed floating PV, and the land area savings compared to land-based PV. Lastly, we estimated how many future hydropower plants could be replaced and how much land area could be saved if 10 % and 30 % coverage of floating PV were installed at existing hydropower reservoirs, respectively.

2. Materials and methods

This section summarizes the data and methodology deployed in order to conduct our analysis of the reservoir coverage required for hydropower replacement, the land savings involved, and the initial investment costs.

2.1. Hydropower plant data

We first identified and collected data on 38 hydropower plants (Huangheyuan is about to be dismantled, therefore excluded) in the upper main stream of the Yellow River from the hydraulic engineering construction and planning released by the Yellow River Conservancy Commission of the Chinese Ministry of Water Resources. We then classified these hydropower plants as existing or future, where future hydropower plants include those under construction and planned. The evaluation required collecting key parameters for each existing and future hydropower plant, including: location, reservoir area (km^2, collected only for existing hydropower plants), installed capacity (MW) and annual generation (TWh/year, or in the case of future hydropower plants, planned capacity and generation). Initial investment costs as well as construction status data were also collected for each future hydropower plant. Lastly, we integrated the above information into a singular database of hydropower plants used for our analysis (Tables 1 and 2).

2.2. Meteorological data

Solar radiation is the main meteorological factor affecting this evaluation, with temperature and wind speed playing secondary roles. Solar radiation data used in our study are derived from SYN1deg-Hourly, a 3-level CERES remote sensing product that provides hourly mean shortwave down flux in $1^\circ \times 1^\circ$ global grids (NASA/LARC/SD/ASDC, 2017). Temperature and wind speed data used in our study are derived from ERA5-land hourly data in $0.1^\circ \times 0.1^\circ$ global grids, which are the atmospheric reanalysis data from the European centre for Medium-Range Weather Forecasts (ECMWF) (Muñoz-Sabater, 2019). All meteorological data are from 2002 to 2021.

Table 2
Characterization of future hydropower plants in the upper main stream of the Yellow River (above Qingtong Gorge).

Name	Latitude (°)	Longitude (°)	Capacity (MW)	Generation (TWh/year)	Initial investment (million US$)	Construction status
Tageer	33.66	100.26	192	0.87	690.45	Planned
Guangcang	33.77	100.39	118	0.48	400.37	Planned
Saina	33.93	100.70	180	0.73	438.65	Planned
Mentang	33.86	101.09	375	1.66	890.88	Planned
Tajike I	33.68	101.41	243	0.99	557.29	Planned
Tajike II	33.69	101.55	60	0.25	157.41	Planned
Shouqu	34.03	101.87	85	0.37	221.93	Planned
Ningmute	34.47	101.16	870	3.41	2166.84	Planned
Maerdang	34.67	100.69	2200	7.05	5176.48	Under construction
Erduo	34.82	100.40	660	2.67	1767.94	Planned
Cihaxia	35.27	100.24	2000	8.72	4511.35	Under construction
Yangqu	35.71	100.27	1200	4.96	2440.81	Under construction
Shanping	–	–	160	0.66	330.11	Planned
Xiaoguanyin	–	–	1400	5.48	3725.94	Planned
Daliushu	–	–	600	2.27	1475.40	Planned
Total	–	–	10,343.0	40.6	24,951.9	–

Note: The order of hydropower plants is consistent with their location order in Fig. 1. Future hydropower plants consist of those under construction and planned. A dash indicates ‘not available’. Data was sourced from the Ministry of Water Resources, China and its commissioned institution – POWERCHINA.

2.3. Reservoir coverage required for hydropower replacement

Calculating the reservoir coverage required for installing enough floating PV on the 23 existing hydropower reservoirs such that it would replace all 15 future hydropower plants, or each individual future hydropower plant, was achieved by using both a 'generation-based' and 'capacity-based' approach. In these two approaches, information on the module types, floating structures, array configurations, allocated quantities, and equipped inverter types for floating PV on the 23 existing hydropower reservoirs was first determined. To simplify the calculations, the following parameters were used with respect to the above information: (i) floating PV adopts VBHN235SA06B module from Panasonic; (ii) floating systems follow pontoon-style floating structures that completely cover the entire surface beneath the modules, without taking into account the positive effects of water cooling (Bontempo Scavo et al., 2021); (iii) floating PV arrays are stationary and tilted southward at 10°, with the distance between two rows greater than 20 % of the height of the modules from the floating systems (in order to prevent shading of panels in adjacent rows to achieve maximum potential electricity generation in a more dense PV array configurations) (Micheli, 2021; Perez et al., 2018; Redón Santafé et al., 2014); (iv) floating PV systems are deployed at each existing hydropower reservoir with the same reservoir coverage, thereby limiting the complexity of allocation; and (v) floating PV systems are equipped with inverter adopted TB8000SHU (240 V) from Trina Solar.

We then used a flexible toolbox named PV_LIB, developed by Sandia National Laboratories, to calculate the reservoir coverage required for generation-based as well as capacity-based hydropower replacement. The toolbox provides a set of well-documented functions for simulating the theoretical output of local solar PV systems, taking into account external conditions including climate, module and inverter design, DC module characteristics, DC to AC conversion, and AC system output. Lastly, it should be noted that the Panasonic VBHN235SA06B module we adopted in the quantification procedure is the most state-of-the-art module contained in the module database of the PV_LIB model, but not the most state-of-the-art module currently available on the market. Consequently, our calculations provide an overestimate of the reservoir coverage required for hydropower replacement. As newer, more efficient modules are updated in the module database, the reservoir coverage required for hydropower replacement as calculated will be significantly reduced.

2.4. Fixed coverage potential for installing floating PV

Two fixed coverage scenarios, 10 % and 30 %, were considered in this study; the former is a relatively conservative scenario (Gonzalez Sanchez et al., 2021; Kakoulaki et al., 2023; Mamatha et al., 2022), while the latter is a coverage threshold proposed on the basis of Mathijssen et al.'s (2020) study on the potential impacts of floating PV on water quality in reservoirs, recognizing the need to limit the negative impacts of floating PV on the local environment, naturally occurring processes, and water quality. Based on the previous information determined on the module types, floating structures, array configurations, allocated quantities, and equipped inverter types for floating PV, we used the PV_LIB model to calculate the generation and capacity potential from 23 existing hydropower reservoirs for installing floating PV in the two scenarios mentioned above, and compared them with the proposed generation and capacity of future hydropower plants.

2.5. Land savings

The potential scale of land savings for installing floating PV with hydropower replacement or a fixed coverage on the 23 existing hydropower reservoirs was similarly calculated using a 'generation-based' and 'capacity-based' approach. In these two approaches, information on the module types, land characteristics deployed, installation technical characteristics, allocated quantities, and equipped inverter types for land-based PV connected to the 23 existing hydropower plants was first determined. To simplify the calculations, the following parameters were used with respect to the above information: (i) land-based PV adopts the module type proposed for the floating PV in this evaluation; (ii) land-based PV modules are deployed on flat horizontal land, making installation simpler; (iii) land-based PV modules are positioned at the optimum fixed tilt and avoiding any inter-row shading for 4 h (noon ± 2 h) throughout the year (i.e., shading factor = 0.05 here) (Martín-Chivelet et al., 2016); (iv) land-based PV systems deployed in proximity to each existing hydropower plant offer equivalent potential to the floating PV systems allocated in this evaluation; and (v) land-based PV systems are equipped with inverter adopted the equipment type proposed for the floating PV in this evaluation.

To derive the most conservative scale of land savings, we calculated the optimal tilt angle (β_{optimal}) of the modules as well as the optimal packing factor (PF_{optimal}, which minimizes the land area occupied by the PV array, consisting of the land area covered by the PV panels and the row spacing between the panels, and maintaining maximum irradiation given shading and orientation) for each land-based PV plant using the method provided by Martín-Chivelet (2016), which are calculated as:

$$\beta_{\text{optimal}} = -0.0049\varphi^2 + 1.0888\varphi \tag{1}$$

$$PF_{\text{optimal}} = PF_0 - A\varphi^2 - B\varphi \tag{2}$$

where φ is the latitude of each PV array centroid; −0.0049 and 1.0888 are fit parameter coefficients with coefficient of determination $R^2 = 0.993$. PF is the packing factor, i.e., the ratio of the PV panel area to the land area occupied by the PV array; PF_0 is the packing factor at 0° latitude, which is 100 % for a fixed PV system on flat land; and A and B are fit parameter coefficients, 0.0098 and 0.9505, respectively (coefficient of determination $R^2 = 0.9995$).

We then used the PV_LIB model to calculate the land area occupied by all land-based PV arrays (S_{al}) with equivalent potential for generation and capacity to that of the floating PV installed at existing hydropower reservoirs, respectively. Based on these results, we further calculated the direct land area (S_{dl}) occupied by all land-based PV plants, consisting of the land directly occupied by solar arrays, access roads, substations, service buildings, and other infrastructure, using the method provided by Martín-Chivelet (2016), calculated as:

$$S_{\text{dl}} = \frac{S_{\text{al}}}{R_{\text{ad}}} \tag{3}$$

where R_{ad} is the ratio of the land area occupied by the PV array to the direct land area for the PV plant ($R_{ad} = 0.80$ here).

Lastly, we calculated the total land area ($S_{tl,g}$, $S_{tl,c}$) occupied by all land-based PV plants (i.e., all land area enclosed by the site boundary of all land-based PV plants) in the equivalent potential for generation and capacity scenarios, respectively, which are calculated as:

$$S_{\text{tl,g}} = \frac{S_{\text{dl}}}{R_{\text{dt,g}}} \tag{4}$$

$$S_{\text{tl,c}} = \frac{S_{\text{dl}}}{R_{\text{dt,c}}} \tag{5}$$

where R_{dt} is the ratio between the direct land area occupied by a PV plant and the total land area it occupies, also known as the suitability factor, i.e., the ratio of the land area suitable for a PV facility to the total land area occupied by a PV plant and $R_{dt,g}$ and $R_{dt,c}$ are the generation-weighted average and capacity-weighted average suitability factors for land use of a PV plant, respectively. On the basis of the data analysis of Ong et al. (2013) on land use for fixed PV plants, $R_{dt,g}$ and $R_{dt,c}$ were assigned values of 0.757 and 0.773, respectively. It should be noted that the above assigned values are the result of the analysis based on the relatively small sample sizes of the U.S. as of September 2012, rather than China, which reflect past performance rather than future trends. Consequently, there may be large uncertainties in the calculation. With the rapid expansion of solar PV projects in China and the maturing of land use practices and regulations, future data tailored to China should be used to update our analysis.

2.6. Initial investment cost

Given the difference in the lifetime between hydropower and solar power projects, this study did not examine per unit energy costs (i.e., the sum of the initial investment and operating costs of one project divided by the total amount of energy generated over its lifetime), but instead focused on the initial investment costs of the 15 future hydropower plants versus the initial investment costs of installing floating PV on the 23 existing hydropower reservoirs under the given scenarios (equivalent generation and capacity potential to the new hydropower projects).

The initial investment costs of the 15 future hydropower plants are shown in Table 2. In order to derive the initial investment costs of installing floating PV on the 23 existing hydropower reservoirs with equivalent generation or capacity potential to that of the hydropower being replaced, we first estimated the installed cost of floating PV to be 912 US$/kW in 2024, based on the installed cost of land-based PV of 857 US$/kW released by International Renewable Energy Agency (IRENA) (2022) and the analysis of the installed cost of floating PV (20–25 % higher than that of land-based PV) by Goswami et al. (2019). We then calculated the initial investment costs of installing floating PV in each of the two scenarios based on the amount of floating PV capacity installed on the 23 existing hydropower reservoirs with equivalent generation and capacity potential to that of the hydropower being replaced, as calculated by the PV_LIB model. Lastly, we compared the financial performance for the initial investment costs of these two energy production approaches under scenarios with equivalent generation and capacity potential.

It should be noted that the initial investment cost, including development, design, procurement, construction, finance and other costs, are somewhat different in different regions and time, and thus our results should be used as a rough guiding average.

3. Results

We identified 38 cascade hydropower plants in the study area, which together would amount to around 25.9 GW capacity, resulting in a total generation of around 93.4 TWh/year (Tables 1 and 2). Of these possible hydropower plants, 23 are currently in operation (i.e., existing hydropower plants), 3 are under construction, and the remaining 12 are planned for the near future. Most existing hydropower plants are located on the lower Longyangxia Reservoir, whereas all hydropower plants under construction and most of those planned are located on the upper Longyangxia Reservoir (Fig. 1). This means that the upper main stream of the Yellow River above Longyangxia Reservoir – a key area for water ecology and biodiversity conservation – is facing serious threats from large-scale cascade hydropower development.

Of all the hydropower plants identified, the total generation of the 23 existing ones is around 52.8 TWh/year, with a total reservoir area of around 753.4 km^2 (Table 1); and the proposed total installed capacity and total generation of the 15 future ones are around 10,343 MW and 40.6 TWh/year, respectively, with a proposed total initial investment cost of around US$24.95 billion (Table 2). The reservoir area of existing hydropower plants ranges from less than 1 km^2 (e.g., Banduo hydropower plant and Dahejia hydropower plant) to 383 km^2 (e.g., Longyangxia hydropower plant) (Table 1). The proposed installed capacity of future hydropower plants is between 60 MW (for Tajike II) and 2200 MW (for Maerdang), the proposed annual generation ranges from less than 0.3 TWh/year (for Tajike II) to 8.7 TWh/year (for Cihaxia), and the proposed initial investment costs range from US$175.4 million (for

Table 3
The estimated equivalent potential of PV systems with respect to future hydropower plant generation and capacity.

Hydropower	Equivalent hydropower reservoir area of PV				Equivalent land area of PV		Construction status
	Generation based (km^2)	Capacity based (km^2)	Generation-based percentage of reservoir area (%)	Capacity-based percentage of reservoir area (%)	Generation based (km^2)	Capacity based (km^2)	
Tageer	4.09	1.23	0.54	0.16	10.66	3.16	Planned
Guangcang	2.26	0.76	0.30	0.10	5.88	1.94	Planned
Saina	3.43	1.15	0.46	0.15	8.94	2.97	Planned
Mentang	7.81	2.40	1.04	0.32	20.34	6.18	Planned
Tajike I	4.66	1.56	0.62	0.21	12.13	4.00	Planned
Tajike II	1.18	0.38	0.16	0.05	3.06	0.99	Planned
Shouqu	1.74	0.54	0.23	0.07	4.53	1.40	Planned
Ningmute	16.04	5.57	2.13	0.74	41.78	14.34	Planned
Maerdang	33.17	14.08	4.40	1.87	86.38	36.25	Under construction
Erduo	12.56	4.23	1.67	0.56	32.71	10.88	Planned
Cihaxia	41.03	12.80	5.45	1.70	106.84	32.96	Under construction
Yangqu	23.34	7.68	3.10	1.02	60.77	19.77	Under construction
Shanping	3.11	1.02	0.41	0.14	8.09	2.64	Planned
Xiaoguanyin	25.78	8.96	3.42	1.19	67.14	23.07	Planned
Daliushu	10.68	3.84	1.42	0.51	27.81	9.89	Planned
Total	190.9	66.2	25.3	8.8	497.1	170.4	–

Note: A dash indicates 'not available'.

Tajike II) to US$5176.5 million (for Maerdang) (Table 2). The above information is the basis for the two thought experiments conducted in this study.

3.1. Reservoir coverage required for hydropower replacement

Our analysis covers both generation-based replacement (reservoir area needed for floating PV replacing future hydropower generation) and capacity-based replacement (reservoir area needed for floating PV replacing future hydropower capacity). In terms of generation-based replacement, 190.9 km^2 is the total reservoir area that would be needed to replace the energy expected to be generated by the 15 future hydropower plants with additional floating PV-generated energy. This amounts to only 25.3 % of the total area of the 23 existing hydropower reservoirs (Table 3). This estimate demonstrates that it is technically feasible to install floating PV on the 23 existing hydropower reservoirs as a generation-based alternative to all 15 future hydropower plants. For individual future hydropower plants, the smallest area needed for replacement is Tajike II, which only requires 1.18 km^2 of floating PV installations to be built at existing hydropower reservoirs (less than 0.2 % of the total area of the 23 existing hydropower reservoirs). The largest area needed for replacement is Cihaxia, which requires 41.0 km^2 (5.5 % of the total area of the 23 existing hydropower reservoirs) (Fig. 2a, Table 3). Overall, covering 12.4 % of the 23 existing hydropower reservoir areas with newly installed floating PV could provide a generation-based alternative to up to 12 future hydropower plants (including all 12 planned hydropower plant scenario, Table 3).

Capacity-based replacement requires even less reservoir area. Regarding capacity-based replacement, a total reservoir area of 66.2 km^2 is needed to replace all the capacity expected at the 15 future hydropower plants with additional floating PV capacity. This amounts to only 8.8 % of the total area of the 23 existing hydropower reservoirs (Table 3). This estimate demonstrates that it is technically feasible to install floating PV on the 23 existing hydropower reservoirs as a capacity-based alternative to all 15 future hydropower plants. For individual future hydropower plants, the area needed for replacement ranges from 0.4 km^2 (one-half of 0.1 % of the total area of the 23 existing hydropower reservoirs) for Tajike II to 14.1 km^2 (1.9 % of the total area of the 23 existing hydropower reservoirs) for Maerdang – all amounting to much less area needed as compared to generation-based replacement (Fig. 2b, Table 3). Overall, installing 4.2 % of the 23 existing hydropower reservoir areas with floating PV could provide a capacity-based alternative to up to 12 future hydropower plants (including all 12 planned hydropower plant scenario, Table 3).

We also estimated the potential resulting from 10 % of the existing hydropower reservoir area being installed with floating PV (Table 4), as a conservative estimate of the amount of existing hydropower reservoir area likely to be occupied if installing floating PV. In general, a reservoir covering up to 10 % of the water area is not likely to have a substantial impact on the ecosystem. If 10 % of the 23 existing hydropower reservoir areas was used for installing floating PV, 16.1 TWh/year could be generated, which is more than the total proposed annual generation from up to 11 future hydropower plants (Table 2 and 4). If a more aggressive scenario of 30 % of the 23 existing hydropower reservoir areas was used for installing floating PV, the total proposed annual generation from all 15 future hydropower plants could be replaced (Table 2, 4 and Fig. 2d). Under the less aggressive scenario of covering just 10 % of the 23 existing hydropower reservoir areas with floating PV, up to 11 future hydropower plants could be replaced in terms of generation-based replacement and all 15 future hydropower plants could be replaced in terms of capacity-based replacement (Table 2, 4 and Fig. 2c).

3.2. Land savings

Our analysis of land savings generated by installing floating PV

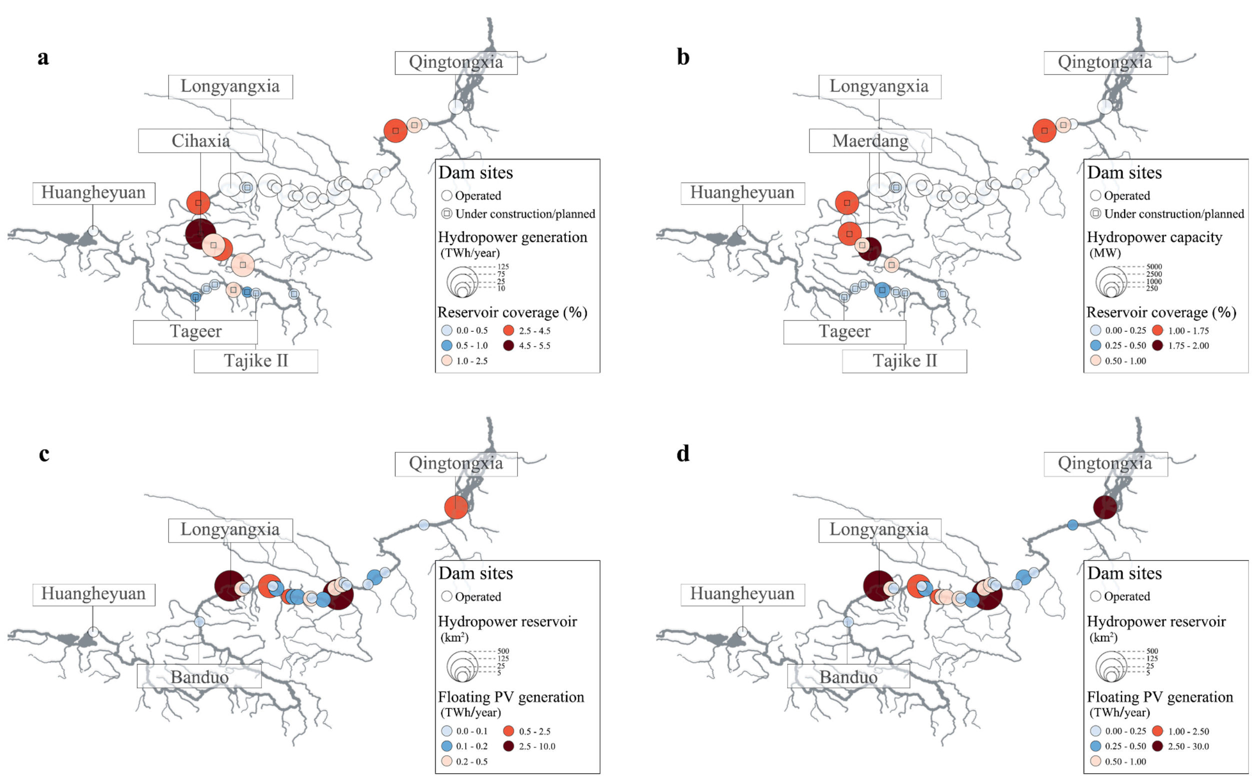

Fig. 2. Aspects of reservoir coverage and floating PV generation. (**a**) and (**b**) Reservoir coverage (%) required for installing floating PV on the 23 existing hydropower reservoirs as a generation- and capacity-based alternative to each future hydropower plant, respectively. (**c**) and (**d**) Potential generation (TWh/year) from installing floating PV with 10 % and 30 % of the 23 existing hydropower reservoir areas, respectively.

Table 4
The estimated equivalent potential of PV systems on land as compared to PV systems on water.

Hydropowerr	Potential of floating PV				Equivalent land area of PV			
					10% of the reservoir area		30% of the reservoir area	
	Area based. 10% of reservoir area (TWh/year)	Area based. 10% of reservoir area (MW)	Area based. 30% of reservoir area (TWh/year)	Area based. 30% of reservoir area (MW)	Generation based (km^2)	Capacity based (km^2)	Generation based (km^2)	Capacity based (km^2)
Banduo	0.02	11.40	0.05	34.21	0.18	0.18	0.55	0.55
Longyangxia	8.22	5982.63	24.66	17,947.89	99.28	98.15	297.83	294.46
Laxiwa	0.30	217.75	0.90	653.25	3.61	3.57	10.82	10.70
Ni' na	0.05	37.49	0.16	112.47	0.62	0.61	1.86	1.84
Lijiaxia	0.65	493.29	1.96	1479.88	8.22	8.09	24.66	24.28
Zhiganglaka	0.03	24.99	0.10	74.98	0.42	0.41	1.25	1.23
Kangyang	0.11	83.73	0.33	251.18	1.39	1.37	4.18	4.11
Gongboxia	0.46	343.65	1.37	1030.95	5.68	5.60	17.05	16.79
Suzhi	0.14	104.97	0.42	314.91	1.74	1.71	5.21	5.13
Huangfeng	0.18	138.55	0.55	415.66	2.29	2.26	6.87	6.77
Jishixia	0.29	212.59	0.86	637.78	3.50	3.46	10.50	10.37
Dahejia	0.02	15.31	0.06	45.92	0.25	0.25	0.76	0.75
Bingling	0.16	122.62	0.49	367.86	2.02	1.99	6.05	5.98
Liujiaxia	2.73	2046.28	8.19	6138.83	33.80	33.37	101.39	100.12
Yanguoxia	0.33	251.49	1.00	754.47	4.17	4.12	12.51	12.36
Bapanxia	0.23	171.82	0.69	515.47	2.86	2.82	8.57	8.46
Hekou	0.05	34.36	0.14	103.09	0.57	0.56	1.71	1.69
Chaijiaxia	0.05	39.68	0.16	119.03	0.66	0.65	1.98	1.95
Xiaoxia	0.08	60.92	0.25	182.76	1.02	1.00	3.05	3.00
Daxia	0.15	109.34	0.44	328.03	1.83	1.80	5.50	5.41
Wujinxia	0.04	32.18	0.13	96.53	0.54	0.53	1.62	1.60
Shapotou	0.09	61.23	0.26	183.70	1.06	1.05	3.18	3.15
Qingtongxia	1.62	1171.53	4.86	3514.60	20.48	20.36	61.44	61.07
Total	16.1	11,767.8	48.3	35,303.5	196.3	194.0	588.9	582.1

Note: Huangheyuan is about to be dismantled, therefore excluded.

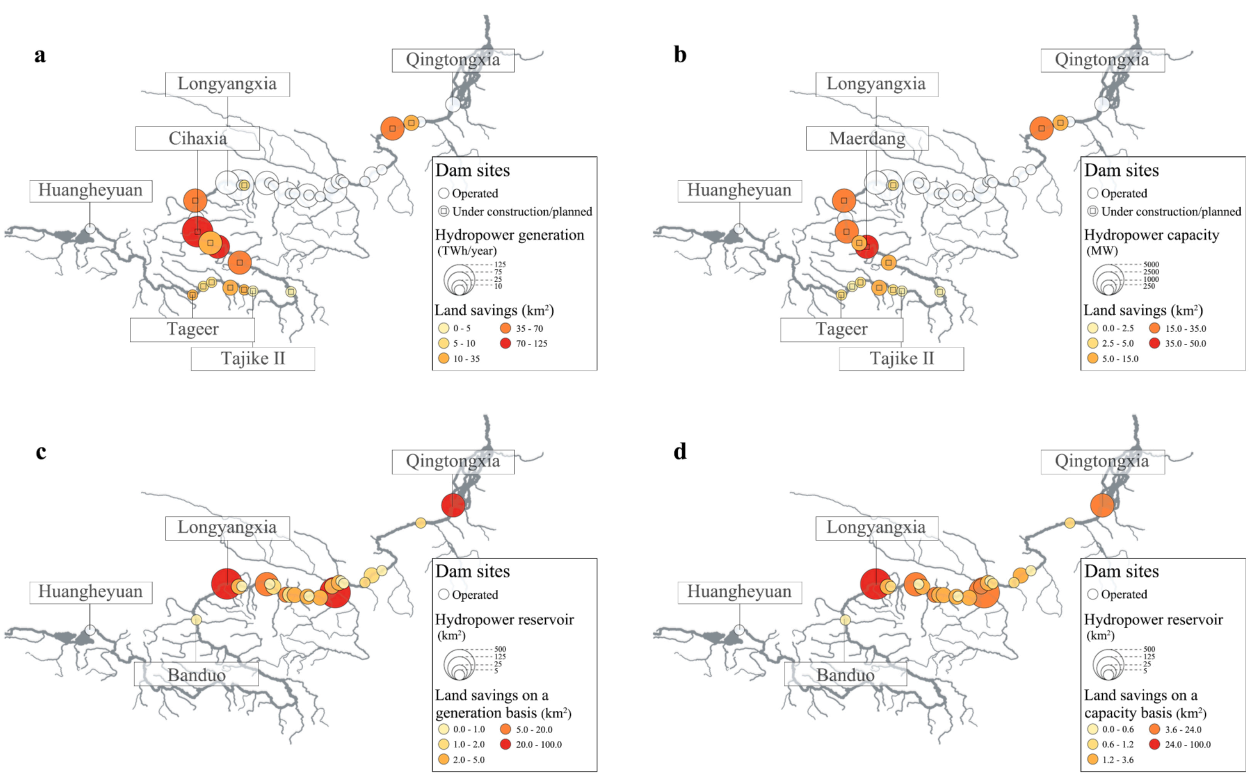

Fig. 3. Aspects of land savings. (**a**) and (**b**) Potential land savings (km^2) from installing floating PV on the 23 existing hydropower reservoirs as a generation- and capacity-based alternative to each future hydropower plant compared to relying on land-based PV as an alternative, respectively. (**c**) and (**d**) Potential land savings (km^2) from installing floating PV with 10 % of the 23 existing hydropower reservoir areas covered for generation-based and capacity-based replacement, respectively.

(compared to land-based PV) at existing hydropower reservoirs also covers both generation- and capacity-based replacement. Regarding land savings from generation-based replacement, we estimated that installing floating PV on the 23 existing hydropower reservoirs as an alternative to all 15 future hydropower plants would save 497.1 km^2 of land compared to relying on land-based PV. This amounts to a savings of 2.60 times the total hydropower reservoir area required (Table 3). This estimate demonstrates that the generation-based average land-saving

Table 5
The financial estimated equivalent potential of PV systems on water with respect to future hydropower plant generation and capacity.

Hydropower		Equivalent initial investment of floating PV					
Name	Initial investment (million US$)	Generation-based			Capacity-based		
		Cost value (million US$)	Percentage of hydropower (%)	Percentage increase (%)	Cost value (million US$)	Percentage of hydropower (%)	Percentage increase (%)
Tageer	690.45	583.14	84.46	−15.54	175.10	25.36	−74.64
Guangcang	400.37	321.73	80.36	−19.64	107.62	26.88	−73.12
Saina	438.65	489.30	111.55	11.55	164.16	34.05	−62.58
Mentang	890.88	1112.66	124.89	24.89	342.00	34.27	−61.61
Tajike I	557.29	663.57	119.07	19.07	221.62	34.76	−60.23
Tajike II	157.41	167.57	106.45	6.45	54.72	34.93	−65.24
Shouqu	221.93	248.00	111.75	11.75	77.52	36.62	−65.07
Ningmute	2166.84	2285.64	105.48	5.48	793.44	37.09	−63.38
Maerdang	5176.48	4725.44	91.29	−8.71	2006.40	37.42	−61.24
Erduo	1767.94	1789.63	101.23	1.23	601.92	38.39	−65.95
Cihaxia	4511.35	5844.80	129.56	29.56	1824.00	38.76	−59.57
Yangqu	2440.81	3324.56	136.21	36.21	1094.40	39.77	−55.16
Shanping	330.11	442.38	134.01	34.01	145.92	40.43	−55.80
Xiaoguanyin	3725.94	3673.11	98.58	−1.42	1276.80	44.20	−65.73
Daliushu	1475.40	1521.52	103.13	3.13	547.20	44.84	−62.91
Total	24,951.9	27,193.1	–	–	9432.8	–	–

Note: A dash indicates 'not available'.

ratio for installing floating PV on the 23 existing hydropower reservoirs is 2.60:1 m^2, meaning that every 1.0 m^2 used for electricity generation on water would save 2.60 m^2 of land (as compared to installing land-based PV). For each future hydropower plant, the land savings we estimated ranges from 3.1 km^2 (for Tajike II) to 106.8 km^2 (for Cihaxia) (Fig. 3a, Table 3).

Regarding land savings from capacity-based replacement, we estimated that installing floating PV on the 23 existing hydropower reservoirs as an alternative to all 15 future hydropower plants would save 170.4 km^2 of land compared to relying on land-based PV. Significantly less than the land savings from generation-based replacement, this amounts to a savings of 2.57 times the total hydropower reservoir area required (Table 3). This estimate demonstrates that the capacity-based average land-saving ratio for installing floating PV on the 23 existing hydropower reservoirs is 2.57:1 m^2, meaning that for every 1.0 m^2 of installed capacity on water, 2.57 m^2 of land would be saved (as compared to installing land-based PV). For each future hydropower plant, the smallest land-saving area estimated is Tajike II (1.0 km^2) and the largest is Maerdang (36.3 km^2). All are much less than the land savings from generation-based replacement (Fig. 3b, Table 3).

We also estimated the land-saving potential from a fixed coverage of the hydropower reservoir area for installing floating PV (Table 4). If 10 % of the 23 existing hydropower reservoir areas was used for installing floating PV, the land savings from the generation-based and capacity-based scenarios would be 196.3 km^2 and 194.0 km^2, respectively. Under the more aggressive scenario of 30 % of the 23 existing hydropower reservoir areas covered, the land savings from the generation-based and capacity-based scenarios would be 588.9 km^2 and 582.1 km^2, respectively (Table 4). Under the less aggressive scenario of covering 10 % of the 23 existing hydropower reservoir areas with floating PV, Banduo offers the smallest potential (less than 0.2 km^2), whereas Longyangxia offers the largest potential (99.3 km^2) in terms of generation-based land savings (Fig. 3c, Table 4). Similarly, Banduo offers the smallest potential (less than 0.2 km^2) and Longyangxia offers the largest potential (98.2 km^2) in terms of capacity-based land savings (Fig. 3d, Table 4).

3.3. Initial investment cost

Our analysis comparing the initial investment costs of future hydropower versus installing floating PV at existing hydropower reservoirs also covers both generation- and capacity-based replacement. In terms of generation-based replacement, US$27.2 billion would be needed as an initial investment to replace the energy expected to be generated by the 15 future hydropower plants with additional floating PV-generated energy. This amounts to only 9.0 % higher than the total initial investment cost of building 15 new hydropower plants (Table 5). This estimate demonstrates that it is relatively economically feasible to install floating PV on the 23 existing hydropower reservoirs as a generation-based alternative to all 15 future hydropower plants. For individual future hydropower plants, the initial investment cost needed for replacement ranges from US$167.6 million for Tajike II (versus US $157.4 million for hydropower) to US$5844.8 million for Cihaxia (versus US$4511.3 million for hydropower). As these figures show, in some cases the initial investment cost of installing floating PV can be higher and in some cases the initial investment cost of future hydropower can be higher. The cost differential of replacing hydropower with floating PV represents at the most an increase of 36.2 % in the initial investment cost (at Yangqu) and at the least a 19.6 % decrease in the initial investment cost (at Guangcang) (Table 5).

Capacity-based replacement requires even less initial investment cost. Regarding capacity-based replacement, a total initial investment cost of US$9.4 billion is needed to replace all the capacity expected at the 15 future hydropower plants with additional floating PV capacity (versus US$25.0 billion for hydropower), representing only 37.8 % of the total initial investment cost of 15 future hydropower plants

(Table 5). This estimate suggests that it is economically preferable to install floating PV on the 23 existing hydropower reservoirs as a capacity-based alternative to all 15 future hydropower plants. For individual future hydropower plants, the initial investment cost needed for replacement ranges from US$54.7 million for Tajike II to US$2006.4 million for Maerdang – all of which are much less of an initial investment cost as compared to generation-based replacement. In terms of cost differential, the highest percentage decrease is Tageer (74.6 % of the initial investment cost of hydropower) and the lowest percentage decrease is Yangqu (55.2 % of the initial investment cost of hydropower) (Table 5).

4. Discussion

Our study demonstrates the technical and economic feasibility of installing floating PV on the 23 existing hydropower reservoirs in the upper main stream of the Yellow River as an alternative to all 15 future hydropower plants in this reach, both for generation-based and capacity-based scenarios. The former requires a larger reservoir area, amounting to just over one-fourth (25.3 %) of the total area of the existing hydropower reservoirs, with a higher total initial investment cost of US$27.2 billion (just over 9.0 % higher than the total initial investment cost of the 15 future hydropower plants, Table5). The latter, in contrast, requires less than one-tenth (8.8 %) of the total area of the existing hydropower reservoirs, with a lower total initial investment cost of US$ 9.4 billion (just 37.8 % of the total initial investment cost of the 15 future hydropower plants, Table 5). Although these calculations remain purely theoretical at this point, and require empirical studies to confirm more detailed specifications, they nonetheless demonstrate that installing floating PV on the existing hydropower reservoirs can replace future hydro-dam construction with relatively reasonable financial performance, while still meeting renewable energy expansion targets. This replacement would likely result in less environmental impacts without compromising energy security.

Our evaluation was based exclusively on installing floating PV at existing hydropower reservoirs as an alternative to future hydropower expansion within the basin. The existing hydropower reservoir area required to replace future hydro-dam construction could be further reduced by (i) inclusion of land-based PV generation, (ii) wind power, (iii) aquatic diversionary or hydrokinetic turbines that capture a portion of a river's energy without damming, (iv) other forms of alternative energy production and (v) energy efficiency measures that reduce total energy demand. Also, as the installed cost of solar PV is anticipated to decrease in the future, this alternative will become more economical over time. In contrast, the installed cost of hydropower has been increasing each year (International Renewable Energy Agency (IRENA), 2022). Furthermore, in terms of time, solar PV installation is preferable. Solar PV projects can be developed quickly (within one year), while hydro-dams can take up to ten years.

Floating PV also offers the additional advantage of land savings versus land-based PV (also connected to existing hydropower). Since solar PV systems are sited directly on existing hydropower reservoirs instead of land, this alleviates land demand for utility-scale, land-based PV installations and avoids the costs of land acquisition in expensive areas. For the generation-based scenario, the land-savings potential from all 15 future hydropower plants for complete replacement is around 497.1 km^2, around fifteen times the size of Macao (32.9 km^2). For the capacity-based scenario, the land-savings potential from all 15 future hydropower plants for complete replacement is around 170.4 km^2, more than five times the size of Macao. Although these quantified land savings are approximations, they are high enough to make floating PV connected to existing hydropower an excellent choice for expanding renewable energy production in the basin as well as reserving land for other purposes.

The advantages of floating PV connected to existing hydropower as an alternative to hydropower expansion are highly attractive, but by no means free of flaws or issues. Generally, the durability of PV modules is only about 25 years, which would make the alternative much shorter than the lifespan of hydropower expansion; and the aging/degradation of PV modules could negatively influence the overall performance of this alternative. Moreover, as a result of the high variability of solar power, the alternative would barely achieve the power dispatch capability of the hydropower expansion without the complement of energy storage or other flexible energy technologies. Finally, installing floating PV at existing hydropower reservoirs may have environmental issues (although most likely fewer environmental issues than building new hydro-dams). For instance, high floating PV coverage can potentially reduce dissolved oxygen levels in hydropower reservoir water bodies, thereby harming fish and other animals (Almeida et al., 2022; Château et al., 2019). Extreme oxygen depletion would favor methane-producing bacteria, which could offset the benefits of decarbonization (Almeida et al., 2022). Further, changes in water temperature and stratification resulting from floating PV, by limiting the amount of solar radiation reaching the water and sheltering the water from the effects of wind mixing, challenge the adaptive capacity of aquatic ecosystems (Almeida et al., 2022; Armstrong et al., 2020). Moreover, aquatic ecosystems may be adversely affected due to the direct contact between water bodies and floating devices as well as electromagnetic fields generated by the cables (Pimentel et al., 2018). These impacts may be minimal if floating PV coverage is low. But it is unclear exactly how severe any particular type of impact would be, nor how these impacts would vary with latitude, water quality, and other factors.

Large-scale field studies are needed to evaluate the response of hydropower reservoir ecosystems to floating PV coverage so as to determine the suitable coverage that minimizes potential negative impacts. Although several small pilot projects have been deployed, such as the Alto Rabagao dam reservoir pilot project in Portugal, most research efforts have focused more on engineering feasibility than ecology. Additionally, the limited number of such large projects in operation as of the end of 2023 (most are less than 4 years old) challenges the long-term documentation of empirical data on system performance, environmental impacts, and other key factors. With the rapid expansion of projects coming online globally and the growing interest in research on floating PV connected to existing hydropower, we can expect an equally rapid increase in case studies and publicly available data. This burgeoning attention will open the door to answering questions about the realistic expectations for floating PV connected to existing hydropower.

5. Conclusions

This study demonstrates the technical potential and economic feasibility of installing floating PV on the existing hydropower reservoirs in the upper main stream of the Yellow River as an alternative to hydropower expansion in this reach. The analysis shows that a higher reservoir coverage of 25.3 % with floating PV could provide a generation-based alternative to all 15 future hydropower plants with a slight increase in initial investment costs of 9.0 %, and a lower reservoir coverage of 8.8 % with floating PV could provide a capacity-based alternative to all 15 future hydropower plants with a decrease in initial investment costs to 37.8 %. If this synergistic "hydro+floating PV" setup could be implemented, it would help reduce the cumulative environmental impacts of hydro-dam construction on the Yellow River basin. It would also result in the additional positive benefits of land savings in an area prioritized for food security along the Yellow River and water savings by limiting evaporation. Finally, floating PV connected to existing hydropower could improve the overall energy security in the upper Yellow River basin by compensating for low water flows during droughts and mitigating risks associated with dam breaks to support the provision of reliable electricity services.

Despite the benefits of floating PV hydropower replacement as demonstrated in this analysis, there are also possible drawbacks and implementation uncertainties. For example, it remains unclear how to determine the optimal sizing of floating PV connected to existing hydropower and how to minimize or avoid adverse impacts to the water resource allocation of existing reservoirs. Floating PV deployment is a new and rapidly emerging field of inquiry within the renewable energy transitions literature and requires robust experimentation in practice. Our study reveals that vast future potential of this alternative for enacting renewable energy transitions, but future research must be performed to realize this potential.

Spotlights

- Hydropower expansion increases renewable energy production, but also causes irreversible adverse ecological impacts.
- Floating solar power can provide enough energy to offset new dam construction, thus providing a preferable alternative.
- Covering ¼ of existing hydropower reservoirs with PV could replace the energy to be generated by planned new dams.
- Replacing new dam construction with floating solar power is both technically and economically feasible.
- Investing in floating solar power can help reduce the unintended ecological impacts of the renewable energy transition.

CRediT authorship contribution statement

Kai Chen: Conceptualization, Data collection, Results calculation, Writing – original draft, and Writing – review & editing. **Yubin Jin:** Model building and Results calculation. **Yueyang Feng:** Model building and Results calculation. **Wen Song:** Data collection and Results calculation, and Writing – original draft. **Yingjie Li:** Conceptualization, Writing – review & editing. **Yanxi Zhou:** Data collection and Results calculation. **Xiaona Guo:** Data collection,and Results calculation. **Yinshuai Li:** Data collection,and Results calculation. **Xiaomei Kou:** Data collection,and Results calculation. **Annah L. Zhu:** Conceptualization, and Writing – review & editing. **Ruishan Chen:** Conceptualization, Supervision, and Writing – review & editing.

Data availability

Data will be made available on request.

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.

Acknowledgments

This study was financially supported by the National Social Science Fund of China (Grant No. 20ZDA085), the China Postdoctoral Science Foundation (Grant Nos. 2022M722055 and 2022TQ0205) and 2023 Youth Talent Cultivation Programme (Grant No. 2023QN029).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107689.

References

Agrawal, K.K., Jha, S.K., Mittal, R.K., Vashishtha, S., 2022. Assessment of floating solar PV (FSPV) potential and water conservation: case study on Rajghat Dam in Uttar Pradesh, India. Energy Sustain. Dev. 66, 287–295. https://doi.org/10.1016/j.esd.2021.12.007.

Almeida, R.M., Schmitt, R., Grodsky, S.M., Flecker, A.S., Gomes, P., Zhao, L., Liu, H., Barros, N., Kelman, R., McIntyre, P.B., 2022. Floating solar power could help fight climate change — Let's get it right. Nature 606, 246–249. https://doi.org/10.1038/d41586-022-01525-1.

An, Y., Fang, W., Ming, B., Huang, Q., 2015. Theories and methodology of complementary hydro/photovoltaic operation: applications to short-term scheduling. J. Renew. Sustain. Energy 7 (6), 063133. https://doi.org/10.1063/1.4939056.

Andrews, R.W., Stein, J.S., Hansen, C., Riley, D., 2014. Introduction to the open source PV LIB for python Photovoltaic system modelling package. In: 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), pp. 0170–0174. https://doi.org/10.1109/PVSC.2014.6925501.

Armstrong, A., Page, T., Thackeray, S.J., Hernandez, R.R., Jones, I.D., 2020. Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees. Environ. Res. Lett. 15 (11), 114055 https://doi.org/10.1088/1748-9326/abbf7b.

Bontempo Scavo, F., Tina, G.M., Gagliano, A., Nižetić, S., 2021. An assessment study of evaporation rate models on a water basin with floating photovoltaic plants. Int. J. Energy Res. 45 (1), 167–188. https://doi.org/10.1002/er.5170.

Château, P.A., Wunderlich, R.F., Wang, T.W., Lai, H.T., Chen, C.C., Chang, F.J., 2019. Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds. Sci. Total Environ. 687, 654–666. https://doi.org/10.1016/j.scitotenv.2019.05.420.

Dörenkämper, M., Wahed, A., Kumar, A., De Jong, M., Kroon, J., Reindl, T., 2021. The cooling effect of floating PV in two different climate zones: a comparison of field test data from the Netherlands and Singapore. Solar Energy 214, 239–247. https://doi.org/10.1016/j.solener.2020.11.029.

Essak, L., Ghosh, A., 2022. Floating photovoltaics: a review. Clean. Technol. 4 (3), 752–769. https://doi.org/10.3390/cleantechnol4030046.

Exley, G., Armstrong, A., Page, T., Jones, I.D., 2021. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. Solar Energy 219, 24–33. https://doi.org/10.1016/j.solener.2021.01.076.

Fang, W., Huang, Q., Huang, S.Z., Yang, J., Meng, E., Li, Y.Y., 2017. Optimal sizing of utility-scale photovoltaic power generation complementarily operating with hydropower: a case study of the world's largest hydro-photovoltaic plant. Energy Convers. Manage 136, 161–172. https://doi.org/10.1016/j.enconman.2017.01.012.

Gonzalez Sanchez, R., Kougias, I., Moner-Girona, M., Fahl, F., Jäger-Waldau, A., 2021. Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa. Renew. Energy 169, 687–699. https://doi.org/10.1016/j.renene.2021.01.041.

Goswami, A., Sadhu, P., Goswami, U., Sadhu, P.K., 2019. Floating solar power plant for sustainable development: a techno-economic analysis. Environ. Prog. Sustain. Energy 38 (6), e13268. https://doi.org/10.1002/ep.13268.

Huang, R., Li, W., 2024. An evaluation of the hydropower planning alternatives at the upper reaches of Yellow River by considering carbon footprints. Environ. Impact. Assess. Rev. 105, 107446 https://doi.org/10.1016/j.eiar.2024.107446.

International Renewable Energy Agency (IRENA), 2022. Renewable Power Generation Costs in 2021. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021.

Jackson, J., 2012. Earthquake Hazards and Large Dams in Western China. A Probe International Study. https://www.academia.edu/25402400/Earthquake_Hazards_and_Large_Dams_in_Western_China_A_Probe_International_Study_PROBE_INTERNATIONAL_EDITOR_PATRICIA_ADAMS.

Kakoulaki, G., Gonzalez Sanchez, R., Gracia Amillo, A., Szabo, S., De Felice, M., Farinosi, F., De Felice, L., Bisselink, B., Seliger, R., Kougias, I., Jaeger-Waldau, A., 2023. Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe. Renew. Sustain. Energy Rev. 171, 112989 https://doi.org/10.1016/j.rser.2022.112989.

Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., Cox, S., 2020. Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renew. Energy 162, 1415–1427. https://doi.org/10.1016/j.renene.2020.08.080.

Li, X.Z., Chen, Z.J., Fan, X.C., Cheng, Z.J., 2018. Hydropower development situation and prospects in China. Renew. Sustain. Energy Rev. 82, 232–239. https://doi.org/10.1016/j.rser.2017.08.090.

Mamatha, G., Kulkarni, P.S., 2022. Assessment of floating solar photovoltaic potential in India's existing hydropower reservoirs. Energy Sustain. Dev. 69, 64–76. https://doi.org/10.1016/j.esd.2022.05.011.

Martín-Chivelet, N., 2016. Photovoltaic potential and land-use estimation methodology. Energy 94, 233–242. https://doi.org/10.1016/j.energy.2015.10.108.

Micheli, L., 2021. Energy and economic assessment of floating photovoltaics in Spanish reservoirs: cost competitiveness and the role of temperature. Solar Energy 227, 625–634. https://doi.org/10.1016/j.solener.2021.08.058.

Ming, B., Liu, P., Guo, S.L., Zhang, X.Q., Feng, M.Y., Wang, X.X., 2017. Optimizing utility-scale photovoltaic power generation for integration into a hydropower reservoir by incorporating long- and short-term operational decisions. Appl. Energy 204, 432–445. https://doi.org/10.1016/j.apenergy.2017.07.046.

Muñoz-Sabater, J., 2019. ERA5-land hourly data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.e2161bac.

Naganathini, R., Nagavinothini, R., Balamurugan, P., 2020. Floating Photovoltaic Thin film technology—a review. Intell. Manuf. Energy Sustainability. 169, 329–338. https://doi.org/10.1007/978-981-15-1616-0_32.

NASA/LARC/SD/ASDC, 2017. CERES and GEO-Enhanced TOA, within-atmosphere and surface fluxes, clouds and aerosols 1-Hourly Terra-Aqua Edition4A. NASA Langley Atmospheric Science Data Center DAAC. https://doi.org/10.5067/TERRA+AQUA/CERES/SYN1DEG-1HOUR_L3.004A.

Nguyen, N.-H., Le, B.-C., Bui, T.-T., 2023. Benefit analysis of grid-connected floating photovoltaic system on the hydropower reservoir. Appl. Sci. 13 (5), 2948. https://doi.org/10.3390/app13052948.

Omran, W.A., Kazerani, M., Salama, M.M.A., 2011. Investigation of methods for reduction of power fluctuations generated from large grid-connected photovoltaic systems. IEEE Trans. Energy Convers. 26 (1), 318–327. https://doi.org/10.1109/TEC.2010.2062515.

Ong, S., Campbell, C., Denholm, P., Margolis, R., Heath, G., 2013. Land use requirements for solar power plants in the United States. United States. https://doi.org/10.2172/1086349.

Ouyang, W., Hao, F., Song, K., Zhang, X., 2011. Cascade dam-induced hydrological disturbance and environmental impact in the Upper Stream of the Yellow River. Water Resour. Manage. 25, 913–927. https://doi.org/10.1007/s11269-010-9733-6.

Perez, M., Perez, R., Ferguson, C.R., Schlemmer, J., 2018. Deploying effectively dispatchable PV on reservoirs: comparing floating PV to other renewable technologies. Solar Energy 174, 837–847. https://doi.org/10.1016/j.solener.2018.08.088.

Pimentel Da Silva, G.D., Branco, D.A.C., 2018. Is floating photovoltaic better than conventional photovoltaic? Assessing Environmental Impacts. Impact Assess. Project Apprais. 36 (5), 390–400. https://doi.org/10.1080/14615517.2018.1477498.

Ran, L.S., Lu, X.X., Xin, Z.B., Yang, X.K., 2013. Cumulative sediment trapping by reservoirs in large river basins: a case study of the Yellow River basin. Glob. Planet Change 100, 308–319. https://doi.org/10.1016/j.gloplacha.2012.11.001.

Redón Santafé, M., Torregrosa Soler, J.B., Sánchez Romero, F.J., Ferrer Gisbert, P.S., Ferrán Gozálvez, J.J., Ferrer Gisbert, C.M., 2014. Theoretical and experimental analysis of a floating photovoltaic cover for water irrigation reservoirs. Energy 67, 246–255. https://doi.org/10.1016/j.energy.2014.01.083.

Schmitt, R.J.P., Kittner, N., Kondolf, G.M., Kammen, D.M., 2019. Deploy diverse renewables to save tropical rivers. Nature 569 (7756), 330–332. https://doi.org/10.1038/d41586-019-01498-8.

Siala, K., Chowdhury, A.K., Dang, T.D., Galelli, S., 2021. Solar energy and regional coordination as a feasible alternative to large hydropower in southeast Asia. Nat. Commun. 12 (1), 4159. https://doi.org/10.1038/s41467-021-24437-6.

Silvério, N.M., Barros, R.M., Tiago Filho, G.L., Redón-Santafé, M., Santos, I.F.S.D., Valério, V.E.D.M., 2018. Use of floating PV plants for coordinated operation with hydropower plants: case study of the hydroelectric plants of the São Francisco River basin. Energy Convers. Manage 171, 339–349. https://doi.org/10.1016/j.enconman.2018.05.095.

Tang, Y.M., Cao, T.L., Li, H.R., Cai, C.X., 2013. Study on cascade development layout for Yellow River main stream upstream of Longyangxia. People's Yellow River 35 (10), 17–19. https://kns.cnki.net/kcms/detail/41.1128.TV.20131010.1049.201310.17_023.html.

Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., Stiassny, M.L.J., Silvano, R.A.M., Fitzgerald, D.B., Pelicice, F.M., Agostinho, A.A., Gomes, L.C., Albert, J.S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J.P., Arantes, C.C., Sousa, L.M., Koning, A.A., Hoeinghaus, D.J., Sabaj, M., Lundberg, J.G., Armbruster, J., Thieme, M.L., Petry, P., Zuanon, J., Vilara, G.T., Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C.S., Akama, A., Soesbergen, A.V., Sáenz, L., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science (1979) 351 (6269), 128–129. https://doi.org/10.1126/science.aac7082.

Xie, J.Y., Tang, W.J., Yang, Y.H., 2018. Fish assemblage changes over half a century in the Yellow River. China. Ecol. Evol. 8 (8), 4173–4182. https://doi.org/10.1002/ece3.3890.

Yi, Y.J., Gao, Y.N., Zhang, S.H., 2022. The impact of dams on the river connectivity of the two largest river basins in China. River Res. Apps 38 (2), 185–193. https://doi.org/10.1002/rra.3892.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. Aquat. Sci. 77, 161–170. https://doi.org/10.1007/s00027-014-0377-0.

Zhang, Q., Zhang, Z.J., Shi, P.J., Singh, V.P., Gu, X.H., 2018. Evaluation of ecological instream flow considering hydrological alterations in the Yellow River basin, China. Glob. Planetary Change 160, 61–74. https://doi.org/10.1016/j.gloplacha.2017.11.012.