Environmental Science & Technology

Article

Cite This: Environ. Sci. Technol. XXXX, XXX, XXX−XXX

pubs.acs.org/est

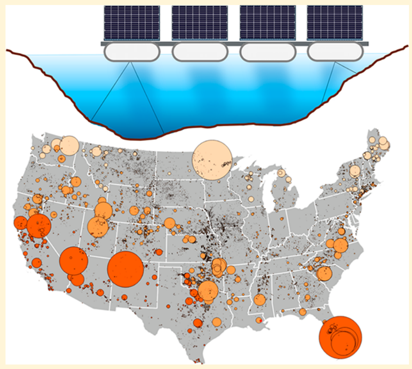
Floating Photovoltaic Systems: Assessing the Technical Potential of Photovoltaic Systems on Man-Made Water Bodies in the Continental United States

Robert S. Spencer,* Jordan Macknick, Alexandra Aznar, Adam Warren, and Matthew O. Reese

National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, Colorado 80401, United States

Supporting Information

ABSTRACT: Floating photovoltaic (FPV) systems, also called floatovoltaics, are a rapidly growing emerging technology application in which solar photovoltaic (PV) systems are sited directly on water. The water-based configuration of FPV systems can be mutually beneficial: Along with providing such benefits as reduced evaporation and algae growth, it can lower PV operating temperatures and potentially reduce the costs of solar energy generation. Although there is growing interest in FPV, to date there has been no systematic assessment of technical potential in the continental United States. We provide the first national-level estimate of FPV technical potential using a combination of filtered, large-scale datasets, site-specific PV generation models, and geospatial analytical tools. We quantify FPV co-benefits and siting considerations, such as land conservation, coincidence with high electricity prices, and evaporation rates. Our results demonstrate the potential of FPV to contribute significantly to the U.S. electric sector, even using conservative assumptions. A total of 24 419 man-made water bodies, representing 27% of the number and 12% of the area of man-made water bodies in the contiguous United States, were identified as being suitable for FPV generation. FPV systems covering just 27% of the identified suitable water bodies could produce almost 10% of current national generation. Many of these eligible bodies of water are in water-stressed areas with high land acquisition costs and high electricity prices, suggesting multiple benefits of FPV technologies.



INTRODUCTION

Floating photovoltaic (FPV) systems, also called floatovoltaics, are an emerging technology application in which solar photovoltaic (PV) systems are sited directly on bodies of water instead of land or buildings.[1,2] Competing uses for land and recognized co-benefits associated with siting FPV systems on water are driving factors in the development of this niche application.[3−6]

To date, FPV has been installed predominantly on man-made bodies of water, such as wastewater storage ponds, reservoirs, remediation and tailing ponds, and agricultural irrigation or retention ponds.[1,7] The first FPV installation came online in 2007 at the Far Niente Winery in California, yet the vast majority of existing systems (98%) became operational between 2014 and 2016.[1,8] As of 2017, global installed capacity was approximately 198 MW, with additional projects, including what will be the world's largest FPV system at 70 MW, expected to come online in 2018.[9] System sizes vary dramatically across the world, ranging from 4 kW to 40 MW.[1,7,9,10] FPV systems have also been installed in more than a dozen countries throughout Southeast Asia, Europe, North America, and the Middle East, but Japan has the majority[1] (80%) of FPV installed capacity, including 70 of the largest FPV systems in the world.[8,9,11] The United States has seen limited adoption of FPV to date, but institutions such as reservoir operations, water treatment facilities, and residential communities are increasingly exploring its applications.

FPV adapts modules used in traditional ground-mounted or rooftop PV, with important mounting design and configuration differences to enable flotation. FPV can be flat, tilted, or tracking.[7,12−15] Electrical equipment, such as inverters, typically resides on shore, and electricity is transmitted from the FPV system via floating or underwater cables. The buoy structures are anchored or tethered to land or the floor of the water body.[7,16] Some FPV systems are designed such that they can rest on the ground when or if the supporting body of water is drained. Systems must be designed to withstand fluctuating water levels, high wind and wave loads, and various extreme weather conditions. Saltwater in some tailings pond and seawater applications may pose additional challenges and require tailored mitigation measures (e.g., corrosion-resistant materials) as a result of the corrosive qualities of water with high salinity.[6,12,17]

FPV systems demonstrate unique energy and non-energy co-benefits compared to land-based PV systems. Research surrounding the performance of FPV systems is relatively

Received: August 23, 2018
Revised: November 8, 2018
Accepted: December 11, 2018
Published: December 11, 2018

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DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

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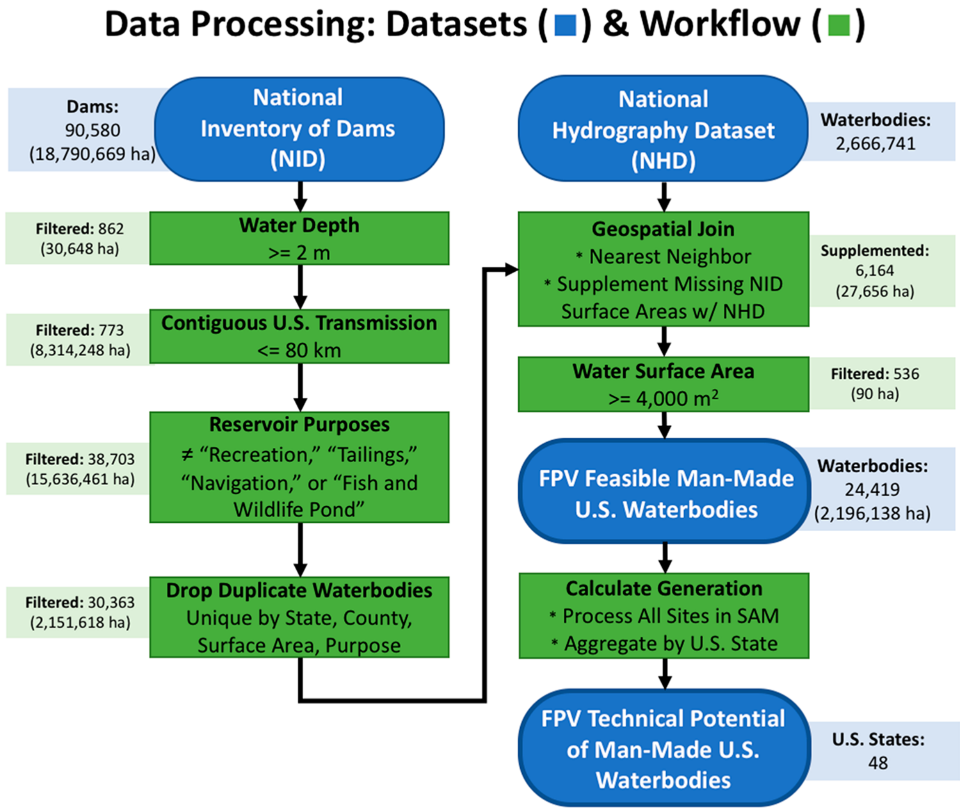

Figure 1. Overview of the data processing used to estimate FPV potential. All filter extents are relative to their original datasets (i.e., not mutually exclusive).

immature, but existing studies indicate that these systems experience power conversion efficiency gains as a result of lower ambient temperatures underneath the panels, regardless of whether the panels are directly or indirectly sited on water.[1,2,13,14,17−22] Power production gains of 1.5−22% have been documented as a result of the cooling effect of water on FPV systems.[17,20,23,24] The collocation and operation of FPV with hydroelectric facilities has also yielded multiple energy benefits, such as increased energy output, better ability to meet peak demand, and cost savings as a result of the existing transmission infrastructure.[24,25] Additionally, FPV systems reduce water evaporation on reservoirs by reducing airflow and absorbing solar radiation that would ordinarily be absorbed by water,[2,16,24,26,27] an attractive quality for water managers. FPV systems reportedly have minimal impact on wildlife, except for the often desirable reduction of algae growth.[7,21] However, it is unclear whether the same reduction in sunlight penetrating the water surface that purportedly reduces algae growth also adversely affects other aquatic life. FPV systems have been evaluated for potential synergies with aquaculture.[28] Avoidance of land-energy conflicts (e.g., fuel versus food, land for conservation) is another purported benefit of FPV,[6,23] and while there are anecdotal claims of lower land acquisition and site preparation costs for FPV compared to land-based PV, comprehensive cost data to confirm these claims is lacking.

FPV systems have emerged as a potential solution to address land-use requirements of PV in land-constrained areas. Roughly 7% (or 685 924 km^2) of the United States is covered by water, including all coastal and inland waters and the Great Lakes.[29] The various benefits of FPV could lead to water being a new key target of solar siting. Although the energy technical potential of different market segments of ground-based PV is well-known,[30] there has been no robust quantification of the technical potential of FPV in the United States to date. This paper further characterizes current FPV projects in the United States and internationally, provides national- and state-level estimates of FPV technical energy potential, and identifies how variations in land value, utility rates, and annual water evaporation rates showcase promising regions for siting FPV.

■ MATERIALS AND METHODS

This paper quantifies the technical potential for the deployment of FPV systems on man-made water bodies in the contiguous United States, subject to physical water body limits, reservoir usage restrictions, reservoir ownership, and proximity to the electric grid. We characterize the theoretical limit of available resources that could feasibly support the development of FPV and set the foundation for future analyses to consider market adoptability and economic potential. Our objective was to determine a conservative upper bound on the potential for FPV deployment in the U.S.

The following methods outlined below utilized free and open-sourced geoprocessing tools (PostgreSQL/PostGIS, Python, and QGIS) to clean, join, filter, and analyze the data as well as visualize the results. Figure 1 provides an overview of the process used to estimate FPV potential, and the source code can be found within the Supporting Information. The extent of the filters shown in Figure 1 are relative to the original dataset to highlight the individual influences of each assumption made, because they are not mutually exclusive (e.g., water depth and water surface area).

The scope of this work considers only the use of man-made bodies of water as a result of the assumption that artificially

DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
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created bodies of water would be more likely suitable for FPV development than natural bodies of water. This assumption serves to (1) provide a more conservative estimate, (2) address the fact that man-made reservoirs are already managed and, therefore, installing solar equipment is likely to be easier as a result of the presence of existing infrastructure/roads/etc., (3) address the fact that there might be greater environmental concerns associated with natural reservoirs, and (4) address that existing FPV projects are almost universally installed on "impounded bodies of water".[9] Therefore, as a proxy for identifying man-made bodies of water, we used the National Inventory of Dams (NID) of the United States Army Corps of Engineers, which provides a dataset of dam structures in the United States.[31] The criteria for the dams included in the NID are outlined in the Supporting Information.

In addition to identifying whether dams are man-made or not, the NID includes attributes such as reservoir surface area, maximum depth, owner types, and purposes. However, surface area was not comprehensive for all entries (missing 24.5%). To supplement the surface area data, we utilize the National Hydrography Dataset (NHD) of the United States Geological Survey, a digital geospatial dataset that maps the surface water of the nation's drainage networks and related features, including rivers, streams, canals, lakes, ponds, glaciers, coastlines, dams, and stream gages.[32] To join these datasets, we performed a spatial collocation on each NID coordinate to find the closest body of water within the NHD using nearest neighbor geoprocessing tools in QGIS. The NID designates the location of the dam structure, and therefore, the coordinates would fall on or near the edge boundary of the NHD water body.

The attributes in the NID allow for additional filtering and characterization based on current FPV projects, including water depth (Figure S3 of the Supporting Information) and surface area (Figure S4 of the Supporting Information). To maintain a conservative estimate and to reflect current industry trends, we used the 10th percentile as the filter criteria, resulting in a minimum threshold of 1 acre (4000 m^2) surface areas and 7 ft (2 m) depths. The depth criteria eliminated 1% of sites and 0.2% of area from the total, while the minimum size criteria eliminated 0.6% of sites and <0.01% of area from the total. We then produced a subset of the data from these criteria by filtering the data with PostgreSQL.

Furthermore, all sites located >80 km (50 miles) away from transmission lines were considered infeasible for the scope of this study (although there could be an additional potential and unique benefit for these remote areas in an international or development context). Man-made bodies of water within 80 km of U.S. ABB's Ventyx provided electric transmission line data for the contiguous United States[33] represent approximately 44% of the surface area of man-made water bodies in all U.S. territories. Using PostgreSQL/PostGIS, we applied an 80 km (50 mile) buffer to these shapefiles containing geospatial line data and then dissolved them into polygons within QGIS to create a clipping mask, which was trimmed further to the boundaries of the contiguous United States and then used to filter out nonfeasible water bodies.

We further filtered these potential bodies of water by their identified purposes. The NID "Purposes" attribute includes a list of all designated purposes of the water body, with the first purpose listed representing the primary purpose. All reservoirs that include any "Recreation", "Tailings", "Navigation", or "Fish and Wildlife Pond" purpose tags were removed as nonfeasible (83% of potential surface area). While the utilization of tailings ponds would be an ideal use of space, they were removed as a result of the uncertain impact of their harsh corrosive environments on FPV systems. It is also possible that some reservoirs with recreational or navigational activities could be suitable for FPV, but the coverage of these reservoirs is uncertain as a result of the potential for usage conflicts; therefore, these were excluded. The remaining water bodies were recategorized by their primary purpose into the following groups: "Water Supply", "Irrigation", "Hydroelectric", and "Control, Stabilization, and Protection".

Finally, because the NID dataset is a representation of dam structures, we cleaned the dataset to represent unique water bodies, because there are many cases where multiple dam structures are associated with the same reservoir. The duplications of water bodies were filtered out by finding unique combinations of state, county, purposes, and surface area. This filtering resulted in the removal of 11.5% of the NID records and 33.5% of the total surface area.

With a new filtered dataset of feasible locations, we scripted the System Advisor Model (SAM) tool[34] to calculate the electric generation at each dam coordinate. On the basis of the characterization of area-to-capacity ratios of current FPV projects (Figure S2 and Table S2 of the Supporting Information), we calculated a capacity density of 10 000 m^2/MW. Additionally, we assumed 27% system coverage of the water surface area based on the median value of current FPV projects shown in Figure S5 of the Supporting Information, because there is very little correlation between the water surface area and system coverage within the current characterized projects (Figure S6 of the Supporting Information). We used a specified tilt angle of 11°, which is commonly used for FPV installations, resulting in high-density arrangements.[15,35] Higher tilt angles are generally not deployed in FPV settings as a result of concerns about wind loading, shading that would occur from densely packed panels, and increased material costs that would arise from installing at higher angles. All other assumptions were set by the SAM default settings, which are based on the most recent standard installations in the United States, including panel/system efficiency and fixed-tilt rigging. We simulated annually generated output for each water body (calculated through SAM), then aggregated for the sum of generation and surface area within each state, primary owner, and primary purpose using Python. These aggregations were then joined to U.S. state shapefiles in QGIS to be geospatially visualized in the figures provided in the Results and Discussion.

With the locations of feasible water bodies already identified, we estimated the current net evaporative losses (without any FPV mitigation) using the weather station statistics input files used by the Cligen model developed by the United States Department of Agriculture (USDA).[36] Cligen is a stochastic weather generator that produces daily estimates of precipitation, temperature, dew point, wind, and solar radiation for a single geographic point, using monthly parameters (means, standard deviations, skewness, etc.) derived from the historic measurements.[36] Using the monthly data of 2648 stations in the contiguous United States from station input files of Cligen, we calculated the net evaporative monthly losses at each station from the Penman–Monteith equation

DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
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$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the net evapotranspiration (mm/day), T is the temperature (°C), Δ is the slope of the vapor pressure–temperature curve (kPa/°C), G is the soil heat flux (MJ m^{-2} h^{-1}), γ is the psychometric constant (kPa/°C), R_n is the solar radiation (MJ m^{-2} h^{-1}), u_2 is the wind speed at 2 m above the water surface (m/s), e_s is the saturated vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).[37] The temperature (T) was estimated as the average of maximum and minimum temperatures. Wind speed was calculated by taking the weighted average of 16 wind directions (i.e., N, NNE, NE, ENE, etc.) The soil heat flux (G) was assumed to be 0.0 for open surfaces of water bodies. Intermediary calculations were required to determine Δ, e_s, and e_a using the following equations:[37]

$$\Delta = \frac{4098(0.6108)\exp\left(\frac{17.27T}{T+237.3}\right)}{(T + 237.3)^2}$$

$$e_s = 6.11 \times 10^{(7.5T/237.3+T)}$$

$$e_a = 6.11 \times 10^{(7.5T_{dew}/237.3+T_{dew})}$$

With the sum of monthly net evaporative losses calculated at each of the 2648 coordinates spanning the United States, we calculated an annual evaporation raster by using a linear triangular interpolation within the QGIS geoprocessing plug-ins to obtain continuous coverage between stations. The feasible FPV locations were then spatially collocated on the resulting raster by intersection in QGIS to extract the approximated annual evaporation rates over individual water bodies. Evaporation rates for individual water bodies are reported in the Results and Discussion as well as the state-aggregated volumetric evaporative losses calculated by multiplying the local evaporation rates by the water body surface areas and then summed by state.

Land values were obtained from the USDA[38] as the average value of croplands and pastures in each state for 2017. These values were tabularized and joined to state shapefiles in QGIS to be visualized alongside the cumulative potential FPV surface area. Land area calculations of ground-mounted PV installations are assumed to be 6 acres/MW (24 000 m^2/MW) based on data from Choi et al.[14]

We obtained utility retail costs from the U.S. Energy Information Administration[39] as the average utility retail rates within each state in 2016. These values were tabularized and joined to state shapefiles in QGIS to be visualized alongside the cumulative potential FPV generation.

RESULTS AND DISCUSSION

Current FPV Projects and Generation Potential. The technical potential of FPV systems in the United States was calculated on the basis of assumptions derived from current configurations of existing FPV systems implemented internationally. We calculated an average system capacity density of 10 000 m^2/MW from an evaluation of 51 projects ($R^2 = 0.994$) throughout the world. As shown in Figure S2 and Table S2 of the Supporting Information, this density is much higher than that of land-based systems, which are represented by green, blue, and yellow dashed lines as fixed, 1-axis, and 2-axis installations, respectively. This is a result of positioning FPV panels at a lower tilt angle (~11°) than their land-based counterparts. This allows for panel rows to be spaced much closer to one another. The trade-off is that the low tilt is no longer optimized for maximum incident solar, particularly at the higher latitudes. Further research is needed on the optimal tilt angle for FPV systems in the U.S. While there is an increase in capacity per acre for lower angles, there is a loss in the effective generation of an individual panel.

According to the NHD, there are 2 666 741 water bodies spanning the United States. Of these, there are 90 580 dammed water bodies, making up about 3.4% of the total. We identified 24 419 of the dammed water bodies as being feasible for installing FPV based on the screening criteria outlined above. The error originating from the geospatial join to the NHD to supplement surface areas is estimated to be less than 2% (an underestimate) as a result of inaccurate joins to adjacent water bodies and/or disagreements between datasets. The supplemented surface areas from NHD only accounted for around 1.3% (27 656 ha) of the total surface area (2 196 138 ha) considered for FPV potential. This error and its derivation is discussed further in the Supporting Information. This dataset provides a conservative starting point, because there are man-made water bodies that are not included in the NID dataset (see NID dataset criteria in the Supporting Information) and it could be feasible to deploy FPV on natural water bodies or reservoirs that were excluded from this analysis. For instance, the FPV system installed in 2007 on the irrigation pond at Far Nientes Vineyard is excluded from this dataset, because it does not meet the criteria specified by NID (shown in the Supporting Information). Although this limitation results in the underestimation of the true technical potential (not including very small water bodies), the NID still provides the best source of reliable data in which to determine any level of siting feasibility at the national scale. Further state- or regional-level studies would benefit from higher fidelity datasets with comprehensive records, including adequate attributions to establish site feasibility.

As shown in Figure 2, if 27% of the surface area of all 24 419 eligible water bodies in the United States were utilized, 2116 GW of installed FPV could produce 786 TWh of electricity per year, roughly 9.6% of 2016 electricity production in the United States.[39] Generation amounts scale linearly with water body coverage, meaning potential generation would double if 54% of eligible water bodies were to be covered by FPV infrastructure. Varying the tilt angle from 5° to 15° led to a change in annual generation of −4 and +2%, respectively, from the 11° standard assumption, assuming constant capacity for a given area. Although changing the tilt angle could result in some variations in panel densities and capacities, this capacity difference was not addressed in the sensitivity analysis as a result of a lack of empirical evidence.

The states with the highest generation potential are relatively dispersed throughout the country. Even though we would expect the southwestern states to dominate with an abundance of solar resources and overall state area (including both land and water), other states have comparable generation potential as a result of a higher availability of feasible water body surface area. Smaller states in the Mid-Atlantic and Northeast have lower generation potentials, limited by their size.

Normalizing FPV potential by current electricity generation in each state shows that FPV generally provides a higher percentage of total state generation in the western United

DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
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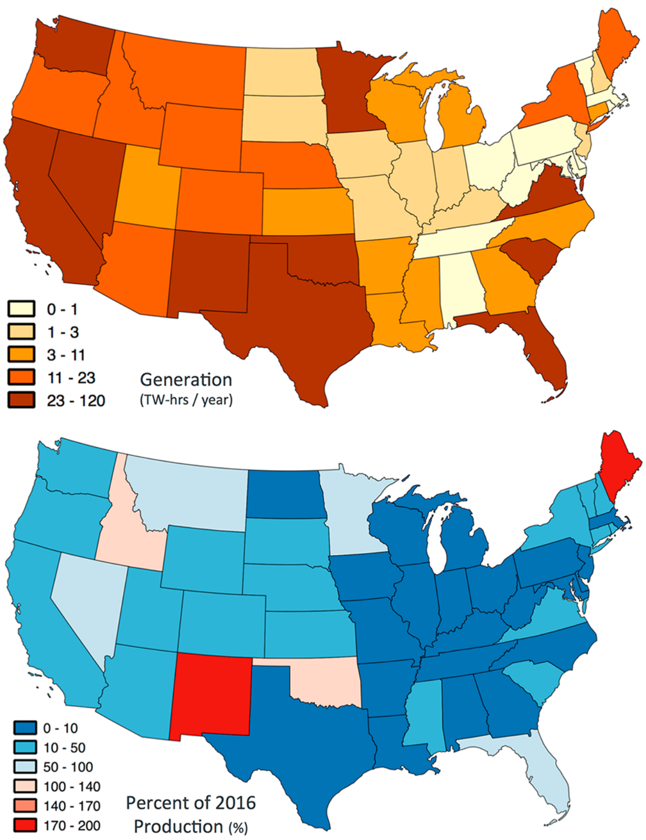

Figure 2. (Top) Potential annual generation of FPV systems covering 27% of feasible U.S. water bodies. (Bottom) Potential annual generation by FPV systems covering 27% of feasible U.S. water bodies as a percentage of the annual production in 2016 by state.

States than in the eastern United States (Figure 2). While the national production potential is 9.6% of current generation, there is substantial regional variation. Four states (Idaho, Maine, New Mexico, and Oklahoma) have FPV generation potential that exceeds current total production in their respective state, whereas 22 states have FPV potential that could contribute less than 10% of current total production.

The feasibility and attractiveness of deploying FPV technologies can be dependent upon primary purposes and ownership of water bodies (Figure 3). FPV potential from water bodies with irrigation as the primary purpose is concentrated in the western United States, whereas FPV potential from hydroelectric, water supply, and control/stabilization/protection reservoirs is more uniformly distributed throughout the country. Considering the primary purpose, the control/stabilization/protection-purposed water bodies account for 47% of all FPV generation potential. For primary ownership, federally owned water bodies account for the plurality of potential FPV generation, at 42% (Figure 3). The makeup of FPV potential by primary purpose varies based on reservoir ownership. For example, federal- and state-owned water body FPV generation potential is dominated by control/stabilization/protection water bodies, but public utility and private owner reservoir FPV potential is dominated by hydroelectric FPV potential. Local-government-owned reservoir FPV potential is primarily composed of control/stabilization/protection and water supply purposes.

Potential Co-benefits and Siting Considerations of FPV. FPV technologies have the potential to provide additional non-energy benefits. Studies have addressed how FPV can be integrated with aquaculture activities as well as water treatment facilities to reduce algae blooms.[1,28] In this section, we quantify some other co-benefits and siting considerations of FPV as they relate to land conservation, local electric utility rates, and evaporative losses.

One major benefit of FPV is the opportunity for land conservation, where the implementation of FPV does not compete with lands used for other purposes, such as crop and pasture land in agriculture. Just as rooftop solar can be suitable in highly dense and high-value urban areas, FPV can alleviate the land demand of traditional ground-mounted PV and avoid costs of land acquisition in expensive areas. Figure 4 illustrates the average value of crop and pasture land by state (as dot color) and the potential accumulated land area (as dot size) that would be saved using FPV over land-based PV installations (on the man-made bodies of water identied by the screening process outlined above). Nationally, there are roughly 2 141 000 ha of potential land savings. The greatest amount of water surface area available is around 309 000 ha in Florida, which is approximately 1.8% of the total area of the state. Additionally, Florida is covered by an abundance of small ponds that are not represented in these results, further suggesting that this state in particular could be significantly underestimated. Florida and California are both states that have a relatively large amount of potential water surface area while also having relatively higher cost land values of $18 323/hectare and $16 816/hectare, respectively. Six of the seven FPV projects currently installed in the United States are located in these two states. New Jersey has the highest average land value of $31 506/hectare and is home to the seventh FPV project. The national average is about $9738/hectare. Table S1 of the Supporting Information provides tabulated values of average land values by state as well as potential surface area.

Another benefit and siting consideration is the incentive of PV market adoptability to generate electricity within service areas of high local utility costs.[40] Figure 5 shows the average retail utility cost (as dot color) and the potential FPV generation (as dot size). California has favorable generation potential with high retail utility costs at 15.5 cents/kWh, while the median cost across all states lies at 9.5 cents/kWh. Table S1 of the Supporting Information provides tabulated values of average retail utility rates by state in cents/kWh. FPV or PV systems in general have the potential to be strong economic alternatives to providing distributed or utility-scale energy production.

The coverage of a reservoir with a FPV system may provide the benefit of mitigating evaporative losses, particularly in hot, arid regions. The calculations and interpolations between stations provide a continuous value map for the net evaporation rate (measured empirically as pan evaporation) at any point across the United States, as shown in Figure 6. The rate ranges from below 90 cm/year in the Northeast to more than 245 cm/year in the dry and arid Southwestern states.

Derived from this data, Figure 6 shows every feasible body of water for FPV installation; the dot color designates the net evaporation rate and the dot size is proportional to the annual evaporation by volume from the reservoir. There is a substantially larger amount of volume lost per reservoir in the southern states where there is larger and sparser water bodies, while there is an abundance of smaller water bodies spread throughout other areas of the United States. The large

DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
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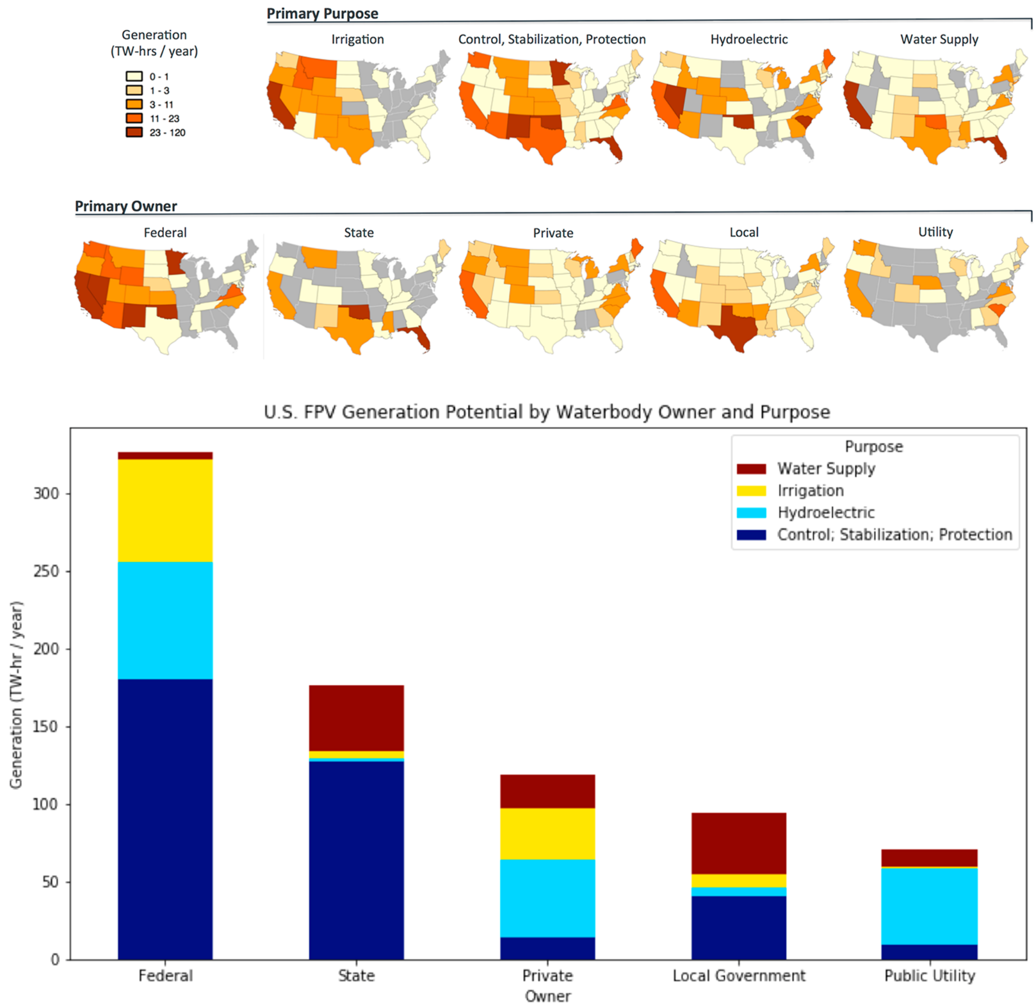

Figure 3. (Top) Potential annual generation of FPV systems covering 27% of feasible U.S. water bodies, categorized by the primary purpose and primary owner of the water bodies.

outlier in Minnesota (Lower Red Lake) has a low evaporation rate but is nevertheless impacted by large evaporative losses as a result of its large surface area of over 125 000 ha. Figure 6 shows total annual volumetric evaporation in each state, and Table S1 of the Supporting Information presents tabulated values. The amount of this evaporation that could be avoided through the installation of FPV technologies would depend upon the FPV technology selected, water body coverage, and specific characteristics of each reservoir, which are beyond the scope of this technical potential study.

Limitations. The field of implementing PV systems over water is a nascent field, with just over 100 projects internationally and seven projects in the United States as of the end of 2017. Most of what we know about FPV is derived from this limited number of projects and has formed the assumptions on which this assessment of its technical potential in the contiguous United States is based. With this limited number of projects (the majority of which are less than 2 years old), there is a lack of empirical data documenting long-term system performance, financial burdens, operations and maintenance, material science, environmental impacts, and other key factors. With the rapid expansion of projects coming online both domestically and internationally and the growing interests in FPV research, we can expect an equally rapid increase in case studies and publicly available data to follow. This burgeoning attention will open the doors to answering questions about realistic expectations for a FPV system. To address these long-term knowledge gaps, research needs to be conducted on the material durability of FPV, such as how these systems may endure in various climates and conditions.

Although this paper calculates the technical potential for FPV systems using geospatial tools, there are other site-specific limitations that may affect the feasibility of a certain location. The high-level data used and analyzed lacks the resolution for case-by-case feasibility, and the results should only be considered as a starting point for national and regional examinations. This analysis is an approximation and can only be as good as the dataset on which it is based. Further analyses should be conducted to look at the technical potential at the state level with higher fidelity datasets and perform case studies on individual water bodies.

Along with the need for further analysis to determine the feasibility of implementing FPV, additional research is needed to understand the added benefits of using water-based installations compared to land-based counterparts. For instance, the evaporative losses quantified in this paper are aggregated as a large-scale approximation simply to capture the extent of the potential impact and lack the granularity and precision at the local level. There is uncertainty associated with the extent to which FPV, with varying levels of water body

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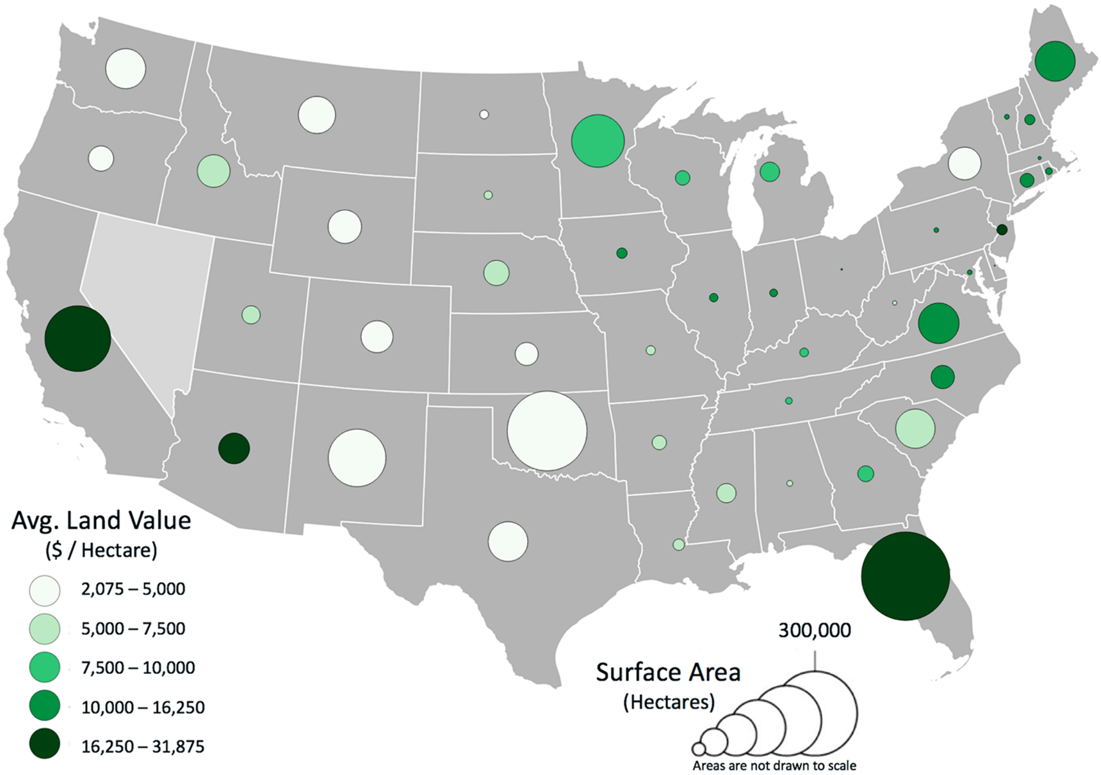

Figure 4. Cumulative surface area (dot size) of feasible U.S. water bodies for FPV installation by state and the associated average land values for the state (dot color). Circles are not drawn to scale of states.

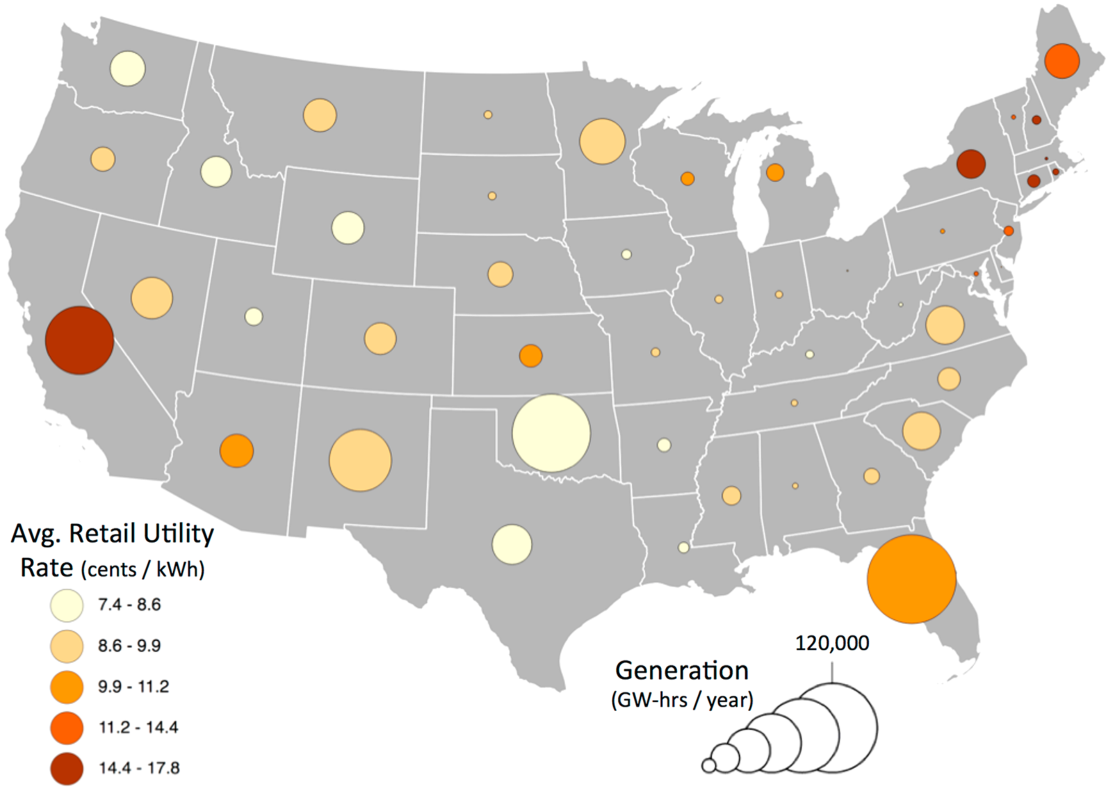

Figure 5. Potential generation (dot size) of FPV installations on feasible U.S. water bodies by state and the associated average retail utility rates for the state (dot color).

coverage, reduces evaporation in various regions. Furthermore, water markets are complex, with high regional and temporal variability, and attempting to assess the economic impact on the national scale is beyond the scope of this study. Targeted case studies can empirically measure evaporation reductions, water quality improvements, panel efficiency gains, equipment

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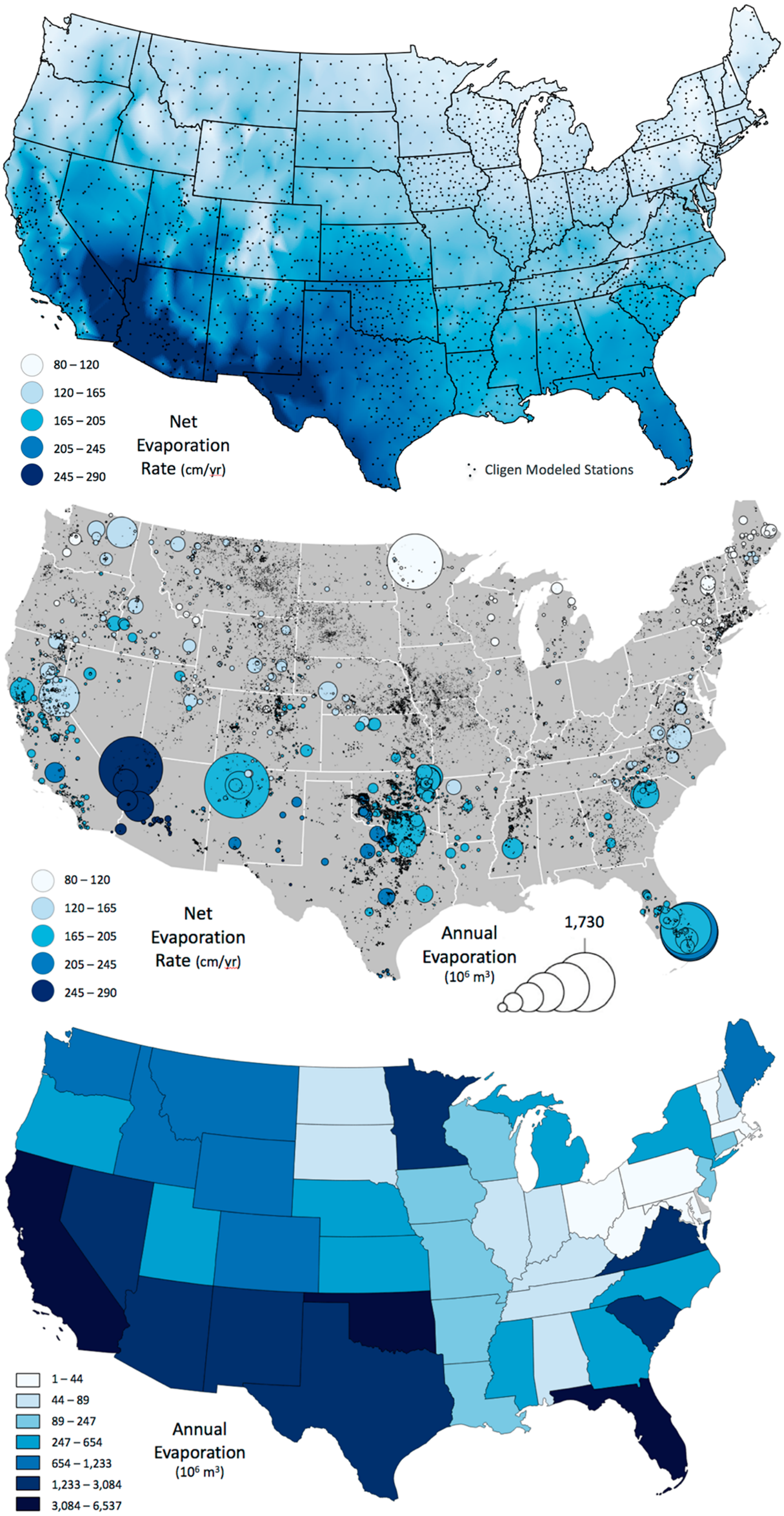

Figure 6. (Top) Estimated net evaporation rates of open surface water bodies in the United States. (Middle) Net evaporation rate (dot color) and annual volumetric evaporation loss (dot size) of each FPV-feasible water body in the contiguous United States. (Bottom) Net volumetric evaporation in each state every year from FPV-feasible water bodies.

weathering, and other factors while assessing associated impacts in terms of the local economic benefits and trade-offs.

Using conservative assumption on the amount of surface area available on man-made bodies of water, we estimated 2116 GW of FPV could be developed in the continental U.S., with the potential to generate 9.6% of current electricity generation. Relaxing some conservative assumptions on reservoir coverage of FPV systems, available reservoirs, and including natural water bodies could substantially increase this potential. This potential shows that the U.S. could benefit from

DOI: 10.1021/acs.est.8b04735
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
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this rapidly emerging technology and that growing focus on FPV within the domestic research community could be advantageous. This significant opportunity warrants future research into the optimal siting, technology configuration, PV chemistries, and material properties of FPV systems. Additional research into potential co-benefits related to evaporation, algae growth, and panel temperature and output are also needed to fully understand the benefits and potential limitations of this new technology.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b04735.

> NID dataset criteria, NHD supplementation of NID: estimation of error (Figure S1), aggregated FPV potential data by state (Table S1), characterizations of current FPV projects (Table S2 and Figures S2−S6), analysis source code, and data citations (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: robert.spencer@nrel.gov.

ORCID

Robert S. Spencer: 0000-0001-8220-5488

Matthew O. Reese: 0000-0001-9927-5984

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank Ciel & Terre, especially Luc Pejo, Miki Sakua, and Eva Pauly-Bowles, for providing the NREL team with data and imagery on their international projects as well as hosting facility tours of FPV sites near Shikoku, Japan. The authors also thank NREL for Laboratory Directed Research and Development funding, Sophia Valenzuela for analytical contributions, Billy Roberts for graphical support, and Karen Petersen for editorial support. This work was authored by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

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DOI: 10.1021/acs.est.8b04735
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