



Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential

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ABSTRACT

Floating solar photovoltaics (FPV) is an emerging, and increasingly viable, application of photovoltaics (PV) in which systems are sited directly on waterbodies. Despite growing market interest, FPV system deployment is nascent, and potential adopters remain concerned about the technology, the benefits it offers, the advantages to pairing it in hybrid systems (such as with hydropower), and how to analyze technical potential. To support decision making, we provide a review of associated benefits of hybrid FPV-hydropower system operation and a novel, geospatial approach to assess the global technical potential of these systems employing publicly available, global datasets. We identify significant potential globally for FPV hybridized with hydropower ranging from 3.0 TW to 7.6 TW (4,251 TWh to 10,616 TWh annual generation), based on the assumptions made. We detail operational benefits that these hybrid systems may provide that could be quantified in future modeling and/or analyses of existing or planned hybrid systems.

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1. Introduction

Technological advances and falling capital costs for solar photovoltaics (PV) have considerably improved the competitiveness of solar power [1,2]. Countries around the globe are exploring ways to complement existing power generation mixes with low-cost PV to ensure reliable, affordable, and sustainable future power supplies [3]. Floating solar PV (FPV) is an emerging, and increasingly viable, application of PV in which systems are sited directly on waterbodies such as lakes, ponds, or reservoirs. Interest in FPV has grown due to competing land-use pressures, climate goals, energy security and resilience motivations, and additional benefits associated with this emerging application [4–6]. Deployment of FPV is accelerating with global installed capacity up from below 1 MW in 2007 to

1,314 MW in 2018 and is expected to reach approximately 13,000 MW by 2022 [5,7]. The majority of existing capacity and projected FPV market growth is located in Asia—driven by high land costs, constraints to land availability, and a large prevalence of hydropower generation paired with reservoirs [8]. Despite growing commercial viability and market interest in FPV, it is a nascent application and potential adopters remain concerned about the technology, the benefits it offers, the advantages to pairing it in hybrid systems (i.e., with hydropower), and how to analyze technical potential.

The claimed co-benefits (beyond primary benefit of electricity generation) for FPV are abundant and include avoided land-energy conflicts, lower land acquisition costs and site preparation costs, increased PV efficiency due to temperature regulating effect of water, reduced algae growth, reduced evaporation, reduced shading effects on modules, and reduced capital costs when co-located with hydropower, among others [9–17]. Despite these claims, a gap remains in consolidated evidence to corroborate these co-benefits. This gap in evidence prevents potential adopters from determining and quantifying the actual co-benefits derived from FPV—potentially hindering investment.

Previous studies estimate the global potential of FPV at 400 to 1,000 GW and the global potential of FPV paired with hydropower

Abbreviations: FPV, floating solar photovoltaics; PV, photovoltaics; U.S., United States; SERIS, Solar Energy Research Institute of Singapore; ESMAP, Energy Sector Management Assistance Program; IRENA, International Renewable Energy Agency; hybrid system, hybrid floating solar photovoltaics-hydropower system; NREL, National Renewable Energy Laboratory; GRandD, Global Reservoir and Dam Database; DOE, U.S. Department of Energy.

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at 4,400 to 5,700 GW [5,18].

But a knowledge gap remains on the benefits that FPV may provide in hybrid systems and the actual potential within hybrid systems to drive data-driven decision making. This work contributes a systematic review of associated benefits and an assessment of global technical potential for hybrid FPV-hydropower systems. Specifically, we address two research questions:

1. What are the benefits that hybrid FPV-hydropower system operations could offer?
2. What is the global technical potential for FPV in hybrid FPV-hydropower systems?

The objectives of this work are to review the potential benefits associated with hybrid FPV-hydropower systems and estimate the global technical potential of hybrid FPV-hydropower systems using global, publicly available datasets. We present a systematic review of the evidence for the claimed benefits of FPV systems in Section 2. Section 3 details a novel geospatial approach to assess the global technical potential for FPV in hybrid FPV-hydropower systems using publicly available global data sets. The results from this global hybrid system assessment are presented in Section 4. Section 5 discusses the results of this work in comparison to other related FPV assessments and actual deployment constraints and challenges. Section 6 concludes with key outcomes of this work, potential applications to support decisions, and future research areas.

2. Overview of floating solar PV systems

Interest in the benefits of hybrid systems—including PV and FPV combined with hydropower—has increased in recent years, with many countries exploring projects [7,19]. Research has examined the potential of combining terrestrial PV with hydropower—finding that hybrid systems have the potential to reduce PV power production variability [20]. Feng et al. (2016) and the World Bank et al. (2019) explored the complementary nature of land-based solar PV coupled with hydropower and identified potential benefits that include exploiting the complementary nature of solar and hydro resources to provide firm, dispatchable power output, and PV curtailment reduction. This is in addition to reduced transmission interconnection costs where PV is co-sited with existing hydropower [5,21]. Less clarity exists on the operational benefits of these hybrid systems, and additional research is necessary as grid-connected hybrid FPV-hydropower systems are still a nascent application. A 220-kW (PV capacity) hybrid system deployed on a pumped storage hydropower reservoir in Portugal is one of the first, and only examples [22].

Beyond the potential benefits, questions remain about the actual global potential for FPV systems. Recent studies have estimated the technical potential (or feasible potential given FPV system performance and topographic and land-use constraints) for FPV system deployment at different scales. The World Bank et al. (2019) estimated that global potential of FPV may range from 400 to 1,000 GW [5]. Additional work from Farfan and Breyer (2018) estimated the global potential for FPV paired with hydropower installations to range from 4,400 to 5,700 GW (6,270 to 8,039 TWh per year of generation) for installation on hydropower purposed reservoirs and all-purpose reservoirs, respectively. These estimates increase as the percent area covered by FPV assumed on the reservoirs increases [18]. At the national level, Spencer et al. (2018) proposed and applied a geospatial assessment approach to estimated FPV potential on artificial waterbodies in the continental United States. This approach demonstrated FPV's potential to contribute 2.1 TW (786 TWh per year of generation at 27% coverage) on 21,961 km² of suitable waterbodies [14]. Kim et al. (2016) investigated FPV

potential on reservoirs at the national level in Korea and estimated the capacity at 2,103 to 21,093 GW (2.9–29.4 TWh per year of generation) for 10%–100% reservoir area coverage, respectively [23]. Liber et al. (2020) applied a geospatial approach, at a finer spatial resolution, to estimate FPV potential at the U.S. state level in Colorado, identifying 11 GW of potential capacity (16.9 TWh per year of generation) on approximately 416 km² of suitable waterbodies [24]. These estimates of FPV potential provide insight into the ability for FPV to augment global renewable generation, and possibility to realize potential co-benefits of these systems at scale.

We differentiate between stand-alone FPV and hybrid FPV-hydropower systems for this assessment and describe each of these systems in the following sections.

2.1. Stand-alone FPV systems

Stand-alone FPV systems are FPV systems that are operated independently and not connected or operated in hybridization with other generators. Fig. 1 shows an example configuration and the key components of a stand-alone, large-scale FPV system connected at the transmission level. To date, stand-alone FPV systems have predominantly been installed on artificial water bodies (i.e., treated wastewater ponds, reservoirs, and agricultural irrigation or retention ponds), as this avoids potential environmental impacts or siting complications for deployment on natural water bodies. The PV modules are generally the same as those deployed in land-based systems; however, FPV systems are mounted on floating platforms constructed with plastic and stainless (or galvanized) steel, instead of fixed racks utilized for land-based systems. A series of these modular platforms is then connected together with designated pathways allowing access for operation and maintenance. The platforms are connected to mooring lines that are anchored to the shore, bottom of the water body, or floating anchors. The system is connected to the main electrical equipment that generally resides onshore and the grid through underwater cables [4,5,25–32]. FPV installations of larger capacities may have to be separated into sub-PV arrays to allow for transmission of larger amounts of energy to the substation [33].

2.2. Hybrid FPV-Hydropower systems

FPV systems used in hybrid systems are identical to the stand-alone systems; however, they are coupled with other generation. Murphy et al. (2020) define hybrid systems as those in which net economic benefits are anticipated from the coupling of multiple generation technologies, relative to the cost and/or value associated with comparable independent, stand-alone technologies [34]. Murphy et al. (2020) propose three possible hybridization configurations, each offering different cost and performance added values:

1. *Co-location hybrid systems* (cost improvements): two or more technologies sited together to achieve cost savings, but operations are separately optimized.
2. *Virtual hybrid systems* (performance improvements): two or more technologies are sited separately, with operations linked through bilateral agreements and some co-optimized operation.
3. *Full hybrid systems* (cost and performance improvements): both cost and performance improvements are achieved through co-optimized planning and operation. These often consist of at least one dispatchable technology paired with one or more variable renewable energy technology, which, when paired, offer operational benefits.

Alternatively, the World Bank (2019) proposes three different

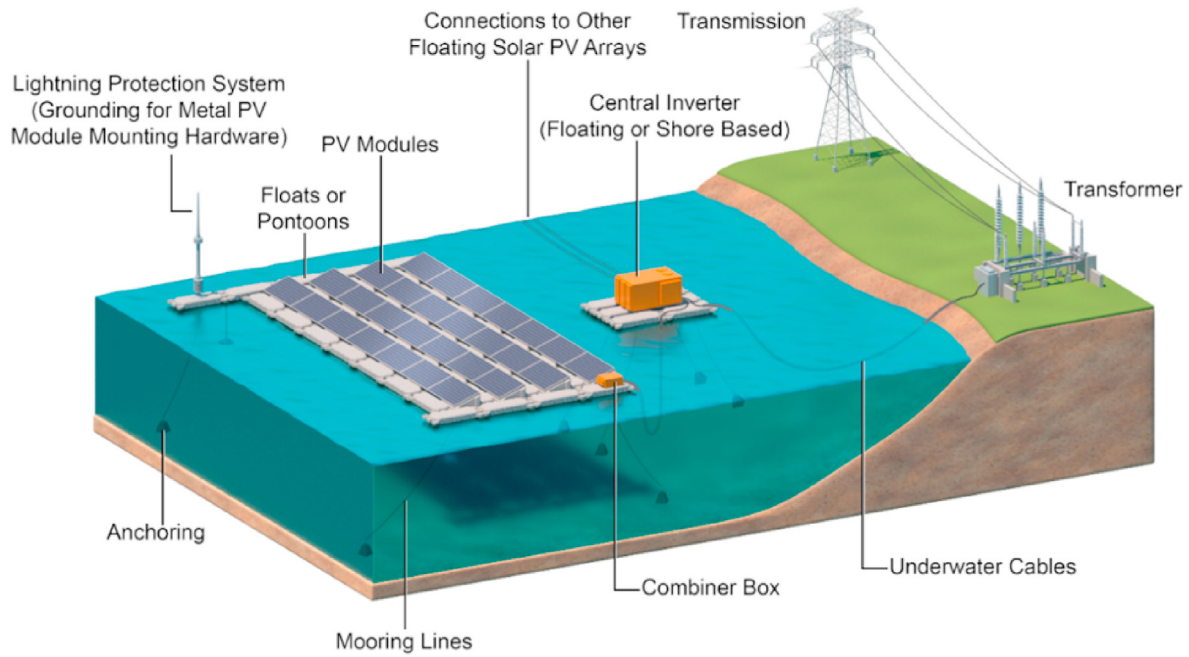


Fig. 1. Schematic of a typical stand-alone large-scale FPV system and key components.

hybridization levels for PV and reservoir-based hydropower differentiated by the peak PV power relative to the hydropower capacity. The highest level includes solar peak power greater than the capacity of hydropower and includes a pumped storage plant beyond the reservoir-based hydropower where the FPV is sited [35].

In this work, we consider full hybrid FPV-hydropower systems with FPV and hydropower coupled at a common substation—allowing for their operations to be co-optimized and dispatched in concert, as depicted in Fig. 2. Hydropower refers specifically to reservoir-based impoundment and pumped storage systems. These reservoir-based systems are often highly-controllable—allowing for the complementary operational benefits discussed in this work. We exclude diversion (run-of-river) hydropower systems for this work as the lack of reservoir area and the

presence of water currents may be problematic for FPV deployment [36].

2.3. Value added from hybrid FPV-Hydropower system operation

The operation of hybrid FPV-hydropower systems may offer additional value beyond the co-benefits of stand-alone FPV systems (see Section 1). We detail the additional operational values that these hybrid systems may add in the following sections, as well as the challenges these systems may present.

2.3.1. Improved system operation at different time scales

Hybrid FPV-hydropower systems can take advantage of the complementary nature of solar PV and hydropower generation

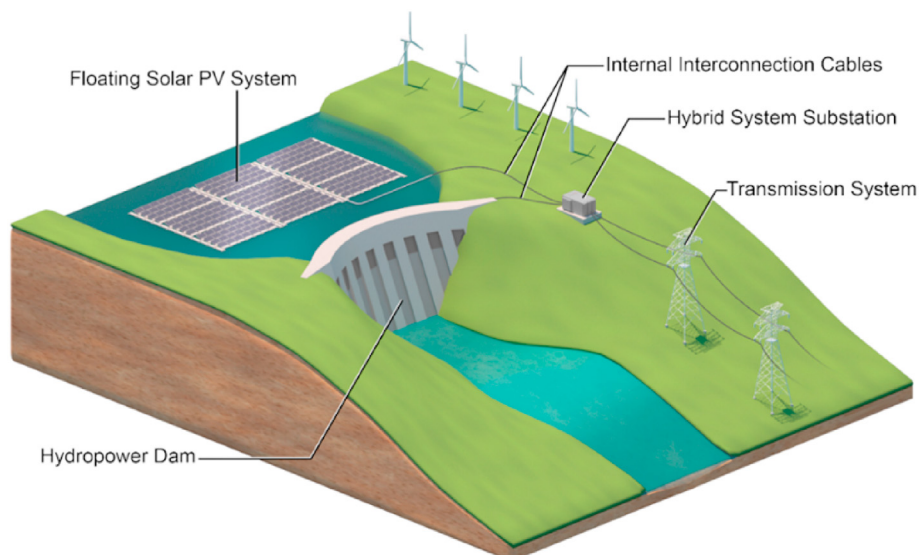


Fig. 2. Schematic of a hybrid FPV-hydropower system.

patterns and characteristics. Solar PV generation is variable and less predictable due to weather conditions, spatial resource qualities, and daily patterns. In contrast, hydropower systems (with sufficient resources) can offer high degrees of generation control and can provide for shortfalls to balance intermittent solar PV generation [18]. We discuss the advantages of these benefits at different timescales.

At the seasonal (or monthly) scale, the availability of solar and hydropower resources are generally asynchronous. Higher quality solar resources are generally available during dry seasons and lower solar quality resources may be available during rainy seasons. Operationally, this means that hybrid system operators could reduce reliance on hydropower resources (increased water storage) during dry seasons, taking advantage of solar resources. Vice versa during rainy seasons; with reduced solar resources, operators could reduce reliance on solar resources to take advantage of the increased hydropower resources [35,37].

At the daily or hourly scale, hydropower can compensate for the intermittent output of solar PV, as solar resources are only available during certain periods of the day. This allows the hybrid system to export power from the PV system when the sun is shining while the reservoir either recharges or holds resources for times when the sun is not shining. An et al. (2015) describe this as the second stage of hybrid-system compensation for intermittent solar resource availability [38].

At the subhourly scale, hydropower can compensate for the variability (random fluctuations) in solar resource availability (solar PV output) as well as demand. An et al. (2015) refer to this as the first stage of hybrid-system compensation for variability of solar resource availability. This would require quick ramping or reactive hydropower turbine technologies [38].

Both the variability and intermittency of solar PV generation can be compensated by hydropower generation—effectively allowing for operation of the hybrid system as a firm and dispatchable generator. As a result, PV curtailment is reduced, and the hybrid system energy output is greater than the output of the individual systems. Fig. 3 depicts how the total dispatchable energy from the stand-alone systems is less than the systems' energy generation potential; however, the dispatchable energy from the hybrid system is equal to the total energy generation of the two systems [35]. This may provide additional benefits for operators, such as an increased dispatch order or higher electricity market prices [22].

2.3.2. Additional energy storage opportunities

FPV-hydropower hybrids could provide energy storage opportunities through different configurations. The first configuration is coupling FPV with pumped storage hydropower to use excess solar generation to pump water into an upper reservoir to store for later use [16]. The second configuration consists of the full hybrid (or virtual hybrid power plants) in which water resources can be conserved during peak solar production hours—utilizing the reservoir as storage for the nondispatchable solar PV. In this configuration, the hydropower plant can supplement the solar generation during periods of high demand or variations in solar output. This also presents an opportunity to store water resources and shift generation to periods with higher time of day pricing (hours of highest demand) [39]. Farfan and Breyer (2018) refer to this as a virtual battery/storage that can balance out the variability of solar resources through ramping of hydropower generation and conservation of hydropower resources during peak periods when solar resources are available [18]. This complementary nature means hybrid systems may follow a pattern similar to that seen in larger balancing areas with both hydropower and solar PV generation. Farfan and Breyer (2018) and Aghahosseini et al. (2017) discuss an example of hydropower and PV generation in the same Southern Mexico balancing area where hydropower shifts away from providing “base generation” into an intermittent operation pattern covering demand during off-peak times, which correspond to periods of low solar irradiance [18,40].

2.3.3. Improved transmission utilization

Connecting FPV to existing transmission infrastructure may increase the utilization rates of transmission lines where additional transfer capacity exists [22]. As high-quality hydropower and solar resources are often far from load centers, lengthy, dedicated transmission lines are often required. These dedicated lines run the risk of being underutilized (low share of total available transfer capacity used)—resulting in high infrastructure costs per megawatt-hour [41]. As hybrid systems may provide increased power generation (improved capacity factor for the hybrid system) over the stand-alone systems, the overall utilization and economics of dedicated lines may be enhanced. This may also improve the economics of stand-alone system development [42].

2.3.4. Reduced solar PV curtailment

As the system operator views the hybrid FPV-hydropower

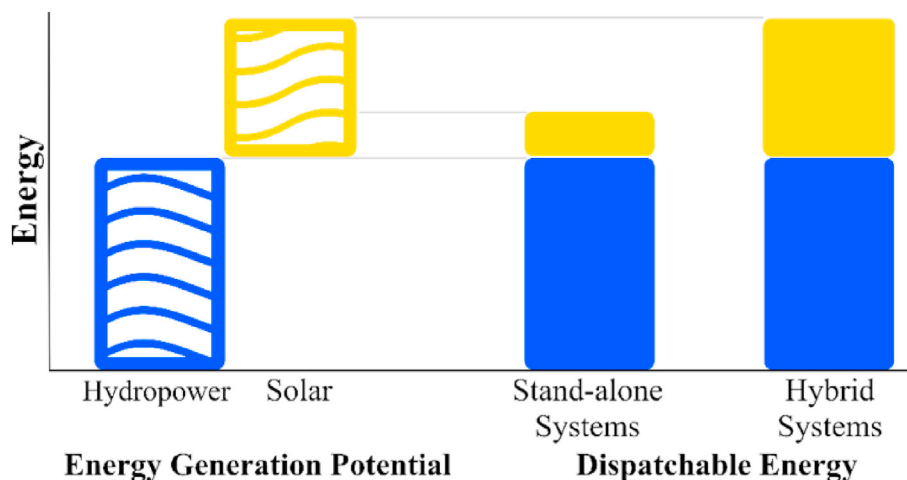


Fig. 3. Generation potential and dispatchable energy from stand-alone and hybrid FPV and hydropower systems (energy not to scale). Figure adapted from Dobrotková (2019) [35].

system as a single generator able to provide predictable, controllable, dispatchable generation (not separate generators), the hybrid system may receive a higher capacity credit—allowing for reduced or no curtailment [43]. The Longyangxia solar PV-hydropower hybrid system in Qinghai provides an example of this reduced curtailment. The 1,280-MW hydropower plant, built in 1989, was complemented with a land-based 850-MW solar PV system with a 30-km interconnection line that allowed for first-of-its kind hybrid system operation. The hybrid operation allowed for elimination of all solar PV curtailment, and the system is now a firm, dispatchable generator [38,44]. During peak solar production hours, solar PV can provide power and hydropower resources can be conserved until solar resources are not available. In this configuration, solar PV would help to meet expected power production, without curtailment, and the hydropower turbines could be ramped up or down as part of a complementary operation strategy [39]. In pumped hydropower storage applications, excess solar PV generation can be used internally to replenish water resources (together with reservoir inflow) for use during other periods, instead of curtailing.

2.3.5. Reduced transmission system interconnection costs

Co-locating FPV systems with hydropower allows for connection to existing transmission infrastructure. This may reduce the additional costs of transmission extensions, substations, and other infrastructure requirements as well as reducing time and siting constraints (such as land acquisition) [10,13,18,45–47]. This may be mutually beneficial, as hydropower, solar resources, and suitable FPV waterbodies may not be located near load centers or existing transmission systems. Additionally, if more FPV capacity is added to a system in the future, it is easier and often less expensive to upgrade existing infrastructure than to develop new interconnections [39].

2.3.6. Resource conservation

Installation of FPV on hydropower reservoirs may help to decrease water evaporation through decreased air flow and absorption of solar radiance—increasing resources for hydropower generation [24]. As such, the hybrid system can help reduce seasonable variance in water resource availability and generation shortfalls [37,48]. Farfan and Breyer (2018) estimated that FPV paired with hydropower globally could prevent approximately 74 billion cubic meters of water evaporation supporting water conservation (increased water availability of 6.3%) and hydropower production—adding an estimated 142.5 TWh of generation from FPV systems on hydropower reservoirs [18].

Table 1 summarizes the potential value added from hybrid FPV-hydropower system operation reviewed in the preceding sections.

3. Methodology: global assessment of hybrid system technical potential

A technical potential assessment estimates the achievable energy capacity (MW), generation (GWh/year), and suitable area (km²) for deployment of a generation technology (such as wind or PV) given system performance, topographic limitations, environmental constraints, and land-use constraints. To estimate technical potential for FPV resources, we need a geospatial approach and the corresponding data that help answer two questions:

1. Where is it technically feasible (suitable area) to deploy FPV?
2. What is the technical potential of FPV deployed, given solar resources and system performance?

To answer these questions, we start with an assessment of the data available as this will influence the geospatial approach we can apply.

3.1. Data-gap assessment

To answer question 1 above, onshore solar PV assessments may not provide a complete picture, as they do not capture the nuances of floating installation paired with hydropower; however, they may provide an initial template. The topographic environmental constraints and land-use constraints for onshore solar PV often include slope (is the terrain too steep or uneven to build?) and land use and/or land cover (is the site in a urban, agricultural, forested, important heritage, or other area of concern?). These land-based constraints are not directly applicable to FPV. Recent geospatial assessments of FPV provide more applicable considerations for this emerging application. These include an assessment of FPV potential in artificial waterbodies for the United States from Spencer et al. (2019), a statewide assessment of FPV in Colorado from Liber et al. (2020), and considerations for pairing FPV with hydropower described by the World Bank et al. (2019) [5,14,24]. Drawing from this literature, in Table 2 we list applicable suitable area considerations for hybrid systems and describe the desired data sets for a geospatial technical potential assessment.

To answer question two above, we also need geospatial, solar energy resource data and assumptions on FPV system performance. Ideally, a global time-series data set of direct and diffuse radiation and technology assumptions allow for modeling system performance; however, for a technical potential assessment, annual average solar resource data are sufficient. We therefore established a set of resource data requirements and conducted a data-gap assessment to identify the available data that met these requirements. Table 3 presents this data-gap assessment based on four questions.

From this data-gap assessment, the Global Reservoir and Dam Database (GRandD) data set provided the best option for identifying hydropower reservoirs and their associated hydropower generator locations.

Also, although the capacity factors provided by the Global Solar Atlas are biased estimates for FPV systems, they offered the best global solar resource data available (given the criteria in Table 3).

We identified the following data-gap concerns to address in potential future work:

1. We did not identify global, publicly available bathymetry data sets with the necessary resolution. The lack of bathymetry data prevents us from estimating water body areas that may be too shallow (or deep) or that have seasonal variations in coverage prohibiting FPV deployment.
2. There are no global data on the spatial-temporal variation of water bodies (water level or coverage area)—preventing us from excluding areas of waterbodies that are dry during part of the year.
3. Capacity factor data available at the global scale (such as the Global Solar Atlas) is biased towards land-based systems (due to system configuration assumptions). Global Solar Atlas data assumes an optimum tilt. This means that the capacity factors in high latitudes (cooler regions) are likely overestimated for FPV systems. Also, these data do not consider any potential cooling effects of the water on efficiency of the FPV systems, which would increase the capacity factors of FPV in warmer climates. These factors may result in a bias in estimated generation between waterbodies in warmer regions, as opposed to cooler regions.
4. The lack of global coverage in attributes of hydropower capacity (MW) and annual generation (GWh per year) limit use of these data to size FPV systems in proportion to hydropower and available transmission system capacities. While this may be an economic concern, the data may also allow for an assessment

Table 1
Summary of potential values added from hybrid FPV-hydropower systems.

Potential Added Value	Summary	References
Improved System Operation		
Seasonal timescale	Leverage asynchronous, seasonal resource availability by reducing reliance on hydropower resources during dry seasons, taking advantage of solar resources. Reduce reliance on solar resources during wet seasons, taking advantage of hydropower resources	[18,35,37]
Daily and/or Hourly timescale	Compensate for the intermittent output of solar PV with hydropower, as solar resources are only available during certain hours of the day, conserving water resources until solar PV is unavailable	[38]
Sub-hourly timescale	Compensate for the variability in solar resource availability as well as changes in demand through ramping of hydropower generation	[35,38]
Energy Storage Opportunities		
Pumped Hydropower	Leverage excess solar generation (instead of curtailing) to pump water into an upper storage reservoir for later hydropower generation	[16,22]
Virtual hybrid system (full hybrid system)	Conserve hydropower water resources during peak solar production hours—utilizing the reservoir as storage for the nondispatchable solar PV	[18,40]
Transmission System Benefits		
Improved Transmission Utilization	Connecting FPV to existing transmission may increase the utilization rates of transmission lines where additional transfer capacity exists	[22,41,42]
Reduced Transmission System Interconnection Costs	Co-locating FPV systems with hydropower allows for connection to existing transmission infrastructure—reducing transmission development costs	[10,13,18,39,45–47]
Reduced Solar PV Curtailment		
Variableness and intermittency of solar PV generation compensated by hydropower generation		[38,39,43,44]
Resource Conservation		
FPV coverage of hydropower reservoirs may help decrease water evaporation and conserve water resources for hydropower generation		[18,24,37,48]

Table 2
Suitable waterbody area and corresponding desired data set criteria for hybrid FPV-Hydropower systems.

Suitable Waterbody Considerations	Corresponding Geospatial Data Set Requirements
1 Suitable areas must be freshwater and used as a hydropower reservoir. We delineate hydropower reservoirs from other reservoirs built for agricultural, drinking water, recreation, or other purposes.	Need the spatial location and extent of waterbodies used as hydropower reservoirs, ideally with data on the spatial variation of the reservoir extent.
2 The FPV system must be deployed close to the hydropower generator to enable interconnection at the same substation and operation as a hybrid system. The length and type of internal interconnection lines may be prohibitive due to environmental, technical, or other limitations related to the waterbody or surrounding area [33,49].	Need the spatial location of hydropower generators that have a reservoir. This does not include run-of-the-river hydropower.
3 The FPV system cannot be deployed in reservoirs that may be too shallow or a reservoir that is sometimes dry due to natural, seasonal variations or variations from hydropower operation. The beaching of FPV systems may damage systems and disrupt generation.	High resolution bathymetry (water depth) data for waterbodies. Data on historic water level variations.
4 There is likely some distance from shore at which the operation and maintenance and interconnection costs become prohibitive, although there is no evidence in current literature to suggest these limits have been pushed at this stage of FPV deployment for inland waterbodies.	Requirements covered by Consideration 1
5 There may be some depth at which the cost of mooring FPV may also become prohibitive, although the literature again does not suggest these limits have not been pushed. Additionally, alternative mooring options may be available.	Requirements covered by Consideration 2

the hybrid FPV-hydropower systems' combined capacities and/or benefits (not just FPV capacity potential in the hybrid system).

- As we are applying datasets with global coverage, their resolution of attributes at the regional (such as European), country, or sub-country scales remains coarse. These datasets do not capture the potential, local project-siting constraints to floating solar that reflect regulations for waterbody use (such as prohibitions on siting on recreational waterbodies) or waterbody conditions (potential freezing during winter months).

3.2. Geospatial approach for FPV technical potential assessment

Fig. 4 depicts our geospatial approach to assess the technical potential of FPV paired with hydropower—drawing from data

identified in the data-gap assessment. This technical potential assessment is limited to the FPV system capacity, generation and suitable area. This assessment does not include considerations of the hydropower capacity or generation or the hybrid operation.

All methods described in this approach were performed in a PostGIS enabled PostgreSQL database.¹ This software platform was chosen for its ability to perform all geospatial (spatial buffers, intersections, reprojections and area calculation), relational (joins and aggregations), and arithmetic steps of the methods in programmatic fashion. QGIS was used to visualize the database layers and illustrate the results.² The programmatic aspect of the platform was critical to ensure the systematic and efficient completion of several discrete steps across all combinations of parameters considered in this assessment. This software and programmatic approach were warranted due to the multiple combinations of parameters run for thousands of reservoirs, hundreds of thousands of natural lakes, and the need to intersect these with millions of solar data points (where solar resource data is calculated) in the

¹ PostGIS as an extension for the PostgreSQL relational database system that gives it the capability to store, manipulate, and perform relational logic on geographically referenced geometric data. More information is available at <https://postgis.net/> and <https://www.postgresql.org/>.

² QGIS is a publicly-available and open source geographic information system. More information is available at <https://qgis.org>.

Table 3

Data-gap assessment for hybrid FPV-Hydropower technical potential assessment[50–59].

Dataset	1. Do the data have global coverage?*	2. Are the data publicly available?	3. Are the data available in high spatial resolution?	4. Are the data applicable for assessing hybrid FPV-hydropower technical potential?
Waterbodies				
Natural Earth Lakes and Reservoirs [50]	✓	✓	✓	✗ • Data for cartographic purposes, focus on large lakes • Significant attribute data; however, inconsistent attribute data • No data on water coverage seasonal variation or levels
ESA Globcover [51]	✓	✓	✗ • High resolution raster data	✗ • Raster data makes it difficult to distinguish independent waterbodies that may located in proximity to other waterbodies • No distinction between lakes, rivers, and hydropower reservoirs • No data on water coverage seasonal variation or levels
Global Lakes and Wetlands Database [52]	✓	✓	✓	✗ • Mixed attribute data quality • No distinction between natural and artificial reservoirs • No data on seasonal variation of water coverage or levels
Global Reservoir and Dam Database (GRanD)—Reservoirs [53]	✓	✓	✓	✓ • Reservoirs are represented. Lakes are not represented • No data on seasonal variation of water coverage or levels
Hydropower Plants				
World Resources Institute Global Database of Power Plants [54]	✓	✓	✗ • Low spatial precision for generators (difficult to match to reservoirs.)	✗ • Unable to distinguish between different hydropower types • Large set of attribute data with estimates of power plant capacity • Generator capacity data is not complete
Global Reservoir and Dam Database (GRanD)—Dams [53]	✓	✓	✓	✓ • Dams are matched with their reservoirs. • Attribute data include dam use (hydropower or other). • No capacity data for generators
Waterbody Bathymetry				
Digital Elevation—Global 30 Arc-Second Elevation (GTOPO30) [55]	✓	✓	✗ • Low spatial resolution (for waterbodies of interest)	✗ • Low spatial resolution • Develop from several different data sources with different qualities.
Global Lake Bathymetry Database [56]	✗	✓	✓	✗ • Lacks global coverage
Solar Resources				
Global Solar Atlas [57]	✓ • Data extent is +/- 60 degrees latitude.	✓	✓	✓ • Includes capacity factor for optimum tilt ground-mount systems, but cannot be used to model different FPV system configurations • The extent of that data is 60 degrees latitude.
NASA Prediction Of Worldwide Energy Resources (POWER) Surface meteorology and Solar Energy (SSE) [58]	✓	✓	✗ • Low spatial resolution	✗
PVGIS [59]	✗	✓	✗ • Mixed spatial resolution	✗ • Lacks global extent, large portions of Oceanica and Asia do not have data • Latest data from 2016

* ✓: Yes, ✗: No

global datasets.

To identify reservoirs associated with hydropower dams, we filtered the GRanD Dams data set for those classified as “electric generation” and then joined the respective reservoirs with the filtered hydropower dams. This associated 2,461 reservoirs with their corresponding hydropower dams.

As a proxy for bathymetry data and waterbody seasonal variation data, we assume a minimum distance-from-shore threshold (yellow area in Fig. 4) to remove potentially shallow areas from the reservoirs. Additionally, we assume that at certain distances from shore and water depths the costs for operation and maintenance and installation (such as mooring and anchoring) may become

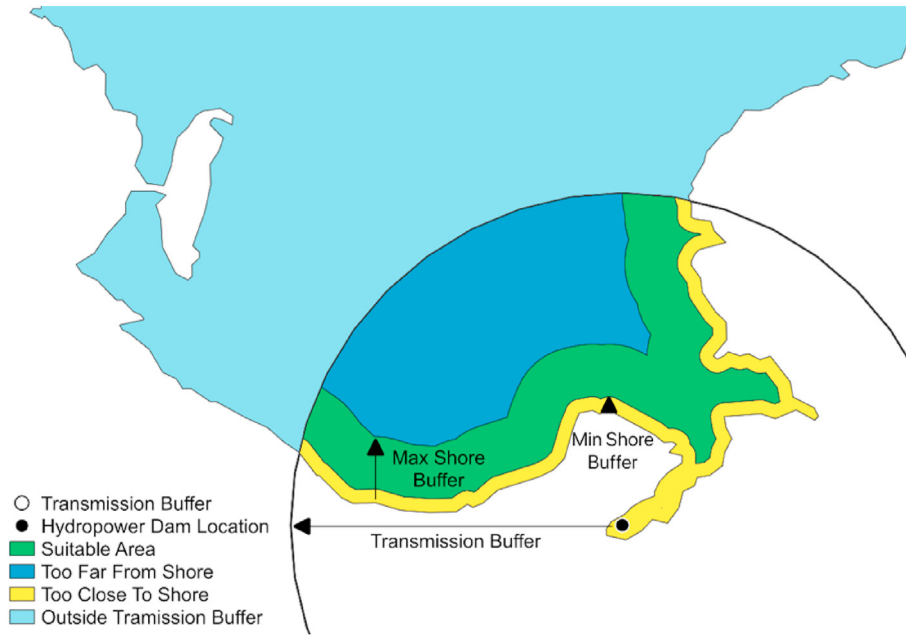


Fig. 4. Spatial approach for FPV technical potential assessment in hybrid systems.

prohibitive (dark blue area in Fig. 4) [5]. We explore sensitivities to these assumptions with three scenarios of minimum (0, 50, and 100 m) and maximum (500, 1,000, and 2,000 m) distances from shore allowable.

Finally, we assume a maximum interconnection line length of 25 km to exclude reservoir areas that are prohibitively far from hydropower plants (see transmission buffer in Fig. 4) [33,44]. The remaining area between these minimum and maximum distances from shore and the interconnection buffer are considered to be suitable area for FPV deployment (see the suitable area in Fig. 4). Reservoirs outside the Global Solar Atlas data extent (between $\pm 60^\circ$ latitude) were excluded (see Table 3).

Technical potential capacity (MW) is the product of the power density (assumed to be 1 MW per hectare or 100 MW per km^2) and total suitable land area (Equation (1)) [14]. To assess the annual generation (GWh per year) we find the product of the capacity, the corresponding solar energy resource capacity factor, and 8,760 h per year (Equation (2)). The corresponding capacity factors were identified from the Global Solar Atlas (downscaled to $100 \text{ m} \times 100 \text{ m}$ resolution with a simple nearest neighbor method).

To explain the calculation of technical potential, we present a hypothetical example of a waterbody with an area of 1 km^2 . We assume that 10% (for this example) of the total waterbody area is suitable for FPV (Fig. 4 and Equation (1)) or 0.01 km^2 . With an FPV power density of $100 \text{ MW}/\text{km}^2$, we find a potential capacity of 1 MW. Next the annual generation (Equation (2)) is sensitive to the quality of the local solar resources and associated generation technology assumptions. With 1 MW of capacity (from Equation (1)) and a capacity factor of 20%, the resulting annual generation is 1.8 GWh/year; however, assuming a capacity factor of 10% (lower resource quality), we find an annual generation of 0.9 GWh/year. Note that technical potential results are also highly sensitive to the suitable area assumed. For this work we examine the sensitivity of results to the suitable area assumptions (min and max shore buffer) in the following section (Results Section 4).

$$\begin{aligned} \text{Capacity (MW)} &= \text{Suitable Area (km}^2\text{)} \\ &\times \text{Power Density (MW / km}^2\text{)} \end{aligned} \quad \text{Eq 1}$$

Where.

Capacity is the maximum amount of electric power (or nameplate capacity) that the floating solar PV generator can produce in megawatts (MW).

Suitable Area is the waterbody area coverage for the floating solar PV system, as described in the preceding section and depicted in Fig. 4, measured in km^2 .

Power Density is the maximum amount of electric power (nameplate capacity) that the generator can produce per unit of installed area (or waterbody area coverage) measured in MW per km^2 .

$$\begin{aligned} \text{Generation (GWh / year)} &= \text{Capacity (MW)} \times \text{Capacity Factor (\%)} \\ &\times \text{Operating Hours (hours / year)} / 1,000 \text{ (MW / GW)} \end{aligned} \quad \text{Eq 2}$$

Where.

Generation is estimated annual electricity generation from the floating solar PV generator measured in gigawatt hours per year (GWh/year).

Capacity is the maximum amount of electric power (or nameplate capacity) that the floating solar PV generator can produce in MW, estimated in Equation (1).

Capacity Factor is a measure of how much energy is produced by a generator compared with its maximum output, and is calculated as a percentage (%), or ratio, of the total energy produced during some time period by the amount of energy the generator would have produced if it ran at full output during that time. This factor is specific to the technology and the potential resources in the location that it operates.

Operating Hours are an estimation of the total annual hours of operation, or 8,760 h per year.

4. Results

Table 4 summarizes the technical potential assessment results for FPV in hybrid systems for nine scenarios (close to shore, median, and distant from shore). Estimates for global installed capacity for FPV deployed in hybrid systems range from 3,039 GW to 7,593 GW in the *Distant from Shore* to the *Close to Shore* scenarios, respectively. These installed capacities correspond to annual generation estimates of 4,251 TWh/year to 10,616 TWh/year in the *Distant from Shore* to the *Close to Shore* scenarios, respectively. The *Median* scenario finds an estimated capacity of 5,333 GW. Global capacity factor averages were approximately 16% across the scenarios. The minimum and maximum reservoir coverage for these scenarios range from 8% to 20%, respectively.

Fig. 5 highlights the sensitivity of technical potential to assumed distance from shore for the nine scenarios. The resulting installed capacities (MW) for this sensitivity analysis appear to be stable and linear. As we increase the maximum distance to shore and hold the minimum distance from shore constant, the potential installed capacity increases. Also, as we increase the minimum distance (offset) from shore, the potential capacity decreases. While the results are affected by these distance threshold assumptions, they are not highly sensitive (doubling the maximum distance to shore does not double the potential capacity). This implies that improved bathymetry data are unlikely to paint a radically different picture of available global capacity. On a global scale, different distances from shore do not significantly affect the capacity factors because solar resources are not highly variable at this scale (km and sub-km scales).

Fig. 6 presents the Median scenario (Table 4) capacity (MW) results for FPV systems by global region. North America has the largest estimated technical potential (1,785 GW); however, other regions, such as South America (739 GW), Eastern (473 GW) and Southern Asia (362 GW), and Northern Europe (404 GW), also have significant potential. We note potential biases in the underlying data sets for these results as North and South America may have more complete hydropower datasets than other regions. The extent to which biases exist and to what they can be attributed could be explored in future work (further discussed with the Conclusions in Section 6).

The Discussion section that follows (Section 5) discusses the results obtained for this novel approach to assessing global hybrid FPV-hydropower potential.

5. Discussion

This section presents a comparison of global assessment hybrid FPV-hydropower systems and other related global assessments of FPV. Additionally, this section addresses the local, real-world

development constraints that likely affect the actual deployment numbers (or capacity) of FPV globally. Finally, we discuss remaining deployment challenges for these hybrid systems.

5.1. Comparison of FPV assessments and limitations

The results obtained in this global assessment of hybrid FPV-hydropower systems are consistent with other recent global FPV capacity estimates. Our most conservative estimate (see Results Section 4) of 3.0 TW global capacity for FPV on hydropower reservoirs for hybrid system applications aligns with the range of 0.4–4.0 TW for global freshwater reservoirs reported by the World Bank et al. (2019), which considers 404,454 total waterbodies versus the 379,068 waterbodies in this work [6]. Farfan and Breyer (2018) estimated global FPV capacity on hydropower reservoirs at 4.4 TW [18]. Spencer et al. (2018) estimated the potential for freshwater artificial waterbodies (not limited to hydropower reservoirs) at approximately 2.1 TW for the United States [14].

The results show that FPV-hydropower systems could significantly contribute to global energy demands. Our estimated annual generation results range from 4,251 to 10,616 TWh/year for the scenarios considered. These estimates represent 16–40%, respectively, of 2018 world electricity generation according to IEA (2019). In the future these FPV generation estimates could contribute 29–72% of the additional generation necessary by 2040 for the Stated Policies Scenario and 35–88% for the Sustainable Development Scenario from the IEA (2019) [60].

Technical potential assessments capture the reality that not all physically available solar resources in an area are feasibly developable. To accomplish this, the technical potential approach presented here assumes broad constraints applying course, publicly available data with global coverage. This assessment does not capture finer, the project-siting constraints that developers will eventually face. These siting constraints require local, often ground-verified data, as well as knowledge of local development regulations (such as colocation on recreation reservoirs). Therefore, the technical potential results presented here are an optimistic, upper bound for global FPV-hydropower system capacity and generation. Additionally, technical potential does not capture the economic or market potential for floating solar PV or potential future technology improvements. Future, studies at the regional, national, or subnational scale are required to improve the resolution of real-world hybrid FPV-hydropower system deployment potential.

5.2. Remaining FPV deployment challenges

Despite these potential benefits, challenges exist that could hinder further investment and deployment. The capacity (MW) of

Table 4
Results: Technical potential of FPV in hybrid FPV-Hydropower systems.

Scenario Assumptions			Technical Potential Results			
Description	Minimum Shore Distance (m)	Maximum Shore Distance (m)	Installed Capacity (GW)	Annual Generation (TWh/year)	Capacity Factor (%)	Reservoir Coverage (%)
Close to shore	0	500	4,948	6,879	15.9	13.1
		1,000	6,407	8,946	15.9	16.9
		2,000	7,593	10,616	16.0	20.0
Median	50	500	3,899	5,441	15.9	10.3
		1,000	5,333	7,470	16.0	14.1
		2,000	6,497	9,112	16.0	17.1
Distant from shore	100	500	3,039	4,251	16.0	8.0
		1,000	4,448	6,246	16.0	11.7
		2,000	5,592	7,863	16.1	14.8

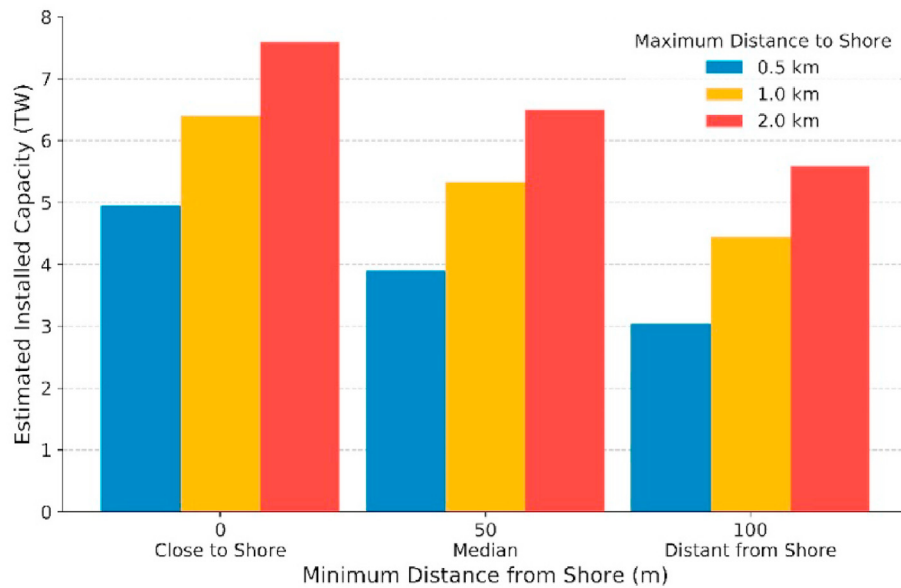


Fig. 5. Technical potential capacity: Sensitivity to shore distance assumptions.

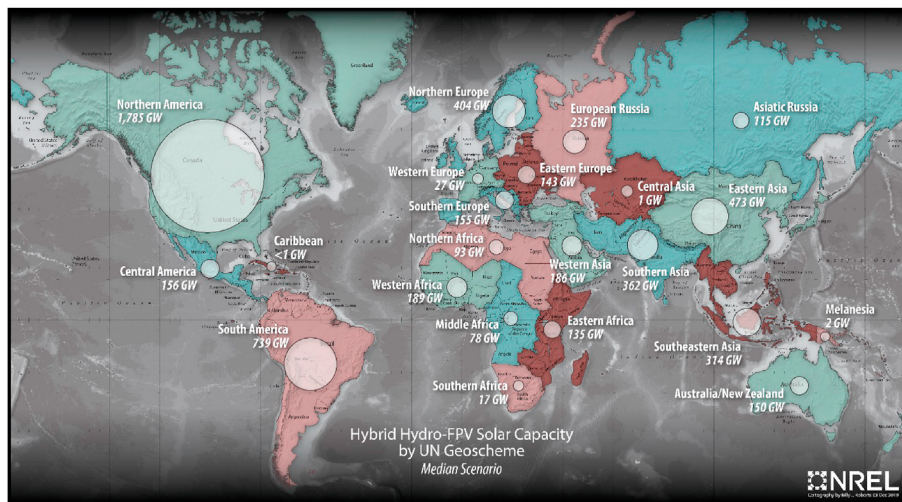


Fig. 6. Potential capacity results by world region.

Note: Colors in this figure only depict the regional boundaries following the United Nations' GEOscheme to show capacity in different global regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the FPV systems in hybrid applications may be constrained by factors beyond the available reservoir surface area. Fang et al. (2017) suggested establishing limitations on the peak FPV power to guarantee that hydropower can compensate for power deficiencies caused by variability of FPV output. This may be done by setting a conservative limit of peak FPV capacity equal to the installed hydropower capacity [21]. A second, related approach is to constrain FPV development to ensure existing transmission infrastructure is sufficient for the additional power supply from FPV when paired with hydropower [39].

The hydropower operation range may limit the full dispatchability of the hybrid system, as reservoir levels are often regulated to avoid erosion on reservoir banks, conserve water for other uses, maintain dam safety (may require water curtailment in rainy seasons). Hydropower turbine ramping rates may also limit hybrid operation as variations in FPV may occur too quickly for some

turbines without high degrees of generation control [39]. These challenges may be overcome in new systems designed for hybrid operation or retrofitted systems; however, it is important to point out that benefits may not be available for all existing systems.

Solar modules, inverters, and floating structures are not novel systems; however, their installation as hybrid systems may present multiple material-related challenges [8]. Previous stand-alone FPV research indicated that insulation failures can lead to frequent unplanned downtime, and long-term exposure to humidity may expedite PV modules degradation, corrosion of floating structures, waterbody contamination, and/or material fatigue of joints may result in debris that interferes with the local ecosystem or hydropower systems [37].

Capital and operation and maintenance costs may also present challenges, as the required electrical and anchoring systems and mooring costs vary dramatically from vendor to vendor and could

be higher than land-based systems [7,61].

Other potential challenges include concerns related to aesthetics, intrusion on recreational waterbodies, and environmental impacts, such as temperature fluctuations that could affect local ecosystems. Hydropower development has historically faced significant attention due to social and environmental impacts, and it is reasonable to assume further development of FPV on reservoir surfaces could also require significant dialogue and analysis to ensure alignment with the broader values of societies [48,62].

6. Conclusions

In this work, we present an approach to estimate the technical potential of FPV deployed in hybrid systems with hydropower and identify significant global potentials from 3.0 TW to 7.6 TW for the scenarios considered (4,251 TWh to 10,616 TWh per year of generation). Additionally, we review potential operational benefits that these hybrid systems may provide. In conclusion, we present pathways to apply the knowledge from this work and potentially improve the assessment.

Scaling the global assessment approach presented here to the country or regional level could support key power system planning decisions internationally. In particular, this could enable policy design and target setting, investment decisions, and planning that supports resilience and cross-border trade and integration [63].

FPV could play an important role in achieving the ambitious renewable energy targets put forth by many countries. With more detailed assessments of FPV, countries can consider more ambitious targets or understand how FPV could help meet current targets. Multiple countries have adopted preferential feed-in tariffs for FPV or explicitly included FPV within current solar tariff programs [64]. With detailed data on the costs of stand-alone or hybrid FPV systems, decision makers can accurately compare FPV costs with those of other technologies to inform tariff design that enables FPV market development.

Countries undertaking tendering processes for renewable energy development could benefit from use of the FPV assessment tools to identify locations with high-quality solar resources, hybrid system potential, and proximity to demand and existing infrastructure. This could support investment in hybrid FPV-hydropower systems. Future work could also enable spatial assessments of levelized cost of energy for these hybrid systems. These assessments could support investment through initial high-level prospecting of sites for FPV and later targeted feasibility assessments.

Power system planning efforts could be informed by estimates of technical potential of hybrid FPV-hydropower systems. Detailed data on the operational benefits of these systems could also inform capacity expansion modeling and/or production cost modeling. These analyses would allow for improved understanding of impacts and benefits of pairing floating PV with hydropower. These planning activities could help decision makers assess how hybrid systems could support resilience through conservation of hydropower resources and diversification of generation portfolios (both spatial and technological). Assessments may also support identification of opportunities to enable cross-border power trade, as FPV paired with hydropower may provide additional generation capacity and operational benefits that align with regional power trade strategies.

Global data availability was one limitation to this work, and access to additional data could improve future assessments and enable decision making in the areas highlighted above. Acquiring hourly solar resource data and developing a method to apply appropriate FPV system configuration assumptions when modeling would likely produce more realistic system performance estimates. Global data on hydropower plants and associated reservoirs that

include attributes of the installed capacity and annual generation would allow for a more dynamic, deliberate approach to estimating FPV capacity coupled with hydropower plant capacity (or assumed transmission capacity). Access to hourly hydropower generation data and solar resource data would allow for high-fidelity modeling of the co-benefits of the hybrid system operation at higher temporal resolutions. Additionally, high-spatial resolution bathymetry data would help to confirm our assumptions regarding use of minimum and maximum distances to shore as a proxy for water-level coverage and depth.

To enable market development and support deployment, future work may examine additional questions specific to FPV and hybrid FPV-hydropower systems:

- What are the actual costs of deployment and operation of these hybrid systems?
- How to properly size the FPV component for hybrid systems coupled with existing or planning hydropower?
- What materials and infrastructure concerns exist for hybrid systems?
- What are the social and political concerns for their deployment and how can these be addressed?
- What are the policy and regulatory uncertainties, and how can these be overcome?

Building on this global assessment, future work will also include dissemination of data-driven FPV decision support tools to enable market development. As a first step, the approach and global data sets used within this study could be integrated in an online platform, such as the Renewable Energy Data Explorer, for visualizing potential FPV locations and analyzing technical potential at country and/or regional scales.³ This would enable developers and decision makers to assess hybrid FPV and hydropower technical potential.

CRedit authorship contribution statement

Nathan Lee: Conceptualization, Methodology, Investigation, Supervision, Funding acquisition, Writing - original draft. **Ursula Grunwald:** Investigation, Writing - original draft. **Evan Rosenlieb:** Methodology, Investigation, Software, Formal analysis, Data curation, Visualization, Writing - review & editing. **Heather Mirletz:** Investigation, Writing - original draft. **Alexandra Aznar:** Conceptualization, Writing - review & editing. **Robert Spencer:** Conceptualization, Writing - review & editing. **Sadie Cox:** Writing - review & editing.

Declaration of competing interest

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

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³ Renewable Energy Data Explorer is a no-cost, web-based application to facilitate renewable energy decision making, investment, and deployment through a dynamic, online analytical tool. Users can visually explore spatial datasets for energy resources, and related geographic information system datasets as well as complete complementary analyses. Find additional information on the RE Explorer website at re-explorer.org.

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