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Floating photovoltaic technical potential: A novel geospatial approach on federally controlled reservoirs in the United States

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ABSTRACT

Floating photovoltaic systems are a rapidly expanding sector of the solar energy industry, and understanding their role in future energy systems requires knowing their feasible potential. This paper presents a novel spatially explicit methodology estimating floating photovoltaic potential for federally controlled reservoirs in the United States and uses site-specific attributes of reservoirs to estimate potential generation capacity. The analysis finds the average percent area that is found to be available for floating photovoltaic development is similar to assumed values used in previous research; however, there is wide variability in this proportion on a site-by-site basis. Potential floating photovoltaic generation capacity on these reservoirs is estimated to be in the range of 861 to 1,042 GW direct current (GWdc) depending on input assumptions, potentially representing approximately half of future U.S. solar generation needs for a decarbonized grid. This work represents an advancement in methods used to estimate floating photovoltaic potential that presents many natural extensions for further research.

1. Introduction

The global floating photovoltaics (FPV) industry is a rapidly emerging sector of the renewable energy industry with an average annualized growth of installed capacity of 142 % between 2014 (the year that global installed capacity surpassed 10 megawatts direct current [MWdc]) and 2022 (the most recent year with data, with cumulative capacity topping 13,000 MWdc) [1]. FPV provides a host of attractive benefits relative to ground-mount photovoltaics such as increased panel efficiency because of cooling effects and low shading, co-location with hydropower resources providing co-benefits in hybrid systems, and potential reductions in water evaporation [2]. Some countries, such as South Korea, have explicitly stated FPV development as necessary to meet their long-term solar energy targets [3].

However, as the global FPV market has taken off, efforts to understand its role in future energy systems is still in a nascent stage. The FPV technology faces its own unique technical and engineering constraints, such as problems posed by currents or ice floes. Understanding how much FPV may be reasonably developed when considering these technical limitations—or the “technical potential” of FPV—is a crucial first step to understanding its future pathway to development. To our knowledge, Spencer et al. 2019 was the first published paper that attempted to quantify FPV technical potential (in its case, for dam reservoirs in the United States) [4]. In the 5 years since then, at least nine other papers have been published that have quantified potential FPV development in other regions, countries or globally. However, to our knowledge no analysis has used spatially explicit methods that consider specific waterbody parameters as limitations to FPV development. This type of analysis has been a standard used for ground-mount solar and wind potential estimates for more than a decade [5,6] but has not yet been developed for this new segment of the renewable energy sector.

1.1. Review of previous methods

As an initial step, we conducted a literature review for previous assessments of technical potential FPV capacity. Although estimates of FPV capacity are frequently created for case studies of a single reservoir or for a subsample of reservoirs [7], we focused on studies that assessed capacity for all reservoirs fitting the study criteria within a defined area (resulting in a sum estimate of FPV potential). Ten previously published papers were identified that met our requirements. Of these 10 papers, only 1 paper—Lee et al. 2020—relied on spatially explicit methods to estimate the amount of developable area within each waterbody [2]. All other attempts to assess FPV potential have included some criteria for which waterbodies should be considered for the assessment but assume

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Table 1
Summary of criteria used for reservoir selection.

Reservoir Selection Criteria	Rationale
NHD waterbody must be identified as belonging to USACE, USBR, or a FERC licensed hydropower project.	Potential for large-scale and hybrid deployment.
The waterbody must not be part of a USACE maintained navigable waterway.	The large wakes caused by freight shipping vessels can render an area unsuitable for FPV development.
The waterbody must not be located where there is an average monthly low air temperature below −15 °C.	The potential ice floes, heavy freeze/thaw cycles, and snow loading associated with very cold locations are incompatible with FPV development.

a flat percentage of each waterbody is developable for FPV and do not consider any site-specific factors that may influence the amount of water suitable for developing FPV. This method of estimating developable area for each waterbody may produce reasonable results when summed over a large area but cannot help address the question of which waterbodies may be the best targets for FPV development. Although other papers have advanced our knowledge of FPV technical potential by examining other relevant parameters such as evaporation mitigation and system performance, the method of estimating the available area has remained remarkably the same.

Lee et al. 2020 used simple minimum and maximum buffers from shoreline as proxies for other more specific factors [2]. Although this approach does incorporate site-specific aspects of the waterbody, distance from shoreline is not something that would usually render FPV development impossible alone; specific factors that may cause direct incompatibilities for FPV development were not considerd (e.g., parts of reservoirs that are too shallow). As such, we did not find any previous research that attempted to quantify FPV potential using such site-specific factors that would preclude FPV development. A summary of these papers is provided in Appendix A.

1.2. *Assessment Goal and Focus*

This assessment aims to develop a novel geospatial method for the estimation of technical potential in the U.S. context to update the current understanding of FPV potential in the United States and apply a similar level of precision to estimates as used for ground-mount solar and wind. Because this represents a significant task by itself, this assessment focuses on technical limitations to FPV only and does not consider other regulatory, social, environmental, or economic limitations, such as the locations of recreation areas on reservoirs. In addition, this assessment estimates potential installable capacity and expected annual generation.

This study focused on federally owned and regulated reservoirs in the United States that fall under the jurisdiction of the U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USACE), and/or are licensed hydropower projects by the Federal Energy Regulatory Commission (FERC) to better assess U.S. technical potential on large bodies of water as well as to understand the potential for hybrid FPV/hydropower projects.

2. Methodology

The process for estimating the technically feasible waterbody area for FPV development for the study populations of reservoirs, as described in more detail in the respective subsections of the methodology section, follows the following steps.

The requisite data for reservoir geometry and attributes for federally owned and managed reservoirs are collected by cross-referencing the base National Hydrography Dataset (NHD) dataset on reservoirs with USACE, USBR, and FERC datasets to ensure the reservoir belongs to the identified study population. Then, reservoirs with qualities that would conflict with FPV development in any quanitity were excluded via spatial intersection with datasets that indicate such conflicts. This process is detailed in Section 2.1, Reservoir Selection Criteria. Next, the proportion of each identified reservoir that may be developed is estimated. Spatial data representing the areas of each reservoir that are not compatible with FPV development are estimated using available datasets relating to conflicting reservoir attributes using spatial methods as described in Section 2.2, Developable Area Criteria.

2.1. *Reservoir selection criteria*

The reservoir selection criteria are summarized in Table 1. The step of compiling a single dataset of waterbody geometries for reservoirs that are either owned and managed by USACE and USBR or form a reservoir that is part of a FERC licensed hydropower project is conceptually straightforward. However, because of the differences in data sources available that catalog these reservoirs, there are still spatial processing steps required to do so with certain embedded assumptions. The other two waterbody selection criteria were determined through consultation with experts in the FPV field about what properties of waterbodies may be likely to pose prohibitive obstacles to the development of FPV on the entire reservoir.

2.1.1. *Use of NHDPlusv2*

To ensure all waterbodies in the analysis are represented by geometries of similar precision and have similar attributes, reservoir locations for each category of reservoir were cross-referenced with a single reservoir dataset, resulting in a study population of reservoir polygon geometries and attributes that are all obtained from a single source. The NHDPlusv2 data product of the NHD program was selected for this purpose because it contains a variety of attributes that are useful for these modeling purposes. It is additionally topologically aligned with a full flowlines network, allowing precise modeling of stream and river inlet and outlet locations. The newer NHD High-Resolution dataset was considered a possibility; however, at the time of analysis, it was not released in its final version and did not contain completed attribute data over the entire domain of analysis.

2.1.2. *USACE reservoir matching*

The USACE reservoirs dataset obtained from the USACE data portal consisted of 401 reservoirs represented as polygon geometries. This dataset includes variables that identify “dry” reservoirs (which are built for flood control and do not hold water under normal circumstances) and water conservation areas, both of which are considered unsuitable for FPV. In this case, the original data source contains full reservoir geometries, and reservoirs that intersect with navigable waterways were excluded before joining with the NHDPlusv2 waterbody polygons. This ensures no waterbodies that intersect with navigable waterways were falsely included because of differences in waterbody spatial extent definitions between data sources. Once waterbodies that intersect with navigable waterways were excluded, 300 USACE polygons were identified as potential candidates for FPV.

These remaining 300 reservoirs were then spatially joined with the NHDPlusv2 waterbody polygons to find the NHD waterbodies corresponding with each USACE reservoir. NHD reservoirs were considered as spurious pairings and thus discarded from the study area reservoir selection if only a small portion of their polygon area overlapped their intersecting USACE polygons. Because of different spatial precisions and differing standards in how the spatial extents of reservoirs are defined, these 300 USACE reservoirs are ultimately associated with 517 NHD waterbodies.

2.1.3. *USBR reservoir matching*

Locations for USBR reservoirs obtained from the USBR Reclamation Information Sharing Environment (RISE) catalog came as point coordinates. Nearest neighbor spatial joins were used to match point

Table 2
Summary of criteria used to determine developable area.

Developable Area	Rationale
Area must have an estimated depth of at least 1 m.	Not deep enough to support FPV development
Area must not be close enough to an inlet or outlet so surface currents may exceed 2 m/s.	2 m/s identified through discussion with developers as the highest current that FPV floats and moorings are engineered to withstand
Area must be in a location that will still hold water at low waterbody volumes or be on a waterbody whose bathymetry is flat enough so floats may be designed to be grounded.	FPV developments can be designed to survive repeated grounding if the underlying waterbody floor is flat enough; if the waterbody floor is steep, FPV must be located where the waterbody will not become dry
Area must be at least 100 m away from a dam.	Areas close to dams are more likely to experience high currents because of either outflows or spillways and also may need space for maintenance

locations to NHD waterbodies. Initially, a maximum search distance of 25 m was used to prevent points from incorrectly matching with multiple waterbodies. The search distance was then incrementally increased by 50 m, and nearest neighbor joins were applied to the remaining unmatched USBR points and NHD polygons. Waterbody names from the USBR data and NHD data were compared for accuracy, and duplicate NHD waterbodies—caused by multiple associated USBR points—were removed. Through this process, 188 USBR reservoir point locations are associated with 148 NHD waterbody polygons. None of these polygons intersected with USACE navigable waterways. Because the USBR's primary responsibility is water resource management in the arid and mountainous western United States where most waterways are not suitable for navigation, this lack of intersection with USACE navigable waterways is not a surprise.

2.1.4. *FERC licensed hydropower reservoir matching*

Reservoirs associated with FERC licensed hydropower projects were determined using the Existing Hydropower Assets (EHA) dataset for 2022 and the Hydropower Infrastructure – LAkes, Reservoirs, and RIvers (HILARRI) dataset v1.1, both obtained from the Oak Ridge National Laboratory Hydrosource data portal. The EHA dataset contains point locations (latitude and longitude) and key characteristics including FERC license status for 2,298 currently operational U.S. hydropower and pumped storage hydropower plants. The HILARRI dataset "is a database of links between major datasets of operational hydropower dams and powerplants, and inland waterbodies" and allows for joining EHA assets and NHD waterbodies through ID. The EHA and HILARRI data were joined by a common ID field and then filtered to include only FERC licensed hydropower projects associated with a reservoir. This is accomplished by filtering for assets categorized by HILARRI as "Hydropower dam associated with reservoir and power plant," "Power plant associated with reservoir; no inventoried dam," or "Hydropower dam associated with reservoir; no power plant." This results in 642 FERC licensed reservoir assets and an associated 511 NHD waterbodies. After removing reservoirs that intersect with navigable waterways, 503 FERC associated waterbodies remain.

2.1.5. *Combined reservoir study population*

The down selecting of reservoirs described in the previous sections resulted in 1,131 unique NHD IDs, which is somewhat less than the sum of the individual categories (1,168) because in certain cases a reservoir was identified as being matched with more than one source. During development of the methods, it was discovered certain adjacent NHD waterbodies are treated as two separate waterbodies by the NHD, where they should be treated as a single waterbody for purposes of this assessment. After merging these polygons, a final number of 1,052 USACE, USBR, and FERC licensed hydropower reservoirs outside navigable waterways were identified.

A small proportion (95) of reservoirs noted in the source datasets were not found in the NHDPlusv2 dataset. Almost all unmatched reservoirs were small reservoirs of approximately 1 ha or smaller. Although there does not appear to be a hard size limit for waterbodies in the NHDPlusv2 dataset, there are very few waterbodies of this size or smaller included—and those small reservoirs probably fall below the spatial precision of the methods used to produce the NHDPlusv2. As the generation capacity of FPV systems that could fit on these reservoirs would necessarily be limited by their surface area, it is not expected their inclusion would have a significant impact on estimated FPV capacity. In addition, it is common for these small unmatched reservoirs to be "pondages" or slightly enlarged sections of rivers behind run-of-the-river dams. Not only are these waterbofies generally small, but they are also likely to have quicker currents and otherwise be unlikely candidates for FPV development.

However, there were also some remaining larger reservoirs that were unable to be matched, such as Lake Nighthorse in Colorado, which was confirmed to be filled after the surveying of the NHDPlusv2. Only two unmatched reservoirs with no apparent records in the NHDV2 were found that were confirmed to both be large enough and old enough to be included: the neighboring Eastman and Hensley USACE reservoirs in California. Potentially, the use of a higher resolution and newer dataset, such as the NHD High Resolution when it is finalized, could solve these issues.

2.1.6. *Temperature exclusion*

Multiple colder climate factors can pose challenges for FPV development, chief among them ice floes whose momentum can stress float moorings past the limits of reasonable engineering [8]. The presence of ice floes is a complex hydrological process that depends on several interactive waterbody properties such as waterbody volume and depth, water velocity and circulation, salinity, and wind patterns that requires a detailed site analysis and defies a nuanced analysis at the continental scale of assessment. Other colder climate factors that may pose considerable challenges for FPV development include heavy freeze–thaw cycles and snow loading and are similarly difficult to estimate from continental-scale publicly available datasets. Because of these factors, the lowest monthly average low air temperature obtained from the WorldClim suite of data products was used as a proxy screening to exclude reservoirs in locations likely to be influenced by these colder climate factors.

Although this exact proxy value is ultimately uncertain, a cutoff value of −15 °C was chosen via consultations with industry experts as a reasonable value. The minimum temperature variable of the 2.5-minute resolution WorldClim product was associated with reservoirs by taking the lowest value of any intersecting raster cells for each reservoir polygon. The application of the −15 °C cutoff leads to the exclusion of 193 reservoirs, mostly in northern interior states such as Minnesota and North Dakota and parts of northern, interior New England as well as in high-altitude reservoirs in the central and northern Rockies. This resulted in a final study area population of 859 reservoirs with a total surface area of 19,345 square kilometers.

2.2. *Developable area criteria*

Even though a waterbody may be potentially suitable for FPV, development may not be feasible in all areas of that waterbody. Therefore, we established criteria for developable areas within waterbodies. Because shallow water cannot support FPV, areas with water depths below 1 m were excluded. Based on discussions with FPV developers, FPV floats and moorings are not engineered to withstand currents that exceed 2 m per second (m/s). Therefore, waterbody areas near inlets and outlets were excluded. NHD flowlines were used to identify inlet and outlet locations on study area waterbodies. FPV components can be designed to withstand repeated groundings caused by water level changes if the bottom of the waterbody is flat enough. FPV should be installed only in areas with underlying floors with steep slopes if the waterbody will not go dry. A model of the underlying floor of the waterbody (or bathymetry) was used to estimate freeboard area as a function of fill volume and to calculate floor slope. Finally, a 100-meter buffer from dams was used because of anticipated high currents near outflows and spillways and space that may be needed for dam maintenance. A summary of these criteria is shown in Table 2.

2.2.1. Bathymetry estimation

Bathymetry is a necessary piece of information to determine many of the developable area criteria. It can be used not only to find shallow areas of reservoirs but also to estimate the areas of the reservoir that will still hold water at low volumes and how flat the exposed floor will be when dry.

High-quality bathymetry surveys of freshwater lakes are not commonly available. Although some surveys are available for certain large USBR reservoirs and a small number of other reservoirs surveyed by USGS, there is nothing approaching a comprehensive bathymetry dataset for the reservoirs considered in this assessment. Although commercial bathymetry data are often available for use by boaters and fishermen, even licensed use of these data does not allow for the use of the raw survey data required for the type of analysis needed for this assessment.

The GLOBathy dataset provided an ambitious solution to this dearth of freshwater bathymetry data when it modeled bathymetry for more than 1.4 million waterbodies found in the Global HydroLakes data [9]. In addition, the dataset was validated against available bathymetry surveys with generally good results. Although an excellent resource, its lack of pairing with a topologically aligned rivers dataset (such as the NHD) greatly limited its potential use for this assessment. Reservoir polygon and river line geometries that are not topologically aligned causes not only imprecision in the location of inlets and outlets but also many cases of false inlets and outlets.

Therefore, it was necessary to compute modeled bathymetry for the NHD polygons used for this assessment. The estimation methods used by the GLOBathy dataset are easily replicated given a value for the maximum depth of the waterbody, and code to replicate the modeled bathymetry is provided along with the dataset. In combination with the waterbody depth estimates provided for all on-river reservoirs as part of the NHDPlusv2 dataset, this allows for the imputation of modeled bathymetry using the GLOBathy method to the NHDPlusv2 polygon geometries. For the 140 reservoirs in the study population that are off-river for which the NHDPlusv2 dataset does not provide maximum depth estimates, the maximum depths were estimated using the same methods used for the NHDPlusv2, provided by the lakemorpho R package. Maximum depth estimates were not able to be calculated for 13 reservoirs because the lakemorpho package did not generate valid depth estimates. Manual examination revealed these reservoirs to be either very small or very flat marshy areas, implying they are likely very shallow. In both cases, the reservoirs were determined likely poor candidate locations for FPV development.

For the rest of the 846 reservoirs, modeled bathymetry rasters were created and used to model the other necessary reservoir attributes. These bathymetry rasters were used as templates for all other rasters so the spatial resolution and extent of all rasters produced subsequently are defined to match those of the bathymetry rasters. Slope rasters were created from the bathymetry rasters using the GDAL DEM tool. A Python script was used to estimate the waterbody area at a given percentage of maximum volume. These three outputs (bathymetry, slope, and waterbody area) give the information necessary to answer two of the four developable area criteria.

It is important to note the modeled bathymetry created by the GLOBathy method creates idealized and smoothed bathymetry estimates compared to real-world waterbody floors. Although these data are useful to help understand if the reservoir floors are generally deep or generally shallow—or whether the reservoir floors are generally steep or generally level—the use of the modeled data means the developable criteria related to the bathymetry data are less spatially precise than other criteria used in the study. With this added uncertainty from the modeled data in mind, two values for the reservoir volume assumption and floor slope were used, respectively, to examine the sensitivy of the outputs to the values used. The values chosen for these cutoffs are discussed in Sections 2.2.2 and 2.2.3, and the results are discussed in Section 3.1.

2.2.2. Reservoir volume and area criteria

The minimum water volume that a reservoir may be expected to experience varies widely, depending on the primary use of the reservoir and the climatic conditions of the reservoir and the streams/rivers that serve as its inflow. In extreme examples, a reservoir built for pumped-storage hydro may regularly fluctuate (known as the “normal operating range”) between 100 and 15 percent volume or below. Reservoirs used for water resource management in the arid West are commonly well below maximum capacity—for instance, Lake Powell and Lake Mead have recently hit all-time lows of 22 % and 27 % full, respectively [10,11]. Most reservoirs, particularly in less arid parts of the country, are typically operated at much higher levels with typical minimum water volumes of reservoirs in the Missouri, Columbia, and Tennessee river basins being 40, 70, and 50 %, respectively [12].

Incorporating minimum water levels that are specific for each reservoir, although ideal, is a difficult task with only a subset of reservoirs having comprehensive water level data available. There has been recent progress in modeling water level variation for less data-rich reservoirs, but results are not available in a format easily applicable to the reservoirs considered.[1] Instead, minimum water levels of 25 % and 35 % were examined for all reservoirs in the study area, representing values below or close to the minimum expected volume for most of the reservoirs in the study population. Rasters of the expected reservoir surface area at both volume levels are generated for all study population reservoirs using the modeled bathymetry as an input.

2.2.3. Floor slope criterion

The use of slope as a criterion for whether the ground is level/regular enough to support the grounding of FPV floats is an abstraction of the factors that could preclude an area for FPV development. For example, localized changes in aspect or surface roughness may pose a problem for FPV floats even if the slope is not very steep on an absolute basis. This is similar to the way that slope has been used as an overall proxy of topographic suitability for development for land-based utility-scale PV technical potential assessments, where a cutoff of 5 % has commonly been used, or concentrating solar power (CSP), where a cutoff of 3 % has been used [5].

Much like these cases, only a detailed site analysis with bathymetric surveys can show the exact developable areas supported by the underlying topography of the land. To choose conservative values for the slope criterion, cutoffs of 3 % and 2 % are used as a marker of whether the reservoir floor is generally flat enough to support the grounding of FPV floats. Because the smoothed bathymetry data are not detailed enough to specify which areas of the reservoir floor are above or below these thresholds, the average slope of the entire reservoir floor is used. If the average slope of the reservoir floor is above the threshold, the entire reservoir is considered unsuitable for grounding of floats, and FPV development is assumed to be limited only to areas that are continuously filled with water. If the average slope is below the cutoff, 75 % of the dry area of the reservoir with a water depth of at least 1 m is assumed to be

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[1] For instance, one such recent model of supply and demand of water to U.S. reservoirs, the ISTARF-CONUS model, used a different base dataset (GRaND) and did not have complete coverage over the smaller reservoirs used in this study.

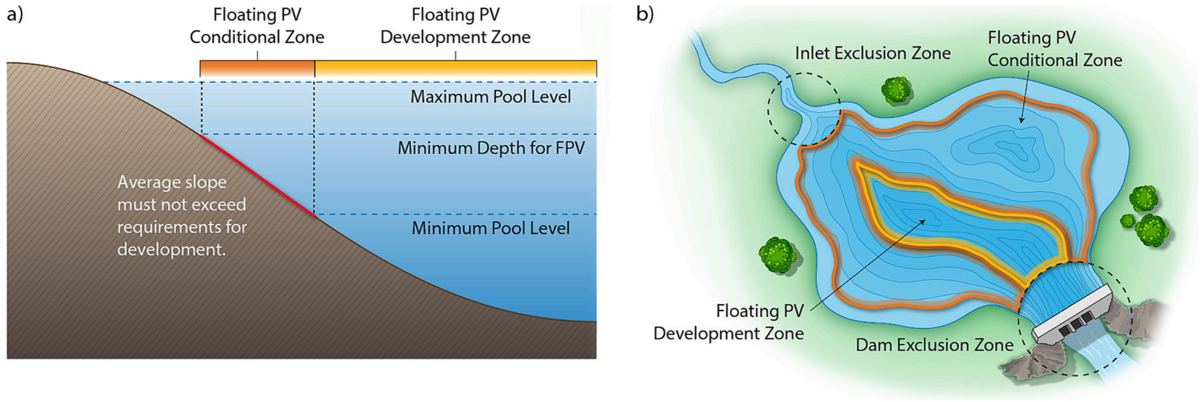

Fig. 1. Example of application of developable area criteria.

Table 3
Summary of installed capacity results by scenario.

	25 % Minimum Water Volume	35 % Minimum Water Volume
2 % Slope Cutoff	861 GW direct current (dc) (1,221 terawatt-hours alternating current [TWh ac])	961 GW dc (1,364 TWh ac)
3 % Slope Cutoff	955 GW dc (1,347 TWh ac)	1,042 GW dc (1,476 TWh ac)

Table 4
Summary of percent reservoir developable results by scenario.

	25 % Minimum Water Volume	35 % Minimum Water Volume
2 % Slope Cutoff	28.1 %	33.6 %
3 % Slope Cutoff	32.7 %	37.1 %

developable—reflecting even in the flattest of reservoirs there will still be localized areas of less floor suitability.

2.2.4. *Inlet, Outlet, and dam buffers*

Consultation with industry experts yielded a general rule that FPV should not be considered in areas where surface currents may exceed 2 m/s. Although areas closer to inlets and outlets are clearly more likely to experience swift currents than areas far from them, the distance from which FPV should be located is a function of the maximum flow rate and velocity of the inlet or outlet as well as the three-dimensional shape of the reservoir at the location of the inlet and outlet and potentially the relative temperature and salinity of the inflowing water and the reservoir.

To approximate likely areas of current influence from inlets and outlets, monthly average predicted values for flowline velocity and flow volume were used from intersecting NHDPlusv2 flowlines. First, we determined whether the intersecting flowline is likely to exceed 2 m/s. The highest average monthly flowline velocity times a factor of 10 is assumed to be approximately the highest instantaneous velocity produced by the flowline. If this value is not greater than 2 m/s, a small 10-meter buffer from the inlet or outlet is assumed.

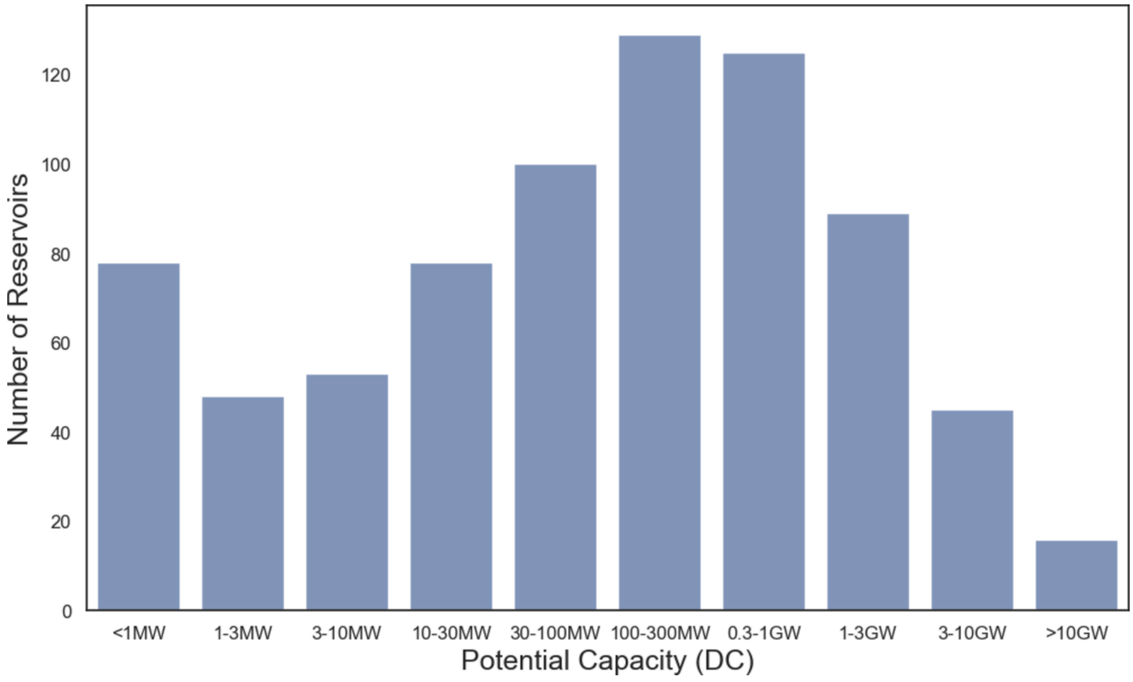

Fig. 2. Distribution of installed capacity of systems.

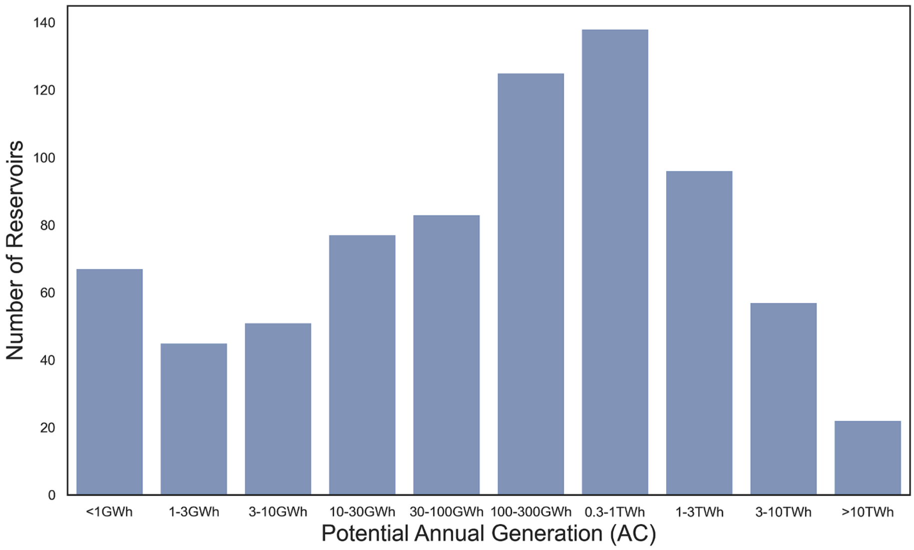

Fig. 3. Distribtuion of expected generation of systems.

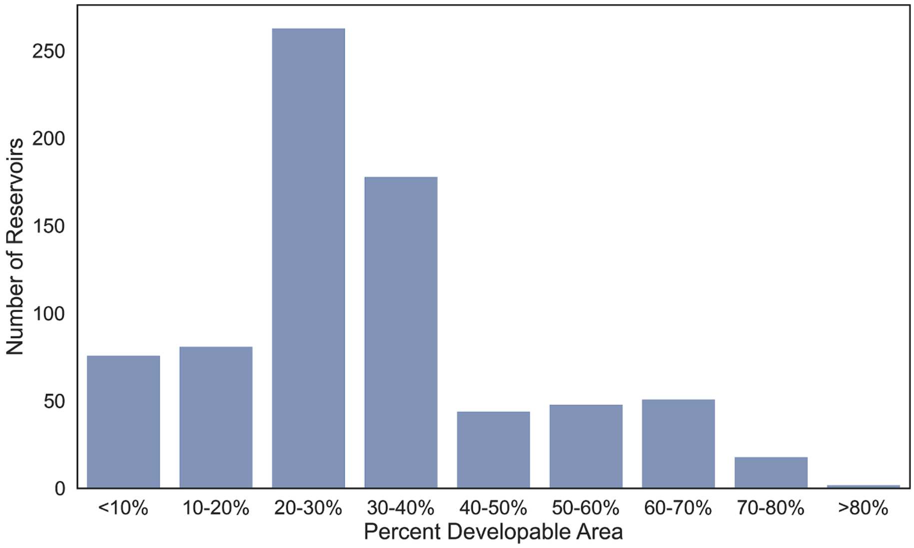

Fig. 4. Distribution of reservoir percent developable area.

In cases where this value does exceed 2 m/s, the distance from which the inlet or outlet may cause currents greater than 2 m/s is assumed to be proportional to the square root of the maximum monthly flow volume. Although this scaling is not mechanistically based, it is informed by the modeled tailrace and forebay currents modeled at a variety of water volume flows on several dams on the Columbia and Snake rivers [13]. The scaling was chosen so the buffer distances are roughly proportional to the hydraulic extents modeled for these dams at similar water volume flows. The report suggests the largest hydraulic extent seen in the sample dams is 11,500 feet in the tailrace of the Bonneville dam in the high-flow 450 cubic feet per second (kfs) rate scenario, whereas approximately a half a mile to a mile is more typical of hydraulic extents for dams modeled with flow rates of 120 kcfs or higher. As such, most inlets and outlets seen in the reservoirs of this study that have flow rates measured in the single-digit kcfs range are expected to have quite low areas of influence in terms of currents.

For a buffer from dams, representing a maintenance and safety area, a flat buffer of 100 m is assumed—although most dams are also outlet locations and may have greater buffers because of the current exclusion. Dam locations are found by snapping the point locations of nearby dams found in the National Inventory of Dams to the closest location on the exterior of the reservoir. Buffers for inlets, outlets, and dams are produced as vectors and converted into rasters for the final developable area analysis.

3. Results

Total developable area for each reservoir (see Fig. 1) was calculated by layering all rasters corresponding to the developable area criteria to find the remaining surface area of each reservoir that is not excluded by any criteria. This analysis was repeated for each of the four combinations of the two minimum reservoir volume thresholds and the two maximum reservoir floor slope thresholds. The final metrics calculated for each waterbody are total FPV developable area in meters squared, the percentage of the maximum reservoir surface area that is estimated to be developable, an estimate for the generation capacity in MWdc that that area could support by applying a power density assumption of 1 MWdc per hectare to the developable area estimates, and corresponding estimated generation in gigawatt-hours per year (GWh/yr). Generation estimates were calculated by associating waterbodies with the closest

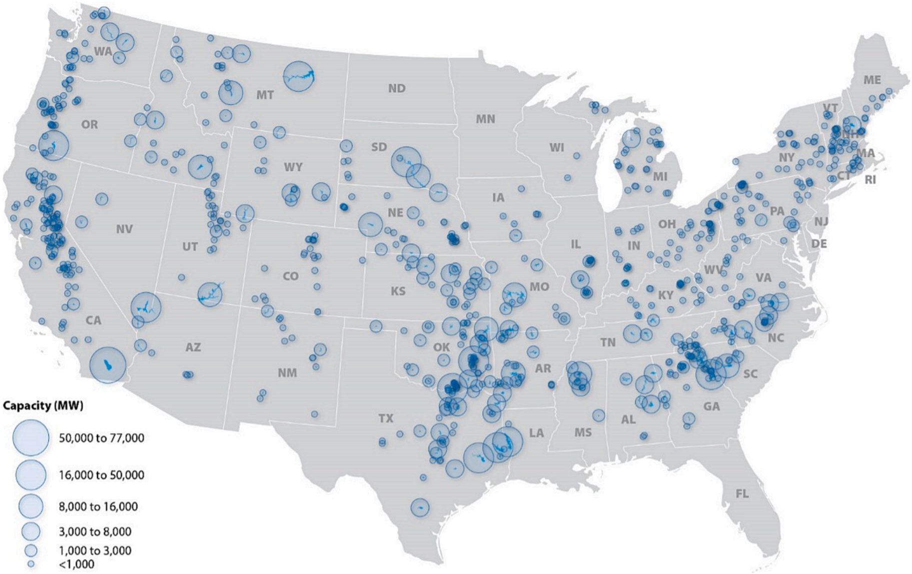

Fig. 5. Map of spatial distribution and size of potential FPV systems.

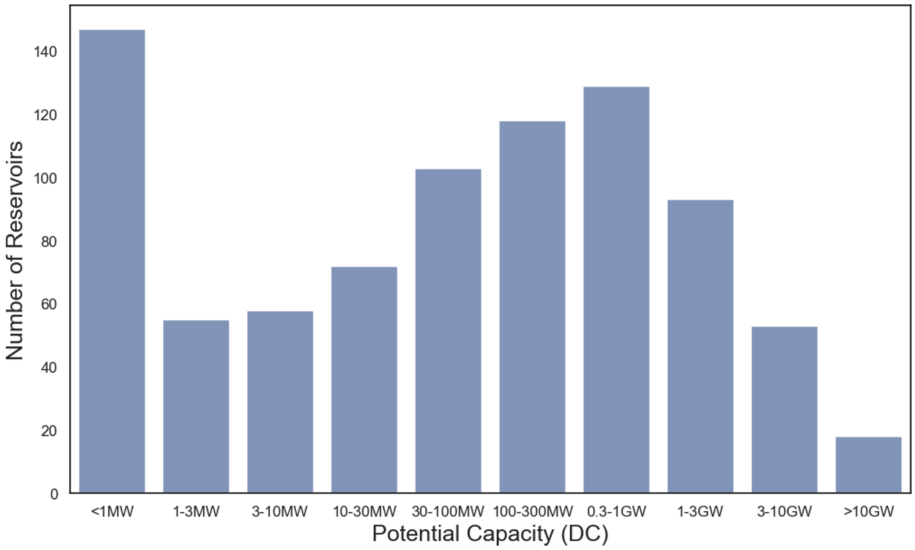

Fig. 6. Capacity distribution of reservoirs with 25% minimum fill assumption and 3% maximum slope assumption.

National Solar Radiation Database coordinate and modeling generation using the Renewable Energy Potential model (reV). Estimates assumed 8,760 operating hours per year, an 11-degree fixed tilt, a 0.7 ground cover ratio, a 1.3 inverter load ratio, and a multiplier of 1.03 to account for the cooling effect of water on FPV units.

This capacity density assumption is conservative and is meant to include the entire footprint of the development—not just panels and floats but required maintenance and safety buffers, fencing, and any other materials that take up waterbody area. This number was estimated based on an analysis of existing plants in the United States as of 2018 in Spencer et al. (2019); higher estimates have been used in the literature such as 1.2-MWdc in Mahmood et al. (2021), but we use the conservative estimate [4,14]. These values are high relative to ground-mount solar because of the low tilts and high panel packing densities used for FPV developments relative to ground mount. These configurations minimize wind loading and the number of floats needed at the trade-off of potentially higher cosine losses because of suboptimal tilt and higher interrow shading between panel rows; the magnitude of this trade-off is a function of latitude and irradiance regime.

3.1. *Sensitivity analysis*

The total estimated potential installed capacity in MWdc for each of the four scenarios is shown in Table 3. The average developable percentage of each reservoir for each of the four scenarios is shown in Table 4. Note this mean is not weighted by size of reservoir.

The estimated developable capacity ranges from 861 GW in the most restrictive scenario to 1,042 GW in the least restrictive scenario—an increase of 21 % vs. the most restrictive scenario. This is a meaningful difference; however, it does not represent a difference of magnitude large enough to suggest the thresholds used are poorly specified. These numbers are also broadly compatible with the Spencer et al. (2019) analysis finding a potential capacity of 2,116 GW in the United States on a less-restrained study population of reservoirs (including reservoirs not federally owned and managed with a total of 24,419 manufactured waterbodies considered). The analysis in Spencer et al. assumed a flat 27 % developable area that was based on the average waterbody coverage of existing FPV installations in the United States. The average developable percentages seen in our assessment range from 28.1 % in

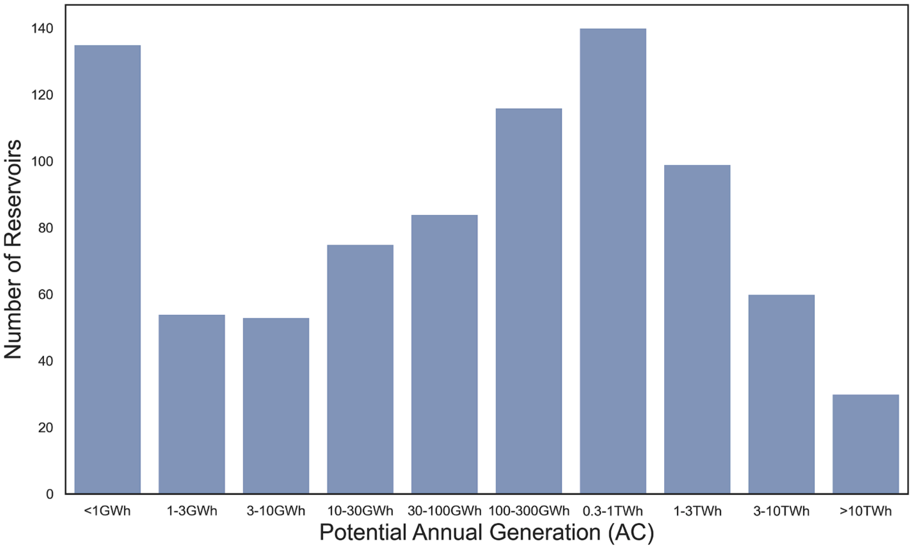

Fig. 7. Estimated annual generation of reservoirs with 25% minimum fill assumption and 3% maximum slope assumption.

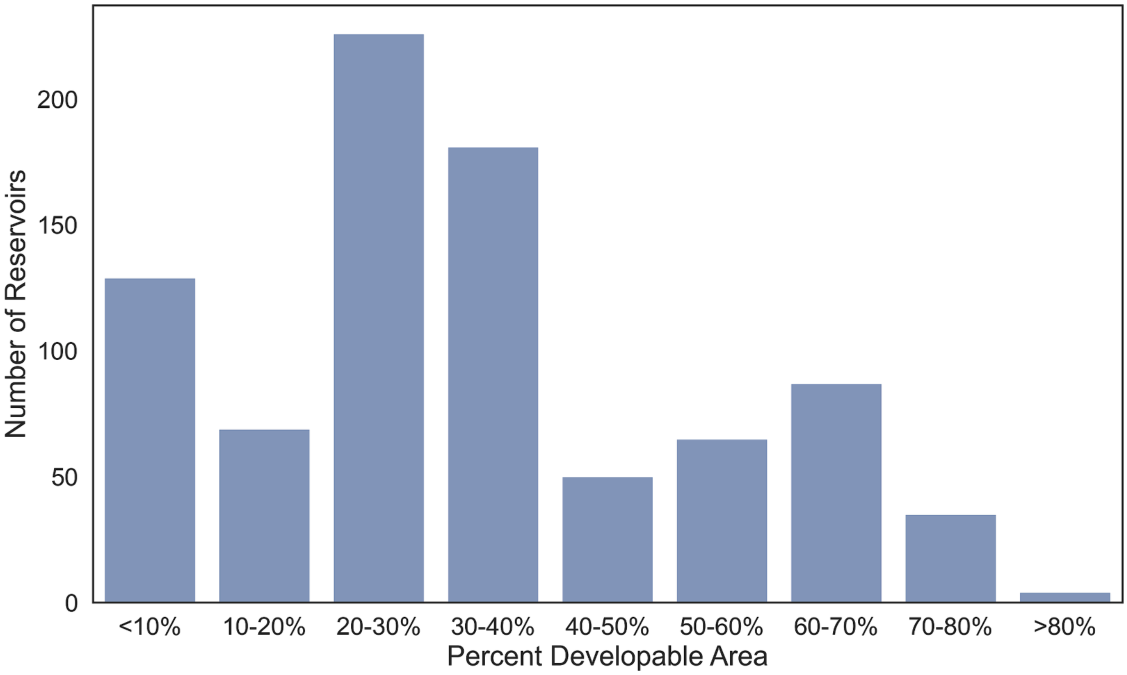

Fig. 8. Percent developable distribution of reservoirs with 25% minimum fill assumption and 3% maximum slope assumption.

the most restrictive scenario to 37.1 % in the least restrictive scenario, a range higher than the average 27 % found in the Spencer et al. (2018) assessment. This is potentially because our analysis considers only technical barriers to development, whereas the analysis of area used by existing installations reflects other regulatory, social, and economic barriers as well.

We believe our sensitivity analysis does not provide any reason to assume the criteria chosen are unreasonable when applied as single thresholds across such a heterogenous population of study reservoirs. Such single thresholds are certainly overly conservative or liberal on a case-by-case basis but likely represent a reasonable approximation of potential capacity on average using novel, spatially explicit methods tailored to specific factors affecting FPV development. For brevity and to present the potential conservatively, from this point the size and spatial distribution of only the most restrictive scenario will be discussed. Summary charts for other scenarios are included in Appendix C.

3.2. *Size distribution*

Of the 846 systems considered, 85 or just over 10 % of the reservoirs were found to have a developable capacity of 0 MW, either because of being too shallow or being small and excluded by inlet, outlet, or dam buffer exclusion zones. The potential system size distribution of the remaining 761 reservoirs is shown in Fig. 2. The corresponding potential generation distribution is shown in Fig. 3.

The size of estimated potential systems ranged from 10 kW direct current (kWdc) to 76.6 GW direct current (GWdc). Although 10 kW likely represents an unrealistically small system, only a small proportion of reservoirs are estimated to be in this far left-hand side of the distribution: 2.5 % of reservoirs with nonzero capacity estimates have

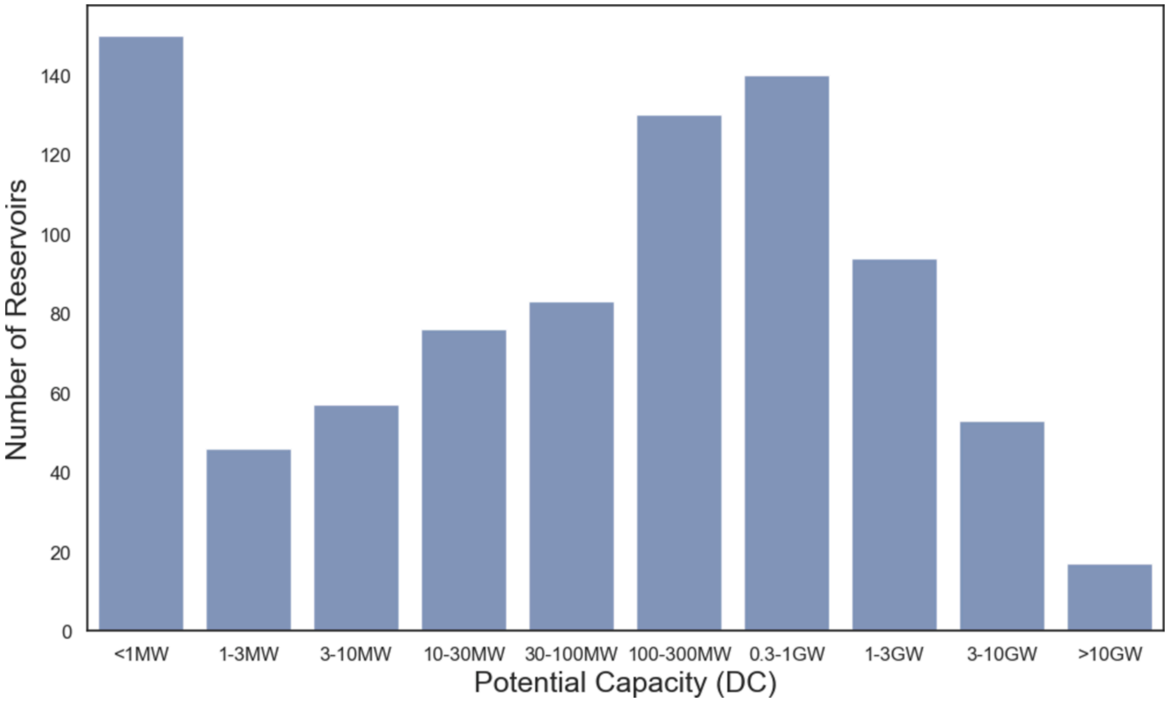

Fig. 9. Capacity distribution of reservoirs with 35% minimum fill assumption and 2% maximum slope assumption.

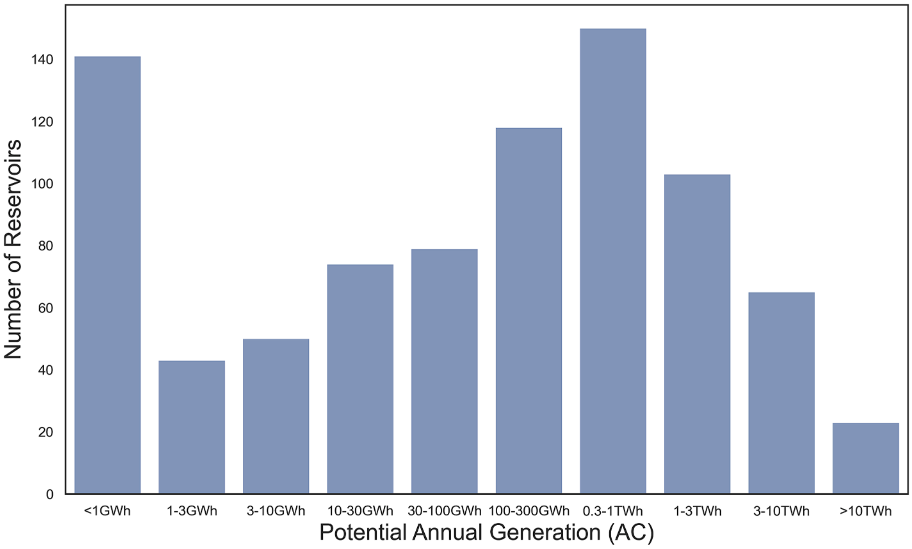

Fig. 10. Estimated annual generation of reservoirs with 35% minimum fill assumption and 2% maximum slope assumption.

estimated sizes below 100 kW, and 10 % of reservoirs with nonzero capacity estimates have estimated sizes below 1 MW. Most reservoirs—57 %—are between 10 MW and 1 GW in size with a median of 123 MW. The estimated generation of potential systems ranged from 12 MWh/yr to 130 TWh/yr. Approximately 35 % of waterbodies have an estimated generation between 100 GWh/yr and 1 TWh/yr.

The wide range of system sizes reflects not only differences in estimated developable percentage between reservoirs but also the large variation in the size of reservoirs in the study population. The distribution of developable percentages for reservoirs, controlling for this factor, is shown in Fig. 4.

The estimated developable area percentages for reservoirs with nonzero capacity range from 2 % to 81 %. Although estimated percentages anywhere along this range are not rare, there is a marked clustering of estimates around the median estimate of 28 %, with 58 % of reservoirs having estimates between 20 % and 40 %. Despite this clustering of reservoirs at the central tendency, the range of developable area estimates produced shows how important the spatially explicit criteria considered in this assessment are; flat percent developable assumptions can be either significantly low or high depending on site-specific factors.

3.3. *Spatial distribution*

A map of the spatial distribution of results is shown in Fig. 5.

FPV potential is well-distributed throughout the country outside of the areas where the cold temperature cutoff removed potential reservoirs from consideration. The reservoirs with the largest capacities are

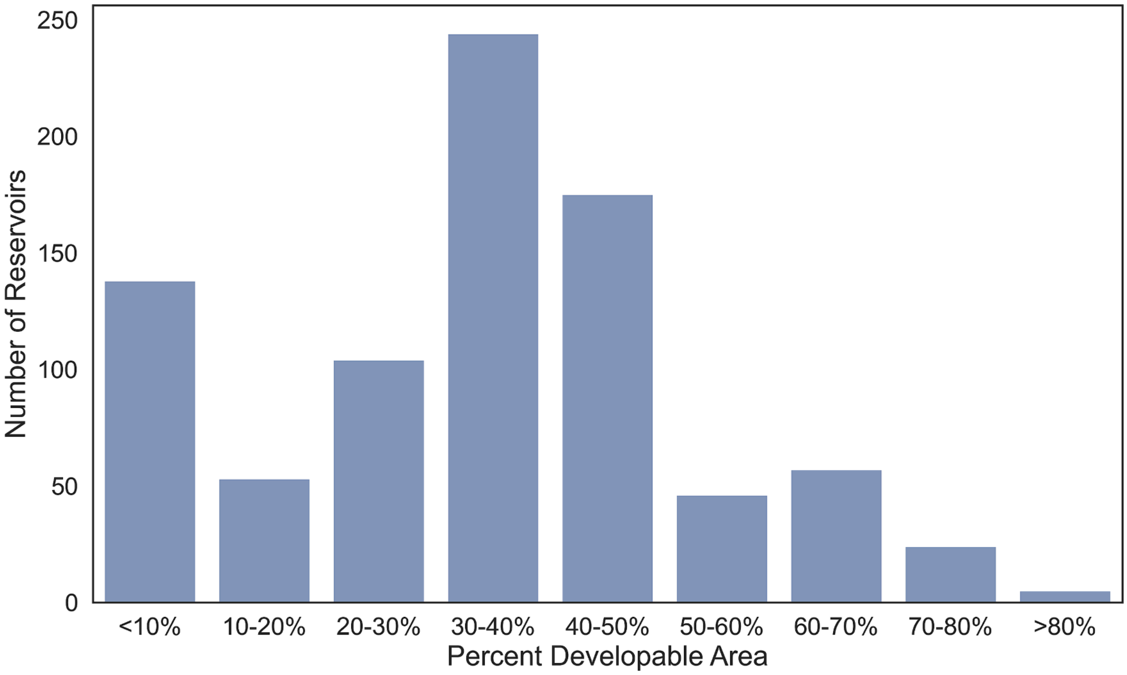

Fig. 11. Percent developable distribution of reservoirs with 35% minimum fill assumption and 2% maximum slope assumption.

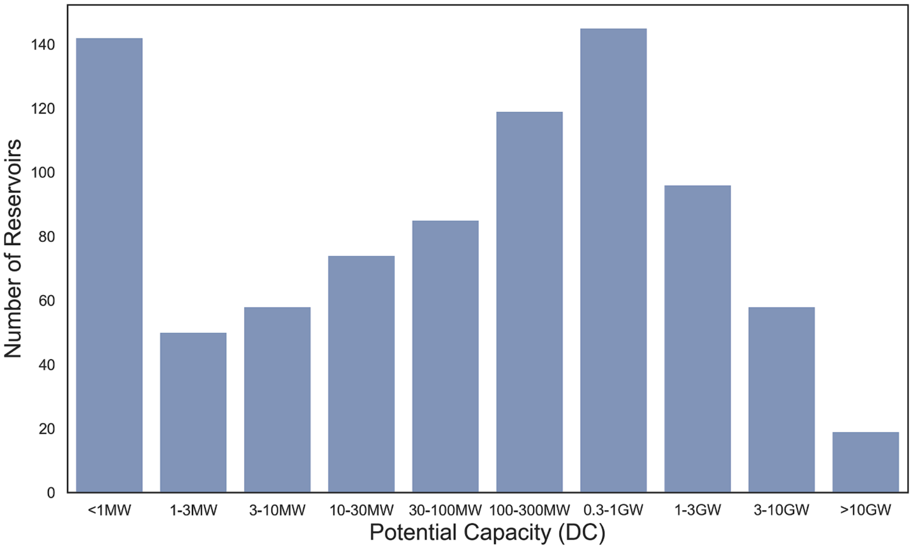

Fig. 12. Capacity distribution of reservoirs with 35% minimum fill assumption and 3% maximum slope assumption.

generally found in the southeast and southern plains states where dense river networks support large numbers of reservoirs built for flood control, hydropower, and other mixed uses. Associating potential capacity by state by assigning capacity in reservoirs that cross state boundaries via area weighting shows three states are outliers in sum capacity relative to other states: Texas, California, and Oklahoma with 137, 102, and 84 GW of potential capacity, respectively. The state with the next largest capacity is Montana with 44 GW; the median state has a potential capacity of 9.6 GW. Under this conservative scenario, Texas contains approximately 16 % of the nation's total FPV capacity.

4. Discussion and limitations

The results of this assessment show two primary takeaways:

1. Accounting for specific technical limitations relevant to FPV development, there is still likely a very high technical potential for FPV on reservoirs in the United States. Even in the most conservative scenario considered for this subset of federally owned and regulated reservoirs, the estimated potential for FPV is more than half the PV capacity estimated to be required for a decarbonized U.S. electricity grid in 2050 (861 GW vs. 1600 GW) [15].
2. The spatially explicit criteria used in this study show the developable area of a reservoir expressed as a percent of the total area can vary widely, depending on site-specific factors for each reservoir. This highlights the shortcomings of methods that assume a flat percentage of reservoir area as developable and the need for continued work to refine these efforts.

As the first attempt to apply such methods for an assessment of FPV

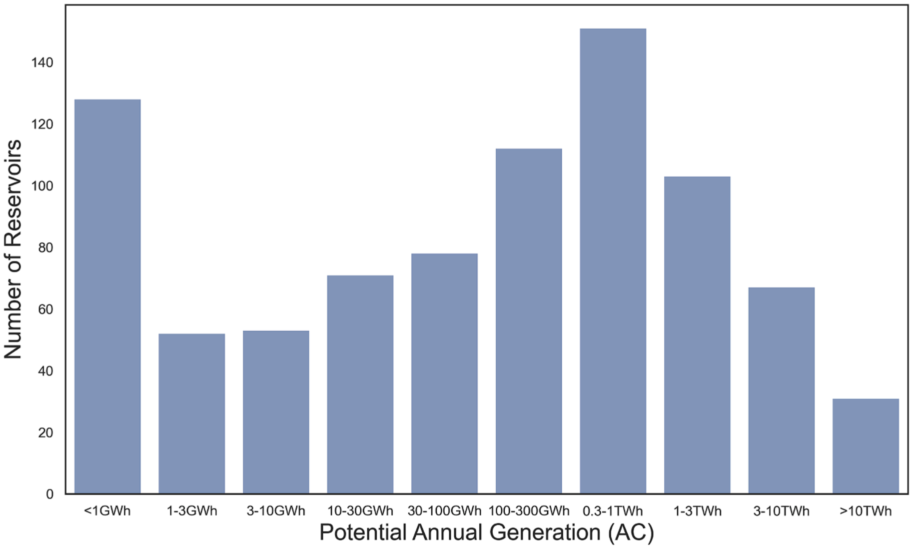

Fig. 13. Percent developable distribution of reservoirs with 35% minimum fill assumption and 3% maximum slope assumption.

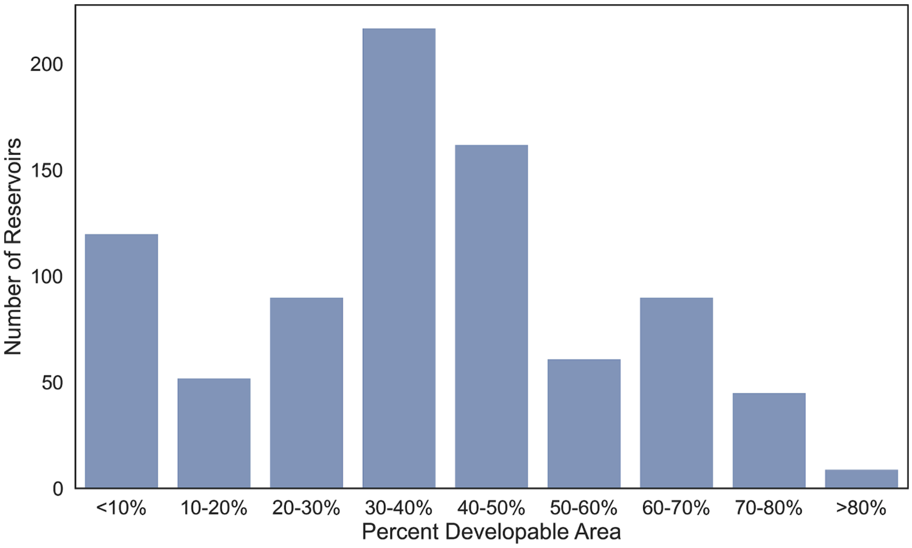

Fig. 14. Estimated annual generation of reservoirs with 35% minimum fill assumption and 3% maximum slope assumption.

potential, there are several limitations and potential extensions to this work in future.

As discussed previously, the purpose of this assessment is to assess the potential for FPV development purely from a standpoint of technical feasibility; the assessment does not consider limits to development posed by other regulatory, social, environmental, or economic factors—which are likely to be substantial. If these estimates are properly understood for what they are, they represent an important starting point from which more limitations can be added. For example, the results of this analysis could be used as a reference for an upper bound of the potential an environmental analysis could use to further constrain as a result of environmental factors. As a greater understanding of these potential limitations is achieved, adding them onto the current work in a spatially explicit manner serves as a natural extension of this work. Including development exclusions for recreation areas in reservoirs represents a straightforward and important example of such an extension.

Similarly, another extension of this work would be to apply similar methods to a less-constrained population of reservoirs, including other reservoirs, natural waterbodies, and potentially estuaries and marine offshore. It should be noted, however, the less similar the waterbody types are to the reservoirs considered in this paper, the more likely it is for different datasets to be required and different exclusion criteria to be developed and applied.

Of the criteria considered in this assessment, many depend on the modeled bathymetry data. Although this represented the best available option for complete coverage for the reservoirs considered, there are many potential shortcomings compared to actual bathymetric survey data. In addition to the modeled bathymetry being too smooth relative to real bathymetry, the form of most reservoirs considered in this assessment caused by dams placed along major rivers causes a bias in average depth along the direction of the river (upstream sections are more shallow; downstream sections are less shallow). This bias is not accounted for using GLOBathy's modeling algorithm. The impacts of the modeled data can be compared to real bathymetry where available and new algorithms developed to better represent dammed river reservoirs.

Although the spatially explicit exclusions of this assessment allow for considerably more tailored results to each waterbody than methods previously used for FPV assessment, many criteria used can be further specified to each waterbody instead of following study-wide thresholds. Specifically, cold climate exclusions could be further refined from a temperature cutoff to better represent actual ice floe and snow loading impacts. Reservoir minimum volume assumptions could be adjusted based on each reservoir's use and climate. The influence of changing climatic conditions could be examined on minimum reservoir volume and inlet/outlet buffers, which is not considered in this assessment.

5. Conclusion

This assessment outlines a novel geospatial method to assess FPV technical potential accounting for factors specific to FPV technology on federally owned and regulated reservoirs in the United States. The results of the analysis show ample technical potential for FPV development on these reservoirs, ranging from 861 to 1,042 GWdc depending on assumptions, which is consistent with previous studies that have attempted to quantify FPV potential. However, unlike these studies, this assessment shows high variability of reservoir suitability for FPV development based on site-specific factors. This serves as an important improvement that will help better inform not only how much FPV capacity may be available but also where this capacity may be more likely to be built.

CRediT authorship contribution statement

Evan Rosenlieb: Writing – original draft, Methodology, Investigation, Conceptualization. **Marie Rivers:** Writing – original draft, Visualization, Methodology, Data curation. **Aaron Levine:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

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

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Appendix A. . Table of previously published assessments

Title	Extent	Waterbody Input Dataset	Study Area Criteria	Developable Area Criteria
Floating photovoltaics systems on water irrigation ponds: Technical potential and multi-benefits analysis [16]	The province of Jaén in Spain	Waterbody Information maintained by the System of Multiterritorial Information of Andalusia	Artificial irrigation ponds	Flat percentage assumptions of 25, 50, and 100 % of waterbody surface area
Energy production and water savings from floating solar photovoltaics on global reservoirs [17]	Global	Global Reservoir and Dam Database (GRanD), Georeferenced Global Dam and Reservoir (GeoDAR), and OpenStreetMap (OSM)	All reservoirs	Flat percentage assumption of 30 % with a maximum size cap
Floating Solar PV and Hydropower in Australia: Feasibility, Future Investigations and Challenges [14]	Australia	Not clear	Hydropower reservoirs	Flat percentage assumptions of 1, 5, 10, and 15 % of waterbody surface area
Floating Photovoltaic Systems: Assessing the Technical Potential of Photovoltaic Systems on Man-Made Water Bodies in the Continental United States [4]	Continental U. S.	National Inventory of Dams (NID) from U.S. Army Corps of Engineers and National Hydrography Dataset (NHD) from USGS	Manufactured waterbodies filtered to exclude reservoirs below a minimum depth, below a minimum size, outside of a maximum transmission buffer, or with an incompatible primary use	A flat percentage assumption of 27 % of waterbody surface area
Techno-economic potential and perspectives of floating photovoltaics in Europe [18]	Europe	Global Reservoir and Dam Database (GRanD)	Manufactured waterbodies filtered to exclude reservoirs below a minimum depth, below a minimum size, or with an incompatible primary use	A flat percentage assumption of 1 % of waterbody surface area
Technical potential of floating photovoltaic systems on artificial water bodies in Brazil [19]	Brazil	Waterbody data maintained by the Brazilian Water Agency	Artificial/manufactured waterbodes outside of protected areas	A flat percentage assumption of 1 % of waterbody surface area
Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential [2]	Global	Global Reservoir and Dam Database (GRandD)	Freshwater reservoirs with filters to exclude reservoirs outside of a maximum distance from transmission lines outside of minimum and maximum latitude	Nine scenarios with varying shoreline buffers (minimum buffers of 0, 50, and 100 m and maximum buffers of 500, 1,000, and 2,000 m)
A sound potential against energy dependency and climate change challenges: Floating photovoltaics on water reservoirs of Turkey [20]	Turkey	Waterbody data maintained by the General Directorate of State Hydraulic Works	"Constructed water reservoirs," all purposes considered; filters to exclude reservoirs below a minimum water area and located within protected wetlands or special environmental reserve areas	A flat percentage assumption of 10 % water surface coverage
Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa [21]	Africa	Reservoir data from satellite data previously developed by authors	A total of the 146 largest hydropower reservoirs in Africa in 2016 with an installed capacity > 5 MW	Flat percentage assumptions of 25, 50, and 100 % of waterbody surface area

Appendix B. . Datasets used

Data Source	Dataset	Purpose
United States Army Corps of Engineers (USACE) Geospatial Data Portal	USACE Reservoirs	Identification of USACE reservoirs
USACE Geospatial Data Portal	National Inventory of Dams	Identification of location of dams on reservoirs; reservoir attribute cross-referencing
Bureau of Transportation Statistics (BTS) Open Data Portal	Navigable Waterways Network Lines	Identification of freight shipping routes
U.S. Bureau of Reclamation (USBR) RISE Data Catalog	RISE Point Location	Identification of USBR reservoirs
ORNL Hydrosource	EHA 2022	Identification of Federal Energy Regulatory Commission (FERC) hydropower project reservoirs
ORNL Hydrosource	HILARRI	Identification of FERC hydropower project reservoirs
USDA EPA	National Hydrography Dataset plus v2 Flowlines	Identifications of locations of inflows and outflows of reservoirs
USDA EPA	National Hydrography Dataset plus v2 Waterbodies	Waterbody polygons used to define waterbody extents; lake morphology data used to model bathymetry
USDA EPA	National Hydrography Dataset plus v2 Hydrology Rasters	Used to estimate waterbody depth for subset of reservoirs that did not already have value estimated
WorldClim	Average Minimum Temperature	Identification of areas prone to heavy freezing

Appendix C. . Summary charts of Additional scenarios

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