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Energy production and water savings from floating solar photovoltaics on global reservoirs

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Growing global energy use and the adoption of sustainability goals to limit carbon emissions from fossil fuel burning are increasing the demand for clean energy, including solar. Floating photovoltaic (FPV) systems on reservoirs are advantageous over traditional ground-mounted solar systems in terms of land conservation, efficiency improvement and water loss reduction. Here, based on multiple reservoir databases and a realistic climate-driven photovoltaic system simulation, we estimate the practical potential electricity generation for FPV systems with a 30% coverage on 114,555 global reservoirs is 9,434 ± 29 TWh yr^{-1}. Considering the proximity of most reservoirs to population centres and the potential to develop dedicated local power systems, we find that 6,256 communities and/or cities in 124 countries, including 154 metropolises, could be self-sufficient with local FPV plants. Also beneficial to FPV worldwide is that the reduced annual evaporation could conserve 106 ± 1 km^3 of water. Our analysis points to the huge potential of FPV systems on reservoirs, but additional studies are needed to assess the potential long-term consequences of large systems.

A global commitment to curb anthropogenic global warming necessitates the development of renewable energy sources to reduce the reliance on fossil fuels for generating electricity[1]. Solar or photovoltaic (PV) power is gaining renewable energy market share because it is economical, quick to install in a wide range of environments and is especially appropriate for smart energy networks[2]. Drawbacks to solar energy expansion are that traditional ground-based PV systems require large land areas for installation, demand routine cleaning with substantial volumes of water to maintain high energy conversion efficiency and suffer from heat-related voltage losses when installed in warm climates[3,4]. The lack of large tracts of available land in many densely populated areas for constructing large solar arrays capable of providing electricity to existing nearby grids limits PV application[5]. Key advantages of floating photovoltaic (FPV) systems installed on existing reservoirs are that they preserve land for other uses, and most reservoirs tend to be located in proximity to existing grid systems[6]. Furthermore, the cooling effect of water in some installations enhances energy conversion efficiencies and FPV panels/floats reduce reservoir water losses from evaporation by blocking radiative energy and lowering water temperatures[7]. The global installed FPV capacity reached 1.3 GWp at end of 2018; this capacity is expected to accelerate as the technologies mature and reach 4.8 GW by the year 2026 (refs. [8,9]).

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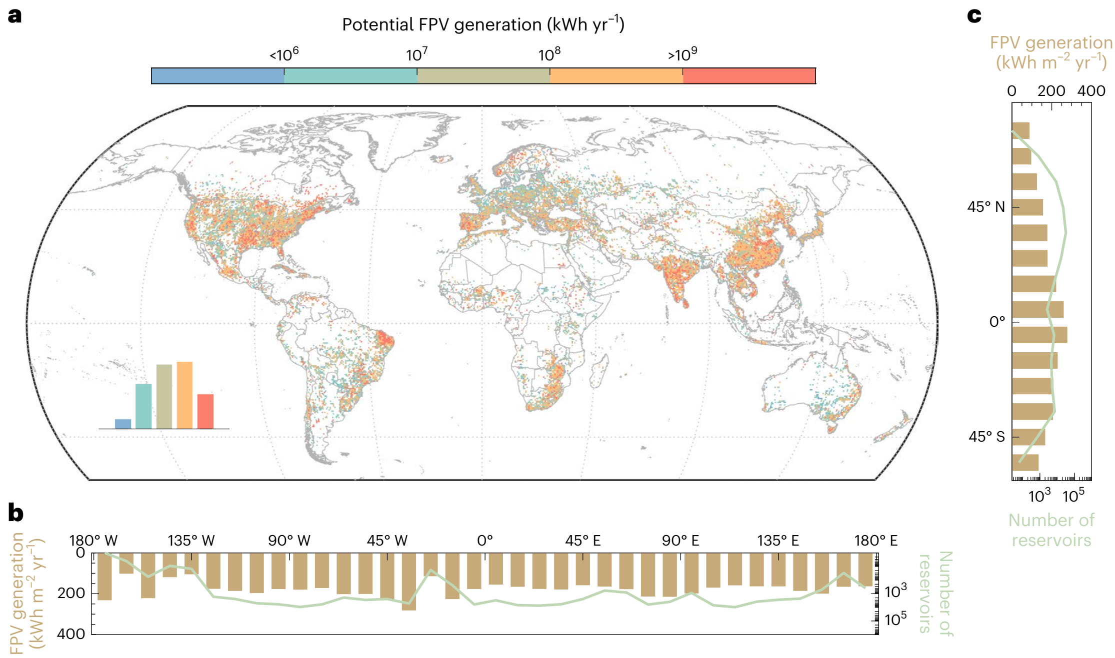

Fig. 1 | Global potential for annual FPV generation. a, Spatial distribution of global potential for average annual FPV generation from 2001 to 2020 across a 0.5° × 0.5° grid, assuming 30% coverage on reservoir surfaces (not exceeding 30 km^2). White areas indicate no reservoirs are present; the bar chart inserted shows the proportion of grids in each interval of potential FPV generation. **b**,**c**, The distribution of the potential for FPV generation per unit area (brown bars) and the numbers of reservoirs (green lines) are shown across both longitude (**b**) and latitude (**c**).

The utility of this technology is demonstrated by the installation of several large FPV systems exceeding 40 MWp in various countries, for example, Brazil, China, India, Indonesia, Singapore, South Korea, Thailand and Vietnam[6,8]. As large-scale renewable energy application is still in its infancy in most of the world[10], accurate estimates of the global practical potential of FPV are needed to frame discussions on its potential role within diversified energy portfolios as countries strive to decarbonize.

One such analysis estimated the global FPV generation potential on more than 6,000 large reservoirs with a 10% area coverage is 5,211 TWh yr^{-1} (ref. [8]). Based on conservative assumptions, the report excludes thousands of small-to-medium reservoirs where viable dedicated systems can potentially be built in the future; and the analysis does not constrain the area of FPV systems to match current technology standards/limits and environmental concerns. For example, the database employed includes only about 6% of the reservoirs worldwide that are candidate locations for FPV development (see below). Several other assessments have been made to assess FPV electricity generation potential and/or water savings for specific regions and countries, including Africa[11], Australia[12], Bangladesh[13], Brazil[14], Iran[15], India[16], Indonesia[17], Malaysia[18], Philippines[19], Thailand[20], the United Kingdom[21] and the United States[22]. One study estimated that a total FPV coverage of less than 1% of the total reservoir area could increase the output of existing hydroelectric plants in Africa by 58%, boosting annual electricity generation by 46 TWh and reducing water loss by 743 million m^3 yr^{-1} (ref. [11]). Another study identified that the global potential for FPV on 2,461 reservoirs with hydropower from the Global Reservoir and Dam (GRanD) database ranges from 4,251 to 10,616 TWh annually for a range of coverage scenarios[23]. These focused studies have demonstrated the applicability of FPV systems to address both energy security and freshwater conservation near areas of high electricity demand, particularly for those located in dry areas of the world[24]. Lacking, however, is a comprehensive assessment of the global potential for generation and water savings of FPV on reservoirs.

Here, we take advantage of recent advances in the compilation of data on existing reservoirs worldwide and a reliable climate-driven PV system performance model to assess with fine precision the potential for FPV on a global scale under realistic climate conditions, both as a source of electricity and as a means of conserving water (Supplementary Fig. 1). In particular, we estimate the electricity generation potential of a 30% coverage for FPV systems built on 114,555 reservoirs worldwide with a total area of 556,111 km^2. Only reservoirs larger than 0.01 km^2 are identified as potential sites for FPV development because small reservoirs are susceptible to desiccation[25]. We gleaned information on water bodies from three global reservoir databases (GRanD, the Georeferenced Global Dam and Reservoir (GeoDAR) database and OpenStreetMap (OSM); Supplementary Fig. 2). Included are 2,461 reservoirs with hydraulic power generation and grid infrastructure already in place (GRanD; Supplementary Fig. 3). Further, taking potential technical and environmental constraints into account, we limit the size of any system to ≤30 km^2 in the initial analysis, but then explore how variable areas and coverages affect the electricity generation potential (the rationale of our criteria is explained in the Methods).

Unlike previous studies that use empirical formulas to estimate the FPV electricity generation potential[11,23], we use a technically rigorous PV system performance model (PV_LIB, Sandia National Laboratories) that considers climate conditions and the specifications of the particular PV module and inverter used[26]. Solar radiation, temperature and wind speed are obtained from the Synoptic 1 degree (SYN1deg) data and ECMWF Reanalysis version 5 - Land (ERA5-Land) data from 2001 to 2020. Because many of the reservoirs are managed by local government entities and in proximity to population centres, we also calculate the FPV potential of dedicated systems that could be built in thousands of cities (that is, second-level administrative divisions such as municipalities, counties and districts) worldwide and compare with local electricity demand. In addition, we estimate the water savings provided by FPV panels on reservoirs through reductions in evaporation based on the Penman equation[7]. Currently, a variety of FPV floating structures have been explored and tested (for example,

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Table 1 | Top 20 countries with annual FPV generation potential at 30% reservoir coverage (not exceeding 30 km^2)

Country	Number of reservoirs[a]	Area of reservoirs (km^2)	Area of FPV (km^2)	FPV generation (TWh yr^{-1})	FPV generation per unit area (kWh m^{-2} yr^{-1})
United States	25,902	64,145	11,164	1,911±18	177±2
China	15,616	29,213	6,967	1,107±17	154±3
Brazil	10,064	35,672	3,735	865±8	252±2
India	7,923	17,107	3,601	766±11	212±3
Canada	1,254	97,033	3,738	506±6	140±2
Russia	3,753	92,952	1,939	236±3	134±3
Mexico	1,685	5,035	1,057	228±3	223±3
Australia	3,441	5,089	1,054	210±4	202±3
Turkey	957	4,853	931	171±2	179±3
South Africa	4,540	2,785	670	144±2	215±2
Thailand	1,169	3,535	614	134±2	218±3
Spain	2,081	2,468	731	132±2	182±3
Argentina	663	3,896	597	117±2	204±4
Vietnam	570	2,459	556	108±3	199±5
Nigeria	131	2,696	356	93±1	262±3
Iran	480	1,331	399	85±1	209±2
Zimbabwe	1,403	3,928	363	84±1	234±4
Sri Lanka	1,379	1,026	308	80±1	260±3
Sweden	285	9,289	844	80±1	249±3
Venezuela	86	5,307	322	80±1	103±2

Values are mean ± s.d. in the columns for FPV generation and FPV generation per unit area. See Supplementary Table 1 for the ranking of 180 countries. [a]Reservoirs from GRanD, GeoDAR and OSM databases that are appropriate for developing FPV.

suspended systems, flexible modules), which affect water evaporation and the cooling effect on the PV module[27]. In this study, we use a floating structure that completely covers for our baseline analysis[7]. Details of all calculations and assumptions are outlined in the Methods.

Global generation potential for FPV

We estimate that the mean annual electricity generation potential from FPV built on reservoirs globally is 9,434 ± 29 TWh (mean ± standard deviation; the standard deviation largely reflects fluctuations in annual solar energy). If installations are limited to 10% or 20% coverages, the global electricity generation potential reduces to 4,356 ± 13 and 7,113 ± 21 TWh yr^{-1} (Supplementary Fig. 4), respectively. In contrast, if 30% coverages are allowed to occupy areas of 40 or 50 km^2 on very large reservoirs (Supplementary Fig. 5), the annual generation would rise to 10,304 ± 31 and 11,012 ± 33 TWh yr^{-1}, respectively. For any location, the design standards would need to be balanced with electricity demands, grid infrastructures, building/maintenance costs, security, and potential impacts on the environment and social systems.

In general, the power generation potential per unit area varies with latitude (Fig. 1), following the patterns for solar energy potential (Supplementary Fig. 6). It is highest at low latitudes near the Equator, approaching 278 kWh m^{-2} yr^{-1}, and this potential is 78% higher than that in areas near 45° N latitude (156 kWh m^{-2} yr^{-1}; Fig. 1c). Differing from general solar energy potential is that several large non-tropical countries with substantial clustering of reservoirs have high FPV electricity generation potential (Fig. 1c and Table 1). Globally, the highest regional potential tends to be concentrated in parts of the United States, eastern Brazil, Portugal, Spain, northern South Africa, Zimbabwe, India and eastern China (Fig. 1a).

Under the assumption of 30% coverage and not exceeding 30 km^2, the United States, with more than 25,000 reservoirs, has the largest FPV potential (1,911 ± 18 TWh yr^{-1}), which per unit area is 177 ± 2 kWh m^{-2} yr^{-1}; however, this technology has not been popular there to date. China, which leads the world in total FPV installed capacity, ranks second with 1,107 ± 17 TWh of annual electricity generation potential, largely because of fewer reservoirs (15,616). Further, few of the feasible reservoirs in China are in areas of high radiative flux (Supplementary Fig. 6), leading to a lower per-unit-area energy conversion rate (154 ± 3 kWh yr^{-1}). Elsewhere, the >10,000 reservoirs that are situated predominantly at low latitudes in Brazil have a high electricity generation potential per unit area (252 ± 2 kWh yr^{-1}) with the capability of producing 865 ± 8 TWh yr^{-1}. India and Mexico, both with large tropical areas, have electricity generation potential of 766 ± 11 and 228 ± 3 TWh yr^{-1}, respectively. In contrast, Canada and Russia have lower per-area generation capacities, but still have electricity generation potentials of 506 ± 6 and 236 ± 3 TWh yr^{-1}, respectively. Other countries with the potential to generate more than 100 TWh yr^{-1} are spread across the continents (Table 1): Australia, Turkey, South Africa, Thailand, Spain, Argentina and Vietnam.

Forty countries, all considered to be developing, have higher FPV potential than current annual electricity demands (Supplementary Table 1). Brazil, with the largest economy in South America, stands out in that it has a very high electricity demand (538 TWh yr^{-1}) that can be fully met by FPV development (865 ± 8 TWh yr^{-1}). Six countries (Zimbabwe, Lao PDR, Ethiopia, Cameroon, Myanmar and Sudan) with abundant reservoirs (larger than 1,000 km^2) have 3- to 10-fold higher FPV electricity potential than their current demands of 1–19 TWh yr^{-1}. These estimates demonstrating FPV potential align with a larger recognition that solar power is a viable energy source in many developing countries with high solar radiation resources[8]. Nevertheless, achieving this vision will require addressing lingering problems related to policy, planning, financing, regulation, technological support and construction/maintenance[28].

Local supply of FPV generation

One of the benefits of FPV is the tendency of resources to be located in proximity to centres of high electricity consumption. Thus, FPV

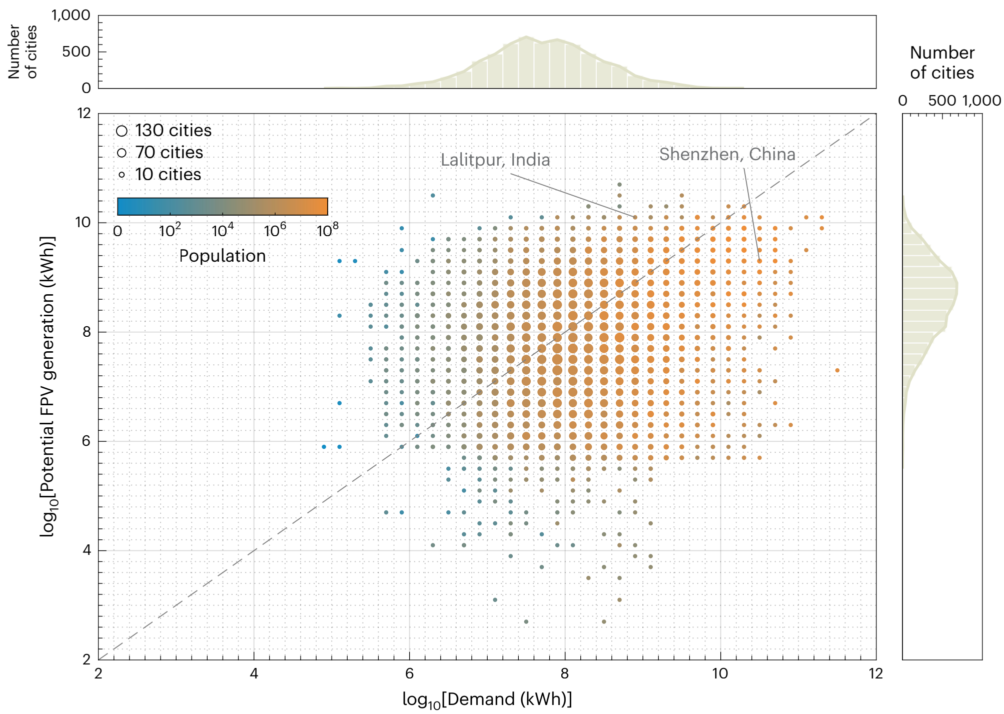

Fig. 2 | Comparison of FPV generation potential and electricity demand in cities with 30% reservoir coverage (not exceeding 30 km²). Cities are categorized into grids at 0.2 $\log_{10}$ kWh intervals based on potential electricity generation versus demand. Circle size and colour represent the number of cities and the total population of all cities in each grid, respectively. The bar chart shows the number of cities where potential FPV generation exceeds demand across different demand values and potential FPV generation values. Supplementary Data provides the FPV generation potential and electricity demand for each city.

would be appropriate for cities/communities with a desire to generate their own electricity through dedicated systems to compete with large power providers and stimulate local economies[29]. Moreover, isolated power systems such as microgrids based on FPV could provide resilient, local and affordable power in remote areas where grid infrastructure is deficient[30]. Worldwide, we find that 6,256 cities in 124 countries could in theory be powered entirely by local, dedicated FPV plants, assuming that adequate energy storage facilities can be developed in tandem (Fig. 2). The electricity generation of these systems (7,106 ± 24 TWh yr^{-1}) far exceeds the current demand of 1,340 TWh yr^{-1}. Most of these cities (71% or 4,424) have a population of fewer than 50,000.

In remote and sparsely populated areas, the central electrical grid is often difficult to expand due to the high costs of construction over long distances and through complex terrains. Rural microgrids based on FPV could be a beneficial solution because they draw energy from nearby sources, independent of regional or national grids[30]. India, where more than a billion people live in rural areas, is facing a serious energy crisis due to surging demand for electricity and the unavailability of coal supplies. Fortunately, there are abundant reservoirs and solar sources in the country, making microgrids powered by FPV promising as an effective solution to improve the sustainability of rural electricity[31]. For example, Lalitpur, which is a somewhat remote district in the Uttar Pradesh state of India, has 12 reservoirs covering 217 km² and could potentially generate 10 TWh yr^{-1} by FPV, an order of magnitude more than local demand (Fig. 2 and Supplementary Fig. 7a).

Of the 1,045 cities with more than 1 million people globally, only about 15% could fully meet their current electricity needs with dedicated FPV systems. Many large and highly developed metropolitan areas lack sufficient reservoirs to meet huge electricity needs. One example of a city with insufficient reservoir area is Shenzhen, a large city with a population of over 13 million in the Guangdong province of China. Shenzhen has 73 reservoirs with a total area of 39 km² that are used for flood prevention, water supply, natural aesthetics and ecological preservation. All the reservoirs are located near areas with high electricity demand and established grid infrastructure (Supplementary Fig. 7b). However, even if FPV is developed at a 30% coverage on all reservoirs, the 1,872 ± 77 GWh yr^{-1} of electricity generated is equivalent to only 5% of the annual demand of the city (Fig. 2). To fill such huge energy needs, the electricity produced by large systems generating more than local demands in other areas can distribute excesses to electricity-hungry metropolitan areas if the grid infrastructure is of sufficient capacity.

Water savings

Regarding water body evaporative losses, we estimate that FPV systems with 30% coverage can reduce evaporation by 46 ± 3% per reservoir. On the assumption that the floats below the FPV modules cover the surface entirely (Fig. 3g), water evaporation under an FPV installation approaches zero, and the evaporation on the surrounding uncovered water surface is also reduced because of the changes to reservoir energy balance variables[7]. A previous study has shown that flexible modules in direct contact with the water can reduce evaporation by about 42%, while suspended systems can reduce evaporation by only 18% for the same coverage[7]. While the type of floating structure we considered saves the most water loss, the cooling effect on PV modules will be negated. The water savings have uncertainties that are related to installation-specific variables such as water depth and system size relative to the water body area. However, with uncertainty in mind, we estimate the evaporation loss reduction worldwide is equivalent to 106 ± 1 km³ yr^{-1}, which is close to that used by 300 million people annually[32]. The global distribution of water conservation per country is similar to that of power generation potential (Fig. 3a). Substantial evaporation losses would be reduced in areas where many reservoirs are concentrated, such as the United States, eastern Brazil, India and eastern China. China and India, the two countries with the most reservoirs in Asia, could reduce surface evaporation by an estimated 14

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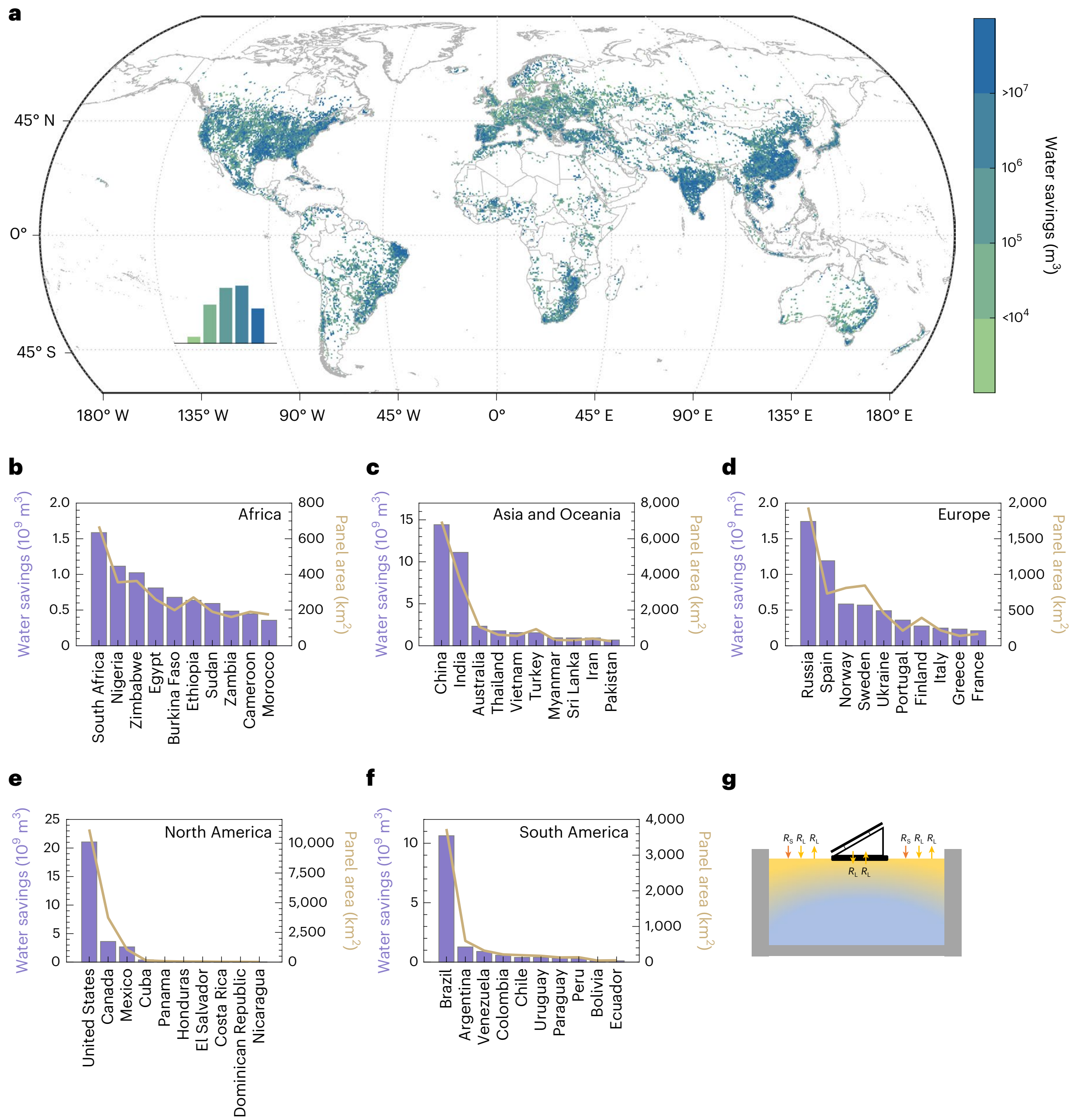

Fig. 3 | Estimated global water savings from FPV development with 30% reservoir coverage (not exceeding 30 km²). **a**, Distribution of average annual water savings from 2001 to 2020 in 0.5° × 0.5° grids; the bar chart inserted shows the proportion of grids in each interval of potential water savings. **b**–**f**, The amount of water savings (purple bars) and the total estimated area of installed FPV panels (brown lines) in the top ten water-saving countries in Africa (**b**), Asia and Oceania (**c**), Europe (**d**), North America (**e**) and South America (**f**). **g**, Schematic diagram of floating solar panel installation and radiation balance. The diagram shows the transmission direction of short-wave radiation (R_S) and long-wave radiation (R_L) as well as the distribution of water temperature.

and 11 km^3 yr^{-1}, respectively, through the installation of FPV on their reservoirs (Fig. 3c and Supplementary Table 2). In the United States, which has the largest number of reservoirs, 21 km^3 yr^{-1} of water could be saved (Fig. 3e and Supplementary Table 2).

By reducing evaporation loss (Supplementary Fig. 8), FPV panels could help alleviate water scarcity in arid and semi-arid areas, particularly in the developing world where food, water and energy security are often critical issues[33]. For example, in South Africa, a total of 670 km^2 of FPV capacity could generate 144 TWh yr^{-1} of electricity (Supplementary Table 1); meanwhile, reservoir water losses could be reduced by 1,586 million m^3 annually (Fig. 3b and Supplementary Table 2). In water-scarce Egypt, a total of 260 km^2 of FPV panels could not only generate 66 TWh yr^{-1} of electricity but also save 810 million m^3 yr^{-1} of water in the desert climate. In Pakistan, studies have proposed combining FPV and hydropower to expand energy output and alleviate recurrent water crises[5]. We find that FPV installed on reservoirs in Pakistan, covering 247 km^2 of areas, could generate 51 TWh and reduce water evaporation by 680 million m^3 annually.

Discussion

As the global energy demand is expected to grow 50% between 2020 and 2050[34], the 9,434 TWh yr^{-1} of electricity that could be generated from FPV systems worldwide would be an important renewable source to help achieve diversification of energy portfolios and improve upon energy security. The potential electricity generation is more than twice that currently generated by hydropower in a year (4,418 TWh in 2020)[35]. To reach net zero emissions by 2050 and limit the rise of global temperature to 1.5 °C, both the International Energy Agency and the International Renewable Energy Agency have aimed to double hydroelectricity generation by 2050 (refs. [36,37]). To achieve that goal, many more dams/reservoirs would need to be built. Problematic is that reservoir construction causes many considerable negative impacts, such as disruption of stream environmental flows, loss of critical aquatic habitat, degradation of water quality, forest loss, emissions of greenhouse gases and population displacement[38]. Looking ahead, augmenting existing hydropower plants with FPV-derived power could be an appropriate approach to increase energy production and avoid a range of environmental impacts. For hydroelectric reservoirs, existing transmission lines would enable the establishment of FPV plants to conveniently mesh with existing electricity networks[23]. Further, the water saved by FPV panels could boost additional hydropower generation[11]. Moreover, the timing could be controlled to balance the fluctuations of solar power production during the daytime and nighttime, as well as hydropower production during rainy and dry seasons[28]. Of the 7,250 reservoirs in the GRanD database, we estimate that the 2,461 designated as hydropower reservoirs could generate an additional 3,992 ± 13 TWh yr^{-1} of electricity by FPV. The complementarity of solar power and hydropower generation could help meet the growing demand for electricity cleanly and enhance energy security[23].

Although there is an additional cost associated with FPV compared with ground-mounted systems, the synergistic benefits are probably more than sufficient to make up the difference. FPV may be more economical over time considering the value of land and the lost revenues of associated activities[11,39]. Further, hybrid FPV systems built on existing hydropower reservoirs have reduced construction and transmission costs compared with the development of new dams and reservoirs. Standalone FPV systems require energy storage to balance the mismatch between electricity demand and generation; however, FPV can be deployed on existing pumped storage reservoirs to avoid energy storage costs[6]. Proper construction planning and water resource management can increase power output while saving water for irrigation and thus increase food production[40]. The gradual reduction in installation costs and the benefits of synergies will further boost the growth of FPV, a boon to developing countries that are facing energy and food shortages[11].

Also, the potential system-specific environmental impacts caused by the installation and operation of FPV need to be balanced versus the gains in renewable electricity[10]. In addition to the benefits of reduced evaporation, the installed FPV could shorten the duration of water stratification that may promote hypoxia in the bottom layer and reduce water quality in some water bodies[41]. Conversely, a high coverage may reduce dissolved oxygen levels, potentially affecting fish production[42]. It may also reduce sunlight to the water, impeding the growth of harmful algae that cause algal blooms[2]. However, the lower water temperature caused by reduced incident solar radiation challenges the adaptive capacity of ecosystems[11]. Furthermore, aquatic ecosystems may be adversely affected due to direct contact between water bodies and floating devices and electromagnetic fields generated by cables[43].

Suitable coverage of FPV systems to minimize the potential realm of negative impacts depends largely on reservoir-specific baseline conditions; however, this type of information is generally lacking[44]. China has recently begun closely regulating the construction of FPV projects because some large-scale projects have affected flood discharge, water supply and ecological processes[45]. Therefore, research to determine the optimal size of an FPV to maximize electricity generation and limit environmental impacts is urgently needed to advance the application of this technology. To assess threats, many projects have used phase-based development approaches that initially monitor the impacts of small test systems over several months to identify critical issues before developing larger projects[44]. Additionally, installing FPV systems on artificial reservoirs, particularly those associated with degraded lands (for example, mines, water treatment plants) is likely to evoke less harm to the environment than installation on natural water bodies or reservoirs with high conservation value[43].

The future performance of PV systems is potentially vulnerable to climate variability. Low radiation, high temperatures or clouds can result in reduced PV power output[46]. Under different greenhouse gas emission scenarios, the most notable changes over the next 20 years are anticipated to occur in autumn in the Indian subcontinent and China, where the solar potential is reduced by 6–10% due to possible increases in cloud cover[47]. In Europe, however, potential increases in clear-sky radiation and reductions of cloud cover will increase PV generation under a fossil-fuel-mitigation pathway (Shared Socioeconomic Pathway 1-2.6)[48]. In a fossil-fuel-dependent pathway (Shared Socioeconomic Pathway 5-8.5), solar power potential would generally be lower, and higher temperatures would exacerbate water evaporation losses. Therefore, the implementation of climate change mitigation policies can be argued to benefit solar power generation and water savings[47,48].

In conclusion, our evaluation of the global FPV power potential, using existing reservoir information, realistic climate data and a PV system performance model, leads to an estimate ranging from 4,300 to 11,000 TWh yr^{-1}, for which a 30% coverage on 114,555 global reservoirs is an estimated 9,434 ± 29 TWh yr^{-1}. However, this potential is unevenly distributed and concentrated in a few large countries or continental regions. Owing to the cost-effectiveness of accessing electricity generated on nearby reservoirs, many cities can potentially build clean, resilient and affordable power to bolster energy resources to reduce reliance on regional and national grids once energy storage system technology improves. Finally, the sparing of land for other municipal uses, and the conservation of water by the reduction of evaporative loss, are additional positive benefits of FPV systems. Several nations in the developing world could potentially utilize FPV systems to improve water and energy security as a part of achieving sustainable development goals.

Methods

Data, calculation methods and limitations of FPV generation potential, electricity demands of cities and water savings are summarized below.

Reservoir data

To improve on prior estimates of FPV generation potential globally, we combined three global reservoir databases (GRanD[49], GeoDAR[50] and OSM[51]). These three databases contain spatial polygons for 7,250, 19,548 and 108,332 reservoirs larger than 0.01 km^2, respectively. GRanD includes detailed reservoir attributes for 2,481 hydroelectric power and 118 natural reservoirs. Compared with GRanD, GeoDAR largely increases the quantity of small-to-medium dams and reservoirs based on existing global dam inventories. Reservoirs in OSM are derived from OpenStreetMap and include a large number of small reservoirs. On average, the same reservoirs are 12% larger in the OSM than GRanD and GeoDAR, which may be caused by the demarcation of reservoir jurisdiction and/or seasonal changes in water levels. We combined these three databases and take the maximum boundary for the reservoirs existing in multiple databases. This combined product represents the most complete reservoir database available, yet it almost certainly does not include all reservoirs worldwide, representing an area where future estimates can be improved.

Meteorological data

Solar radiation is the main meteorological factor affecting solar PV generation, with temperature and wind speed playing secondary roles. Solar radiation data are based on SYN1deg, which is a three-level remote sensing product from the Clouds and the Earth's Radiant Energy System (CERES) project that contains hourly mean shortwave down flux in 1° × 1° global grids[52]. Temperature and wind speed are provided by ERA5-land hourly data in 0.1° × 0.1° global grids, which are the climate reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF)[53]. All meteorological data are from 2001 to 2020.

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FPV generation

We used a flexible toolbox named PV_LIB developed by Sandia National Laboratories to calculate the PV generation[26]. 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. We assume the installation of the Panasonic VBHN235SA06B module and the TB8000SHU (240 V) inverter for all simulated systems, regardless of geography. With the improvement of engineering technology, newer and more efficient modules and inverters will greatly increase the generation potential of FPV in the future. Solar panels in the Northern Hemisphere face south; those in the Southern Hemisphere face north. The tilt angle is equal to latitude but does not exceed 20° to maximize incoming solar radiation and reduce the risk of wind and waves damaging the array[54,55]. The distance between two rows is 20% larger than the height of the modules from the floats to avoid the negative effect of shading adjacent panels[56]. The positive effect of cooling by evaporation under the modules is not taken into account because the floating structure that completely covers the water will block evaporation.

We use the threshold of 30% coverage in recognition of the need to limit negative impacts on local ecosystems and water body processes/uses[57]. The coverage area of any one system is limited to 30 km^2, which is the area of the current maximum footprint of FPV technology at the Saemangeum site in the Yellow Sea off Korea[58]. This restriction also, in part, accounts for the situation that many reservoirs built in sloping terrain have irregular shapes that present installation/design challenges for large coverages. We calculated the FPV potential of each reservoir from the combined database by assuming that the panels are located in the middle of the reservoir and cover 30% of the surface (but not exceeding 30 km^2). This positioning is chosen to simplify the calculation; usually, FPV systems are situated to allow easy access from at least one particular shore and have shapes that are dictated by the shape of the water body.

Electricity demands of cities

The electricity demands of 145 countries in 2018 are provided by the International Energy Agency[59]. To assess the contribution of FPV on electricity demand on a city scale, we allocated each country's electricity demand to each city in proportion to gross domestic product (GDP). Municipal electricity demand is determined by the relationship between national electricity demand and GDP[60]. The Global Administrative Areas (GADM) spatial database contains the location of the worldwide administrative boundaries[61]. We consider the second-level divisions (city, county, district, municipality and so on) in each country as the administrative unit. The GDP of countries and cities is estimated based on LandScan, a global population distribution dataset for 2019[62], and gridded global datasets for GDP per capita in 2015 from the Dryad dataset[63]. Although there is no consistent time frame for these data, they are acceptable for a rough estimate of city-scale electricity demand (Supplementary Fig. 9). If a reservoir is distributed among multiple cities, the power generation on the reservoir is allocated to each city according to the proportion of the reservoir area in it.

Water savings

The assessment of water savings from the reduction in evaporation from reservoir surfaces is based on regional hydrology simulations, using available climate data. Monthly vapour pressure and air temperature (maximum, minimum, mean) in 0.5° × 0.5° global grids from 2001 to 2020 are obtained from the Climate Research Unit (CRU)[64]. The monthly wind speed and solar radiation data are from the ERA5-Land and SYN1deg, respectively[52,53]. We use the Penman equation to estimate potential evaporation (E_{pen}; mm d^{-1}) on reservoirs as[65]:

$$E_{pen} = \frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta+\gamma}\frac{6.43(1+0.536u)D}{\lambda} \quad (1)$$

where Δ is the slope of saturation vapour pressure curve (kPa °C^{-1}), γ is the psychometric constant (kPa °C^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), u is the wind speed at 2 m height, D is the saturation vapour pressure deficit (kPa) and R_n (MJ m^{-2} d^{-1}) is the net radiation. R_{ns}, the sum of the net shortwave radiation, and R_{nl}, the net longwave radiation, are computed as[66,67]:

$$R_{ns} = (1-\alpha)R_s \quad (2)$$

$$R_{nl} = -f(0.34 - 0.14\sqrt{e_a})\sigma(T+273.2)^4 \quad (3)$$

where α is the reflection coefficient or albedo, R_s is the solar radiation (MJ m^{-2} d^{-1}), e_a is the actual vapour pressure (kPa), σ is the Stefan–Boltzman constant = 4.903×10^{-9} (MJ m^{-2} K^{-4} d^{-1}), T is the mean air temperature (°C) and f is the cloudiness factor, calculated as[66,67]:

$$f = 0.9\frac{n}{N} + 0.1 \quad (4)$$

where n/N is the relative sunshine duration, n is the actual duration of sunshine (hours) and N is the maximum possible duration of sunshine or daylight hours (hours).

As we assume that the floating systems entirely cover the surface below the solar panels (Fig. 3g), the net contribution of the shortwave radiation is considered zero, and the net contribution of the longwave radiation is modified assuming the relative sunshine duration n/N is zero[7].

Owing to the lack of data on sunshine duration, we estimate the cloudiness factor on the free water surface as done by others[66,67]:

$$f = 1.35\frac{R_s}{R_{so}} - 0.35 \quad (5)$$

where R_{so} is the clear-sky solar radiation (MJ m^{-2} d^{-1}).

The net radiation R_n^* of the entire reservoir is contributed by the net radiation of both the FPV installed area ($R_{n,cover}$) and the uncovered water surface ($R_{n,free}$), which are computed as[7]:

$$R_n^* = R_{n,free}(1-x) + R_{n,cover}(x) \quad (6)$$

where x is the fraction of the reservoir surface covered by FPV panels (for example, 30% in our baseline analyses).

Assuming that the floats under FPV panels entirely cover the surface below the module, the evaporation from the installed area approaches zero. Evaporation from the uncovered water surface is calculated by substituting R_n^* into equation (1). Combined with the area of the reservoir, we estimate the difference in water evaporation before and after installing FPV systems.

Limitations

We realize that there are still some limitations in our analysis. The completeness of reservoir databases may vary from country to country due to differences in information collection and sharing. Regarding the FPV generation potential, it may be underestimated due to the lack of state-of-the-art equipment currently available on the market in the module database of the PV_LIB model. The FPV structure we considered will reduce evaporation loss most, but it will not increase the efficiency of FPV generation via a cooling effect. If the FPV module is anchored to a tubular buoyancy system, the efficiency of FPV will increase by 5–11% with the decreased water-saving capacity[68]. Although our FPV structure almost eliminates the interference of water evaporation on the PV module performance, the humid environment and convective heat transfer may still increase the uncertainty of power generation simulation[69]. When estimating municipal electricity demand, the method of using GDP to allocate the demand of the whole country is based on the assumption of equivalent energy use per unit of GDP (for example, rural versus urban), but we recognize the associated uncertainty as this relationship varies geographically in space and time[70].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The solar radiation data are available at https://ceres.larc.nasa.gov/data/#syn1deg-level-3; the temperature and wind speed data are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview; the GRanD database is available at https://sedac.ciesin.columbia.edu/data/collection/grand-v1; the GeoDAR data are available at https://doi.org/10.5281/zenodo.6163413; the latest global reservoir database from OSM can be extracted from https://www.openstreetmap.org/; the electricity demand data for countries are available at https://www.iea.org/reports/global-energy-review-2021; the GADM data are available at https://gadm.org/index.html; the global population distribution data from LandScan are available at https://landscan.ornl.gov/; the gridded global datasets for GDP are available at https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0; and the CRU data are available at https://crudata.uea.ac.uk/cru/data/hrg/. The data that support the findings of this study are also available from the corresponding author upon request.

Code availability

The scripts used to generate all the results are written in MATLAB (R2022a). All data and code are available at https://www.zhenzhong-zeng.com/resources/.

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Author contributions

Conceptualization, funding acquisition, project administration and supervision was carried out by Z.Z. Methodology was carried out by Y.J., Z.Z., S.H. and R.X. Investigation was carried out by Y.J. and S.H. Visualization was carried out by Y.J. Y.J. and A.D.Z. wrote the original draft. All authors contributed to interpreting results, and writing and editing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Study description	Based on multiple reservoir databases and a realistic climate-driven PV system performance simulation, we estimate the practical potential electricity generation and water savings for FPV systems on global reservoirs.
Research sample	N.A.
Sampling strategy	N.A.
Data collection	N.A.
Timing and spatial scale	The data were between 2001-2020 at hourly interval and on a global scale.
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