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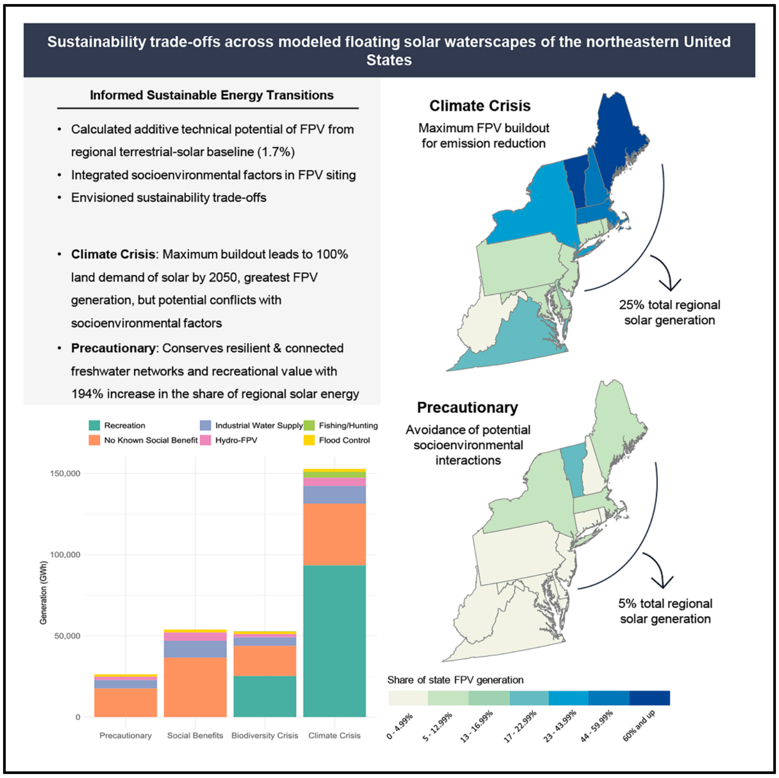
Sustainability trade-offs across modeled floating solar waterscapes of the Northeastern United States

Graphical abstract



Sustainability trade-offs across modeled floating solar waterscapes of the northeastern United States

Informed Sustainable Energy Transitions

- Calculated additive technical potential of FPV from regional terrestrial-solar baseline (1.7%)
- Integrated socioenvironmental factors in FPV siting
- Envisioned sustainability trade-offs

- **Climate Crisis**: Maximum buildout leads to 100% land demand of solar by 2050, greatest FPV generation, but potential conflicts with socioenvironmental factors
- **Precautionary**: Conserves resilient & connected freshwater networks and recreational value with 194% increase in the share of regional solar energy

Highlights

- FPV deployment could meet 25% of regional solar demand on technically suitable waters
- Technically feasible FPV can offset all projected land needs for solar by 2050
- FPV can reduce land use but requires trade-off assessments for biodiversity impacts
- This study provides a framework for balancing FPV potential with socioecological values

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In brief

The study assesses the potential of floating photovoltaic (FPV) systems to significantly expand solar capacity in the Northeastern US, offsetting land requirements for solar by 2050. It highlights the need for balanced deployment that minimizes impacts on biodiversity and social values, providing a framework for sustainable FPV siting.

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Sustainability trade-offs across modeled floating solar waterscapes of the Northeastern United States

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SCIENCE FOR SOCIETY Floating photovoltaic (FPV) solar energy is sited on water, thereby reducing the burden of solar-energy development on land. However, the biodiversity and social values of the freshwaters where FPV is predominantly developed are often greater than many of the recipient environments for terrestrial solar. Our analysis reveals that FPV energy contains the technical potential to meet a quarter of regional renewable electricity demands while avoiding any further solar development on land by 2050. Nevertheless, trade-offs occur and can vary depending on the percentage of waterbody coverage by FPV systems. Further, strict avoidance scenarios for maintaining biodiversity and social values still yield substantial electricity generation from FPV energy. By integrating biodiversity and social values into FPV siting—a transdisciplinary approach—we establish a framework for holistic understanding of FPV systems in the energy transition. Our research suggests that technical potential alone does not capture socioecological effects known to drive decisions on local renewable energy adoption.

SUMMARY

Expansion of floating photovoltaic (FPV) solar systems provides a low-conflict renewable energy option to help mitigate climate change while sparing land, but potential sustainability trade-offs remain unquantified. We compare the technical potential of maximum FPV deployment to address the climate crisis with FPV-buildout scenarios that prioritize biodiversity and social values across waterscapes. FPV deployment on all technically suitable waterbodies (3.5% of available sites) in the Northeastern US could generate nearly a quarter of the region's solar energy while offsetting all the land required for solar by 2050, but trade-offs, including maintenance of freshwater biodiversity and recreational benefits, exist. Avoidance of socioenvironmental interactions yields FPV-electricity generation potential equal to a 5% increase in regional solar generation while sparing water for biodiversity and social values, though opportunities for co-location make this a conservative estimate. Our framework extends technical potential assessments to holistically inform FPV siting and support diverse Sustainable Development Goals.

INTRODUCTION

Climate change is one of the greatest challenges facing society in the 21st century,[1] and its mitigation largely hinges on decarbonizing the electricity sector through increased renewable energy development.[2,3] To remain aligned with the International Energy Agency's roadmap to net zero emissions by 2050, accelerated development of up to 1,120 gigawatts (GW) of wind and solar energy annually is required by 2030.[4] Emerging renewable energy technologies, such as floating photovoltaic (FPV) solar energy,[5,6] can contribute to climate change mitigation; as of 2020, global installed capacity of FPV solar energy was 2.6 GW,[7] yet potential electricity generation from FPV systems could reach between 4,356 and 10,304 terawatt hours (TWh) globally.[8] However, deployment of solar energy on water may create sustainability trade-offs.[9] Currently, pathways to achieve 100% renewable energy tend to overlook inherent trade-offs between renewable energy systems and the ecosystems that support them.[10]

Solar energy is land intensive,[11] which has framed current solar-siting decisions in the context of avoidance of land-use competition in an age of increasing land scarcity[12,13] and varied social acceptance of local renewables.[14,15] Solar energy development most often occurs on agricultural lands, both globally[16] and locally,[17,18] and there is increasing pressure from renewables on biodiversity areas.[19] Land-sparing approaches to solar energy development offer opportunities to reduce pressure on agricultural and conservation lands, for example, by siting solar energy systems in human-modified environments such as landfills and reservoirs.[20] Deployment of FPV inherently offers the potential to reduce existing pressures from utility-scale solar development as land-use change because it solely occurs on water.[9,21] However, avoidance of land-use competition from solar energy may shift the socioenvironmental burden of renewable energy development from landscapes to waterscapes. The freshwater environments currently supporting FPV systems are far scarcer than land-based recipient environments for solar energy deployment.[22]

Freshwater ecosystems provide socioenvironmental benefits in the form of nature's contributions to people[23–25] that could be affected by FPV deployment similar to the socioenvironmental impacts documented for terrestrial renewables.[26] Freshwater provides climate and water-quality regulation, habitat to support biodiversity, drinking water, agricultural irrigation, and cultural values such as sense of place, recreation, and cultural heritage,[23,27–30] all of which may be affected by FPV development.[9] Current research on FPV systems largely focuses on the technical potential of deployment in artificial waterbodies, such as hydroelectric reservoirs, with the primary aim of siting to avoid socioenvironmental impacts.[8,31–33] Although these studies provide valuable insights into FPV generation and system efficiency, they often neglect the broader implications of FPV deployment across diverse freshwater ecosystems, particularly natural waterbodies where potential trade-offs involving biodiversity, recreational use, and cultural values may exist.[25] Moreover, current inventories of FPV technical potential lack applied frameworks to envision synergistic sustainability outcomes such as ecosystem services. Indeed, system design approaches that emphasize techno-ecological synergistic outcomes[34] can potentially mitigate conflicts between renewable energy and socioenvironmental factors.[35,36]

The freshwater biodiversity crisis is deepening[37,38]; population declines of 83% of global freshwater species outnumber those in terrestrial and marine systems.[39] Conservation of biodiversity hinges on site resilience and inter-site connectivity (e.g., linked waterbodies via functionally connected networks[40]) within conservation networks to enable species to adapt to climate-change-induced environments.[41,42] Water availability and connectivity significantly influence freshwater resilience and biodiversity[40]; thus, maintaining resilient and connected freshwater ecosystems across waterscapes is a top conservation priority.[40,43] Geospatial data to represent freshwater resilience and connected networks at large geographic scales (e.g., Continental United States) just recently became available.[40] Globally, most current FPV systems are sited on smaller lakes and ponds,[22] necessitating an increased relative surface-area coverage of FPV systems to optimize electricity generation and thereby introducing potential risks to freshwater biodiversity.[25]

Our objective was to holistically quantify sustainability trade-offs among FPV-buildout scenarios that embody responses to interfacing Sustainable Development Goals (e.g., Climate Action: SDG 13, Affordable and Clean Energy: SDG 7, Life on Land: SDG 15, and Life Below Water: SDG 14; see Exley et al.[44]). We used the Northeastern United States (hereafter "Northeast"), with its vast freshwater resources,[40] population density 13 times greater than average in the United States,[45] and high consumer electricity rates compared with the national average[46] (Figure S1), to estimate and evaluate interactions among sustainability trade-offs in modeled FPV solar energy waterscapes. Broadly, we aim to extend inventories of technical potential of FPV systems (i.e., basic requirements for industrial development such as interconnection and roads) and resultant avoided emissions to include additional FPV siting considerations for ecosystems and people. The "climate crisis"[47] scenario reflects maximum FPV buildout required for aggressive climate change mitigation,[48] with no avoidance of technically suitable waterbodies. The "biodiversity crisis"[37] scenario aims to guide FPV buildout that avoids freshwater ecosystems with high biodiversity and waterscape connectivity and resilience to climate change.[25,40] The "social benefits" scenario reflects social values of freshwater by avoidance of potential FPV system interactions with nature's contributions to people based on available regional data—recreation (e.g., swimming, fishing, and boating; see Spencer et al.[33]). The "precautionary" scenario is a conservative estimate of FPV technical potential that integrates combined avoidance measures of the biodiversity crisis and social benefits scenarios. We envision sustainability trade-offs as spatially explicit gains or losses in energy generation and land and water sparing from utility-scale (≥1 megawatt [MW]) FPV systems and through comparisons of interactive socioenvironmental factors among sustainability scenarios. Elucidation of spatial locations that present particular sustainability trade-offs of FPV systems allows for deeper discussions and new pathways that aim to strike a balance between competing interests.[9]

RESULTS

Our results indicate that utility-scale FPV solar energy has the potential to generate a substantial amount of renewable electricity on waterbodies throughout the Northeast. We estimated annual electricity generation from FPV systems in the Northeast as follows: 152,805 gigawatt hours (GWh) (climate crisis), 53,916 GWh (social benefits), 52,828 GWh (biodiversity crisis), and 26,318 GWh (precautionary) (Table S1). Utility-scale FPV systems can increase current regional solar-energy generation from terrestrial solar alone (1.7%; Energy Information Administration [EIA][46]) to between 5% and 23% (Figure 1). Although FPV generation drops by ~2/3 from the climate crisis scenario when avoiding interactions with biodiversity and social benefits, respectively, the biodiversity crisis and social benefits scenarios each still constitute a 9% increase in total utility-scale solar energy generation regionally as of 2022 (Table S2).

We detected variation in technical potential of FPV systems among northeastern states (Figure 1). Under the climate crisis

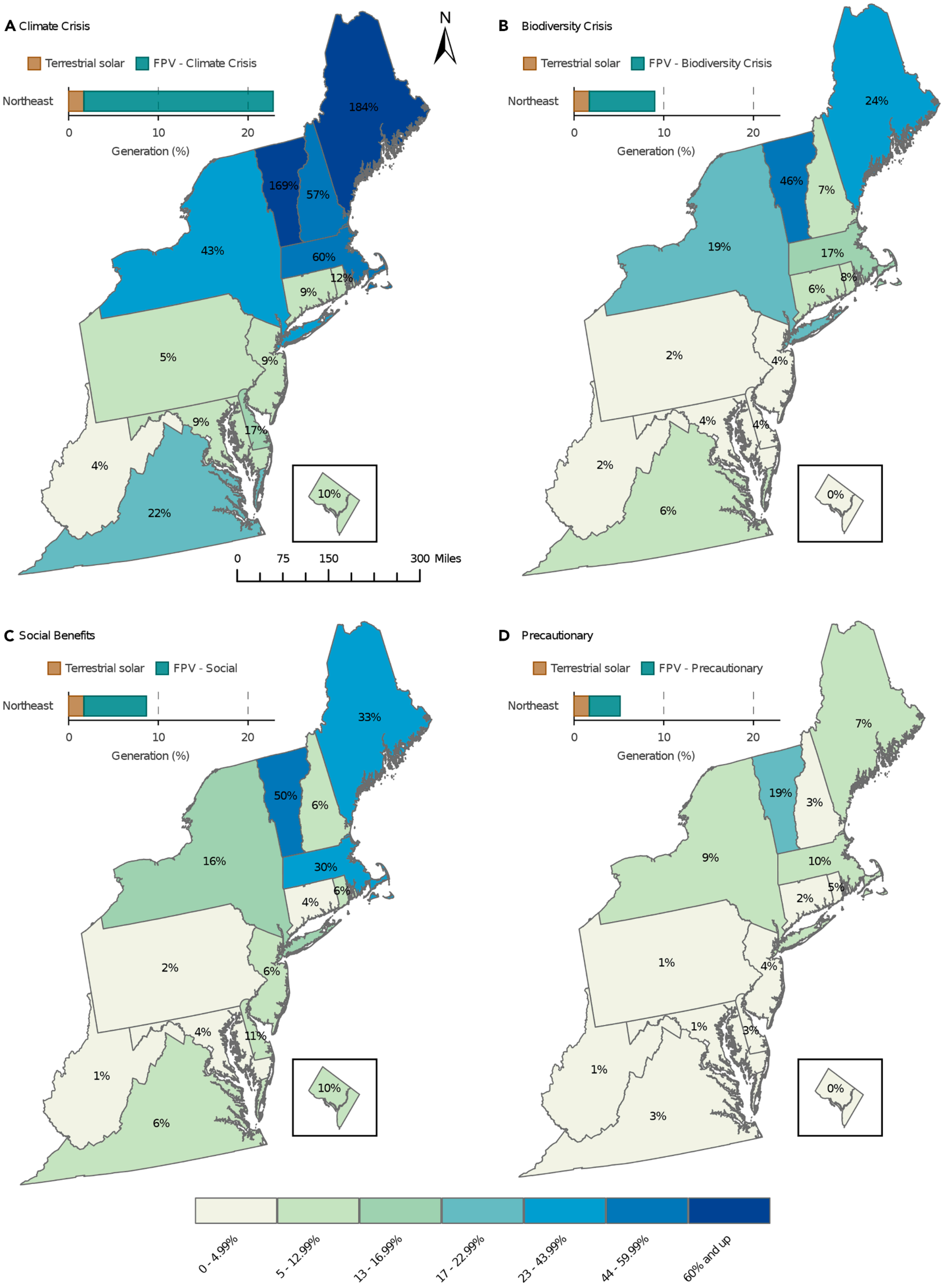

Figure 1. Potential FPV generation in the Northeastern United States

(A)–(D) depict potential FPV generation (GWh) by state for each FPV solar energy buildout scenario. Bar graphs in each figure show the share of terrestrial utility-scale solar generation, which was 1.7% in 2022 (brown), and share of utility-scale solar energy when including potential FPV generation (teal) in the Northeast. The axis for each bar graph is set relative to FPV production in the climate crisis scenario to highlight the sustainability trade-offs of FPV generation between scenarios. Electricity data for share of utility-scale solar energy for the Northeast originate from the EIA electricity data browser and reflect data as of 2022.

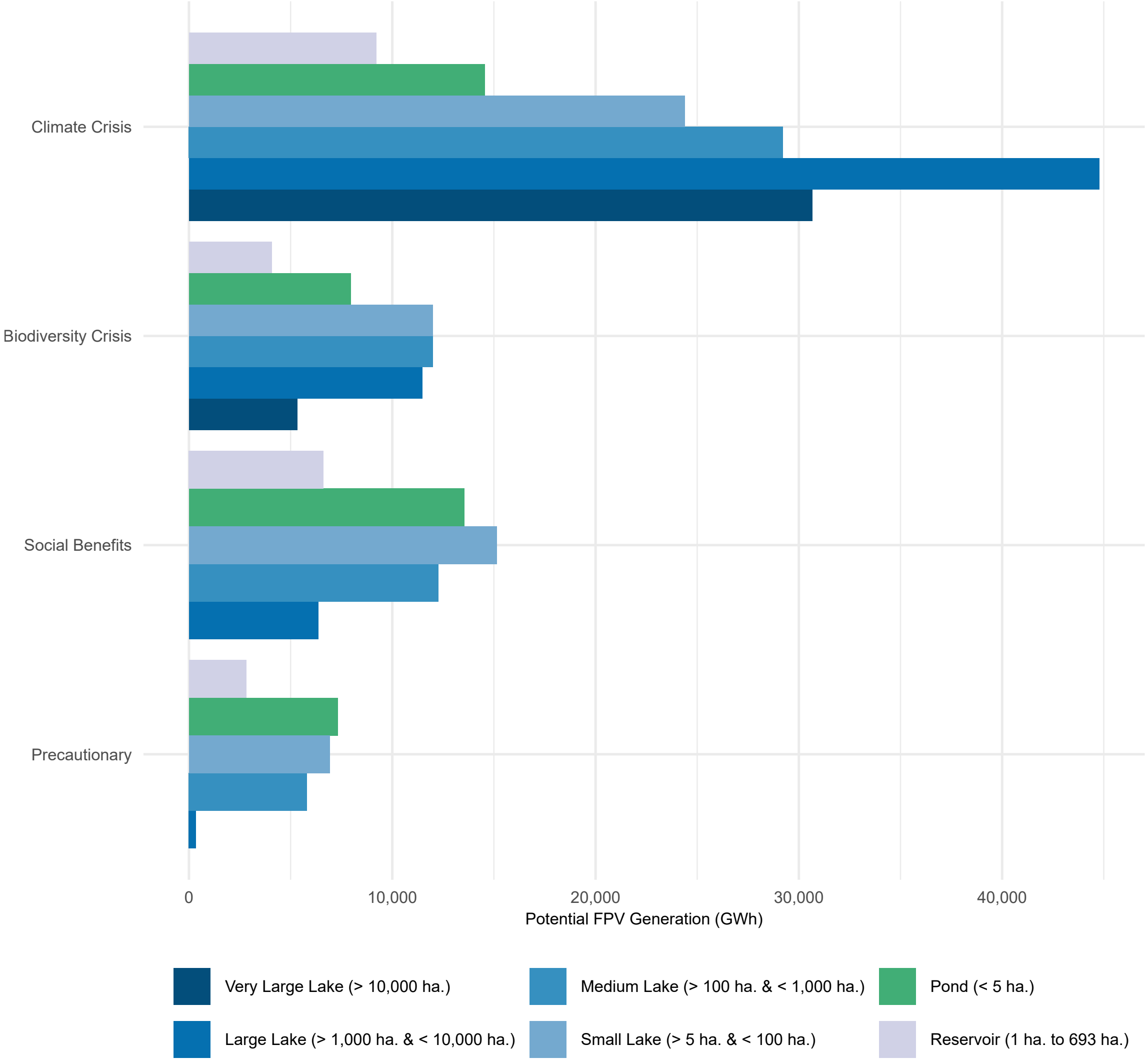

Figure 2. FPV technical potential by waterbody type

Characterization of suitable waterbodies for FPV solar energy development in the Northeast by buildout scenario, subdivided by water body type. We derived categories for lakes,[49] ponds,[50] and reservoirs[51,52] from the peer-reviewed literature.

scenario, FPV systems have the potential to substantially increase utility-scale solar energy generation in states throughout the Northeast, ranging from 4% (West Virginia) to 184% (Maine) (Table S2). The great technical potential for FPV systems in Maine is juxtaposed by a reduction in FPV generation by a factor of six when avoiding potential biodiversity and social impacts in the state, for example (Figure 1; Table S1). Across scenarios, we estimated potential for hybrid FPV-hydropower systems in the Northeast on 58–117 waterbodies across scenarios, capable of producing 2,080–5,103 GWh, respectively (Table S3). Our results suggest that non-baseload emissions avoided from FPV generation can be as high as 55% for unrestricted FPV system buildout and ranges from 10% to 20% when considering biodiversity and social benefit trade-offs (Figure S2).

We identified 469,009 available waterbodies comprising 1,259,536 ha of freshwater surface area in the Northeast. Across scenarios, the number of technically suitable waterbodies (see methods) for FPV systems ranged from 7,477 (22,085 ha) to 16,620 (129,442 ha), representing between 1.6% and 3.5% of identified waterbodies in the Northeast. Natural lakes and ponds dominate the waterscape of the Northeast and outnumbered reservoirs as suitable recipient environments for FPV systems across scenarios (Figure 2). Ponds ranging from 1 to 5 ha in area comprise 72%–78% of suitable waterbodies for FPV systems, whereas electricity generation potential is highest on large lakes that span ∼1,000 ha to greater than 10,000 ha in area and can provide 49% of potential FPV generation (Figures 2 and S4B; Table S4). To achieve utility-scale FPV generation on highly abundant and suitable small waterbodies (∼1 ha), average FPV system area coverage is 62%–64% across scenarios, whereas large waterbodies capped at 27% FPV system coverage—a conservative estimate for surface-area

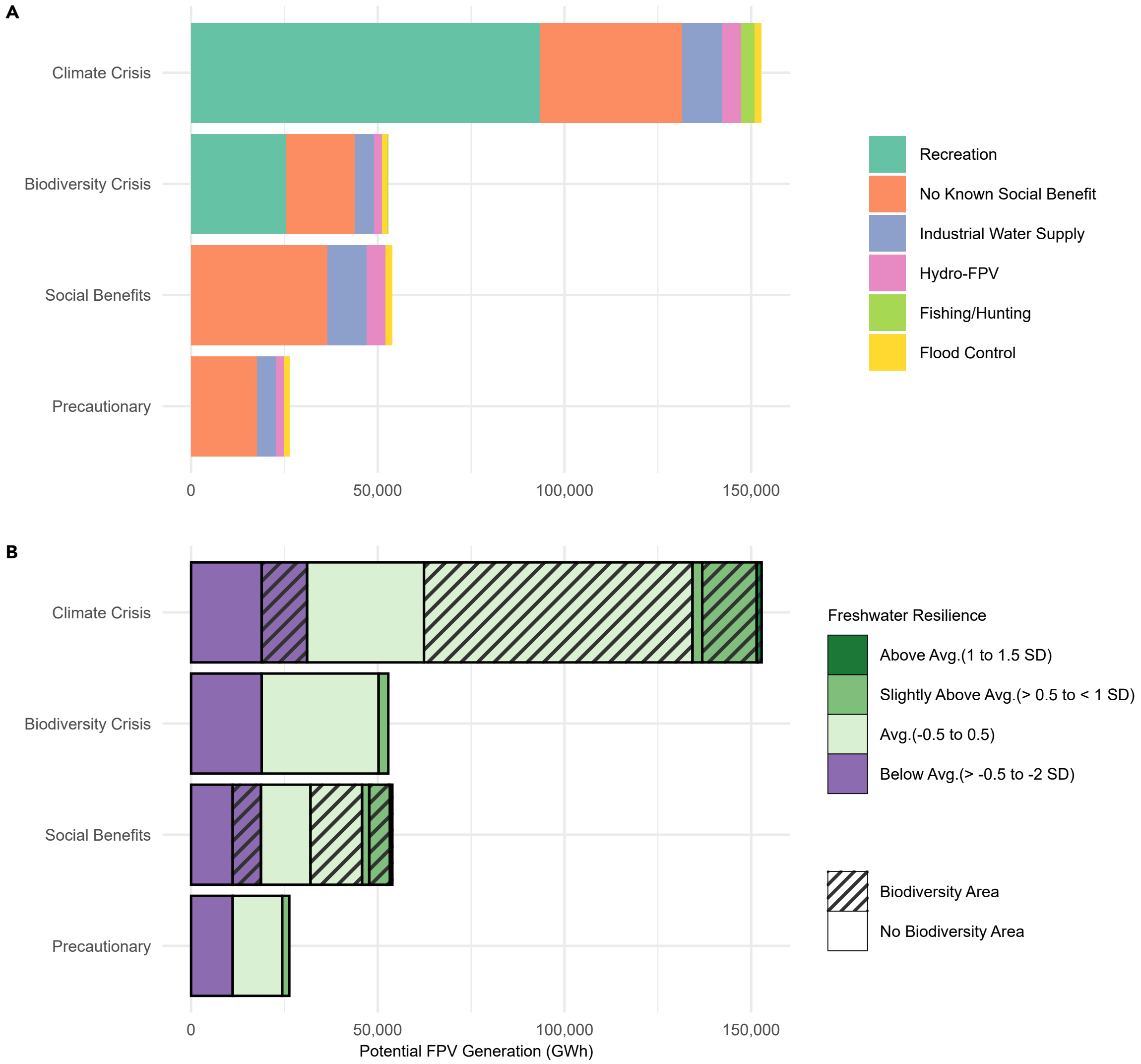

Figure 3. FPV technical potential by socioenvironmental value

Sustainability trade-offs among FPV solar energy buildout scenarios by potential FPV generation.

(A) Total potential FPV generation (GWh) across social benefits. Industrial water supply represents a group of water bodies with similar attributes (e.g., fire protection, irrigation, tailings, etc.; see suitability analysis in supplemental methods and Table S3). No known solar benefit are waterbodies that have no recreational value (i.e., spatial link to the NID or USGS boat ramps representing gaps in social values datasets for freshwater environments).

(B) Total potential FPV generation by freshwater resilience and among biodiversity areas (Table S6). Resilience scores, represented as standard deviation (SD), are based on methods described in The Nature Conservancy's Resilient and Connected Freshwater Network.[40]

coverage based on previous literature (see Spencer et al.[33])—average 20 MW of utility-scale FPV generation (Figure S3). For the climate crisis and biodiversity scenarios, recreational waterbodies have the greatest potential for FPV generation relative to alternative human uses (e.g., irrigation, hydroelectric, etc.), and most recreational waterbodies across both scenarios (i.e., climate crisis and biodiversity crisis) support utility-scale FPV systems at a maximum 27% surface-area coverage (Figure 3A). Across all scenarios, small to large lakes support utility-scale FPV systems at a maximum of 27% surface-area coverage, while small ponds necessitate the highest surface-area coverage of FPV systems to reach utility-scale generation (Table S8).

For the climate crisis scenario, we found that nearly 60% of estimated annual FPV generation is derived from waterbodies with recreational value (Figure 3A). We estimated that ~53% of waterbodies occur outside of designated biodiversity areas at maximum FPV buildout, of which ~45% occur in waterbodies with below average freshwater resilience (i.e., ecologically marginalized waterbodies) (Table S6); as such, FPV buildout trended toward lakes and ponds with high biodiversity value (Figure S4A). Freshwater biodiversity is particularly vulnerable to unrestricted FPV development because ~35% of suitable waterbodies are located within recognized biodiversity areas and exhibit above average, slightly above average, or average freshwater resilience (Table S6). For the social benefits scenario,

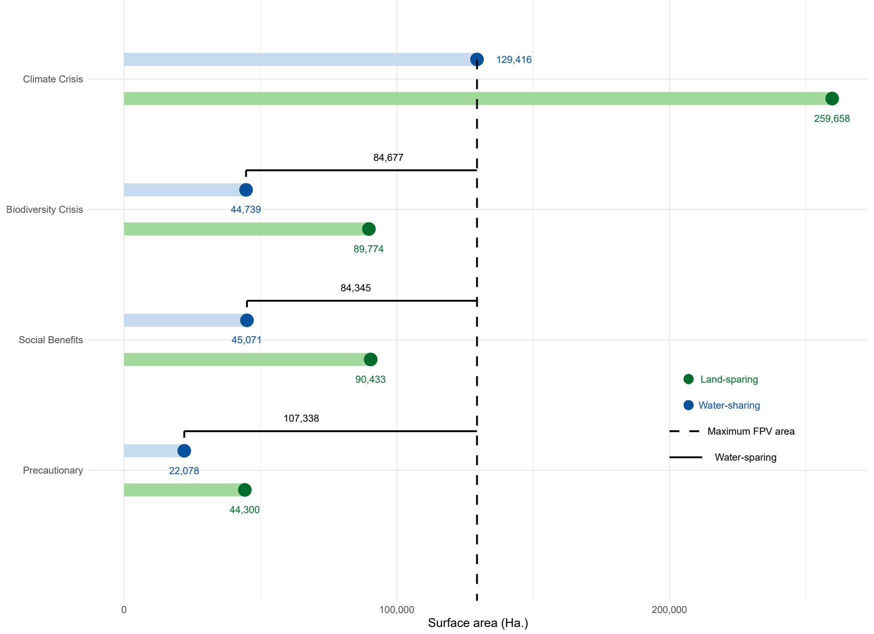

Figure 4. Surface-area comparison of FPV solar energy to terrestrial solar energy

Potential land sparing, water sparing, and water sharing across FPV solar energy buildout scenarios in the Northeast. Green points represent land sparing (i.e., terrestrial hectares not developed for solar), blue points represent water sharing (i.e., FPV energy generation potentially shared with other water uses), black dotted line represents the maximum suitable area for FPV systems in the Northeast, and black solid lines represent water sparing (i.e., freshwater hectares not developed for FPV solar energy). Surface-area values represent the direct area only and do not consider spacing for buffers; values therefore represent a conservative estimate of the land- and water-sparing potential of FPV systems. Land-sparing potential is calculated using an energy density of 2.03 ha per megawatt (MW) (see methods for details).

we estimated that half of annual FPV generation overlaps with waterbodies in freshwater biodiversity areas (Figure 3B; Table S6). Under the biodiversity crisis scenario, there exists large potential (∼67% estimated annual generation) for FPV system interactions with social values (Figure 3A). When balancing the social benefits and biodiversity crisis scenarios, trade-offs become evident: prioritizing social benefits can adversely affect biodiversity and vice versa.

Given the higher energy density of FPV systems compared with terrestrial systems (i.e., ∼1 ha per MW FPV to 2.03 ha per MW terrestrial solar[33,53,54]) and availability of suitable waterbodies, FPV systems have the potential to spare all land required to meet average terrestrial utility-scale solar energy demands in the Northeast by 2050 (Table S5; Gagnon et al.[55]). For each scenario, FPV systems represented a 49% reduction in land required for utility-scale solar energy (i.e., land sparing), a reflection of the fixed relationship between solar energy densities on land and water; land-sparing potential of FPV systems ranges from 44,300 ha (precautionary) to 259,658 ha (climate crisis) (Figure 4). In contrast, biodiversity crisis, social benefits, and precautionary scenarios yielded larger rates of water sparing, with a maximum potential of around 107,338 ha (83% reduction in water use for FPV systems) compared with the climate crisis scenario (Figure 4), while maintaining biodiversity, social benefits, and some land-sparing capacity.

DISCUSSION

Meeting global climate targets requires rapid deployment of renewable energy,[2,3] but a primary obstacle facing the acceleration of renewable energy buildout is perceived siting conflicts.[56] At face value, expansion of FPV systems on water could provide a low-conflict renewable energy option; envisioned sustainability trade-offs of FPV solar energy can help realize siting conflicts and synergies. Here, we demonstrate that FPV solar energy can significantly contribute to a regional renewable energy portfolio with deployment on less than 3.5% of total available waterbodies, while, with its increased power density relative to ground-mounted solar,[33,53,54] sparing highly sought-after land resources in the Northeast. By avoiding socioenvironmental interactions entirely, FPV systems can still constitute 5% of the Northeast's utility-scale solar energy generation mix (Table S2), signaling significant renewable energy generation under strict avoidance scenarios. A paucity of empirical, field-collected data on interactions among FPV systems and socioenvironmental factors with sufficient geographic breadth currently precludes analysis of scenarios beyond avoidance. Yet, potential for co-location (i.e., use of waterbodies for multiple values) of FPV systems and socioenvironmental elements like recreation and biodiversity, especially in systems with low percentages of FPV system surface area coverage, may make our avoidance-based estimates of technical potential conservative. Furthermore, land and water sparing from FPV systems may be even greater than we report because studies suggest that panel cooling via evaporation can increase annual FPV generation by 1.5%–6% compared with terrestrial solar,[35,57] given the higher power densities of FPV systems.[33,54] Increased performance and reduced evaporation are largely driven by lower tilt angles of FPV systems compared with terrestrial ones, while also increasing the structural stability of the floating platform.[58] However, the extent of generation gains from cooling effects is contingent on geographic and site-specific conditions. Notably, System Advisor Model (SAM) has limitations in accurately estimating the performance of FPV systems as it does not completely account for thermal dynamics and albedo effects specific to aquatic environments.[59] Additionally, modern FPV system designs such as east-west system configurations (see Osama et al.[59]) could achieve greater power densities than assumed in this study, further increasing land-sparing benefits (see Wei et al.[6] for a detailed review). Future assessments should reflect ongoing innovations in FPV system design and PV module efficiency[60] rather than rely solely on historical performance data to more accurately project deployment potential and trade-offs. In short, FPV systems may provide win-win opportunities wherein renewable electricity is generated, land is spared for food and ecosystem services, and conflicts with biodiversity and social values are avoided at a time in which regional viability of terrestrial co-location strategies such as agrivoltaics is still largely unknown. However, sustainability trade-offs indeed exist and can depend on siting philosophies.

Envisioning sustainability trade-offs of FPV deployment via avoidance of social and biodiversity interactions can provide valuable insights into FPV siting that concurrently align with climate and conservation goals,[10,61] United Nation Sustainable Development Goals (e.g., Climate Action: SDG 13, Affordable and Clean Energy: SDG 7, Life on Land: SDG 15, and Life Below Water: SDG 14, see Exley et al.[44]), and more informed siting decisions among stakeholders. Avoidance of recreational water bodies led to increased potential interactions between FPV systems and freshwater biodiversity areas; meanwhile, sustainability decisions such as renewable energy siting are known to affect ecosystem function and environmental justice.[26] For example, losses in recreational value can diminish water-based sense of place,[62] which, in turn, can affect local socioeconomics, as seen with coral reef ecosystems.[63] Understanding potential variations in how residents value nearby waterscapes provides another opportunity for envisioning sustainability trade-offs between FPV systems and socioenvironmental characteristics, such as permitting, social acceptance, and capital expenditures at a local level.[64] Ultimately, our results indicate that potential sustainability trade-offs of FPV solar energy can be minimized at the cost of renewable energy generation via FPV deployment, but FPV systems can still significantly contribute to diversifying renewable energy portfolios that include terrestrial solar and other renewable technologies under the most conservative deployment scenarios.

Although land sparing currently inspires FPV development,[20] scarcity of global freshwater resources[65] and the high ecosystem-services value of freshwater[44,66] point toward the need for accurate accounting of water sparing in the energy transition. Although FPV systems could potentially reduce evaporation—with studies indicating reductions in evaporation ranging from 18% to 73% depending on floating structure type (i.e., suspended canal systems versus direct contact FPV systems[67]) and water-surface coverage ranging from 30% to 50%[8,67]—and therefore retain water resources,[33] we frame water sparing under the assumption of avoidance of socioenvironmental water uses (e.g., Spencer et al.[33]), as is done under land-sparing scenarios that conceptualize conversion of a preexisting land use (e.g., prime agricultural land) to mutually exclusive energy production.[68] Although FPV solar energy greatly increases potential for land sparing, prioritization of freshwater for biodiversity may be warranted due to the greater biodiversity value of waterscapes versus more abundant land-based recipient environments for solar, especially marginalized lands with relatively lower biodiversity.[39] Water sparing for socioenvironmental uses and FPV generation can be simultaneously accomplished if portions of recipient water bodies maintain socioenvironmental function, which likely hinges on thresholds for percentage of FPV system array coverage.[69] Empirical data on local-scale interactions among FPV systems and socioenvironmental factors are required to determine whether the two are mutually exclusive, thereby imparting an avoidance approach, or whether multiple water uses can be co-located on water bodies with FPV solar energy.[9]

Similar to co-location of terrestrial solar (e.g., agrivoltaics), co-location of water uses such as hydropower and FPV systems can theoretically stimulate water sparing elsewhere. Although paired hydro-FPV systems have great potential for global electricity generation[32] and offer unique co-benefits relative to single FPV systems, including proximity to existing infrastructure[32] and hybridized system design to enhance overall reliability and energy generation,[31] their deployment across waterscapes may be regionally specific. Paired hydro-FPV systems constitute a relatively small proportion of realized FPV technical potential in our modeled waterscapes, presumably because hydroelectric reservoirs are less common in the Northeast than the Western United States, for example.[70] However, lack of classification of socioenvironmental uses (i.e., single-use, hydroelectric versus multi-use) from reservoirs currently presents a challenge for envisioning co-benefits of FPV systems.[44] Previous FPV solar energy modeling efforts exclude drinking water and recreational water bodies from consideration (see Spencer et al.[33]), although hydroelectric production and other potential uses of reservoirs are not mutually exclusive.[9] Co-location of FPV systems and socioenvironmental uses may be feasible on hydropower reservoirs, especially given that the percentage of FPV surface area coverage on large water bodies like reservoirs typically does not exceed 27%.[33] Field studies and a deepened understanding of the socioenvironmental interactions of FPV systems on varying waterbody types and uses can help determine FPV surface area coverage thresholds (e.g., open water surface area) to enable sustainability goals.[9]

Solar energy development on marginalized lands has been proposed to potentially lessen its deleterious land-use change implications,[20] but the analogous concept of FPV systems on marginalized waters is largely unexplored. Marginalized lands like rights of ways, abandoned cropland, landfills, barren land, and environmentally contaminated sites could generate around 34,000 GWh of solar energy in the Northeast.[71] Although ground-mounted solar over irrigation canals in the Western US, for example, exemplify possible use of marginalized waters,[72] these waterscapes are largely absent from temperate climates. Hydrological alterations from anthropogenic activities such mining and damming have degraded freshwater ecosystems worldwide,[73,74] creating potential sites for FPV deployment. However, the restoration of these degraded and marginalized waterscapes holds significant promise for enhancing the resilience of connected freshwater networks,[40] which raises concerns about prematurely categorizing such waters as permanently marginalized. Reservoirs, in particular, have been identified as high-priority sites for FPV development (see Almeida et al.[9]), often under the assumption that they possess low ecological value while offering potential co-benefits.[32,35,36] Yet, our models suggest that reservoirs may overlap with areas of significant socioenvironmental value, which could be overlooked if they are broadly classified as marginalized waters. This broad categorization risks creating perverse incentives to retain dams that might otherwise be removed to restore natural ecosystems.[75] Moreover, current freshwater datasets used for utility-scale FPV site selection do not explicitly identify variably defined marginalized waters, introducing uncertainty and limiting the predictive power of geospatial models applied to FPV development on marginal waterbodies.

Our modeled FPV solar energy waterscapes indicate significant potential for FPV deployment on lakes and ponds with inherently high biodiversity, which resonates with trends of current globally installed FPV systems on smaller water bodies rather than more ecologically marginalized reservoirs,[22,76] stemming waterscape-level freshwater biodiversity concerns. Indeed, we show that FPV solar energy has low potential on waterbodies lacking resilience to climate change, while potential FPV deployment could significantly overlap with resilient waterbodies among connected freshwater networks. We not only found high potential for FPV deployment on lakes and ponds but also determined that the percentage of surface area coverage is inherently higher on smaller water bodies to reach utility-scale deployment—again a result in line with current operational trends in global FPV system installations.[22] Deployment of FPV systems on lakes can modulate meta-ecosystem fluxes affecting socioenvironmental interactions across spatial scales (summarized in Nobre et al.[25]). For example, shading and resultant reduced temperatures of lakes with FPV systems could affect primary production[25] and chlorophyll-a concentrations, potentially altering predator-prey dynamics and evolutionary trajectories of species.[44,77–79] However, FPV panel shading could offer varying benefits for fish, aquatic birds, otters, and aquatic reptiles to name a few.[80] For instance, FPV system structures may provide shelter from predators, concealment from prey, or a serve as a substrate on which to deposit eggs.[81–83] In some cases, artificial structures may enhance local fisheries by creating microhabitats that attract target species, potentially improving catch rates and community perceptions of FPV systems as a co-beneficial use of space.[84] However, research has also shown that species abundance and diversity could be negatively impacted by large anthropogenic structures in waterbodies among certain species, specifically those that rely on visual foraging methods.[85,86] Empirical data are required to contextualize potential interactions with FPV systems and aquatic ecosystems, especially in lakes and ponds with intrinsic socioenvironmental value.[25,76]

As renewable energy development continues to boom, siting and management decisions at individual waterbodies across waterscapes[70] can play an increasingly important role in a sustainable energy transition.[10,61] FPV buildout may be managed via the mitigation hierarchy for development,[87] wherein the first step is to avoid siting FPV systems in places with high biodiversity and social value (i.e., biodiversity crisis and social benefits scenarios), albeit with significant trade-offs in renewable electricity generation. To minimize the negative effects of FPV systems on sensitive freshwater ecosystems,[39] stakeholders could consider development offsets (e.g., restoring freshwater biodiversity, improving habitat connectivity, and enhancing ecosystem resilience) in nearby or comparable undeveloped areas, similar to mitigation strategies used for terrestrial solar.[88] However, the application of offsets in aquatic systems is still a nascent concept that requires further empirical research to assess its feasibility and effectiveness. Although offsets may help compensate for ecological impacts, they should not be viewed as a substitute for careful, evidence-based siting decisions. Prioritizing informed siting and impact minimization from the outset is always preferable to relying on offsets to address the consequences of poorly sited FPV projects.[10] In regions like the Northeast, where restoration potential remains high, strategic deployment of FPV systems alongside proactive conservation efforts could enhance ecological outcomes. Co-locating FPV systems with other social uses of water, including reservoirs and hybrid FPV-hydro systems, shows theoretical promise, yet FPV buildout may follow trends for terrestrial solar, with development largely occurring outside of the built environment.[10,89] Our framework can integrate additional, standardized geospatial datasets, including spatially explicit ecological and social data, to better capture socioenvironmental interactions with FPV buildout. However, availability of such datasets at large geographic scales remains a major limitation, particularly for assessing social dynamics such as cultural values and stakeholder acceptance.

Regardless of regional foci, our modeling framework envisions that sustainability trade-offs may be transferable globally. Concepts of land and water sparing, socioenvironmental avoidance, and co-location apply broadly to regions facing similar pressures from land competition, biodiversity conservation, and renewable energy expansion; of course, regional differences in climate, ecology, and market behaviors can influence interpretation of results. As geospatial and socioenvironmental datasets, particularly those integrating climate resilience, become more available globally, our framework can be adapted to inform FPV deployment strategies in other regions around the world. Countries with high population densities, limited land availability, or increased water stress—such as those in Southeast Asia, Europe, and parts of Africa—may particularly benefit from insights into FPV siting that balance climate and conservation priorities.[10]

Our results point to the importance of considering interactive trade-offs of renewable energy siting, rather than technical potential inventories alone, and provides a framework for identifying potential synergistic relationships of renewables deployment, a key attribute of a sustainable energy transition.[10,34] Our results can directly inform FPV policy at the federal level (e.g., proposed House Bill 9399: *Protect Our Waters and Expand Renewables on Our Reservoirs Act*[90]) by conceptualizing and validating the co-benefits driving government incentives for increased FPV deployment. By calculating emission offsets based on FPV-electricity generation and avoided use of fossil fuels, our study highlights the balance between renewable energy benefits and potential socioenvironmental trade-offs beyond local waterbodies. For instance, prioritizing emission reductions may conflict with the conservation of nature's services to people from freshwater ecosystems, underscoring the need for interdisciplinary frameworks that weigh climate mitigation against biodiversity and cultural values.[26] Our approach emphasizes realistic climate mitigation outcomes in an age of rapid energy development; in doing so, we bring to the forefront a theoretical approach for envisioning sustainability trade-offs while meeting necessary climate goals in a holistic modeling framework that embodies robust interdisciplinary thinking and inputs.

METHODS

Identification of suitable waterbodies for floating solar energy

For this analysis, we estimated FPV-electricity generation (i.e., technical potential) in the Northeastern United States (hereafter Northeast). In this context, the Northeast is defined as Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, Pennsylvania, New Jersey, Delaware, Maryland, West Virginia, and Virginia, along with Washington D.C. (Figure 1). Before estimating FPV-electricity generation, we performed a suitability analysis to determine which waterbodies could support potential FPV development. We leveraged the United States Geological Survey (USGS) National Hydrography Dataset (NHD) to identify waterbodies suitable for FPV deployment.[51] Because solar energy development typically avoids wetlands due to regulatory constraints and ecological importance,[91] we excluded wetlands from consideration, using data from the United States Fish and Wildlife Service's National Wetlands Inventory.[92] We also incorporated geospatial data from the United States Army Corps of Engineers' National Inventory of Dams (NID)[52] to assign social use values (e.g., recreation, hydroelectricity, fishing, irrigation, etc.) to waterbodies with dams. This integration enriched the original NHD data by providing higher-resolution information on waterbody use and characteristics. To further account for recreational value, we supplemented the NID with a dataset of USGS boat ramp locations[93] to identify sites presumed to have recreational significance (e.g., Lake Seneca in New York) that lacked a spatial relationship with NID data. After determining total waterbody availability, we refine our suitability analysis by focusing on industry-level drivers of utility-scale solar energy development, primarily interconnection (i.e., connecting the FPV system to the electricity grid) and road access.[54] For interconnection, we applied a standard criterion used for land-based solar systems[18]: a maximum system-to-transmission distance of 1 mile (1.6 km), based on data from the Homeland Infrastructure Foundation-Level Database (HIFLD; Figure S5).[94] Similarly, we identified waterbodies within 0.5 miles (0.8 km) of a road as suitable for FPV deployment,[54] using a local roads layer from the Environmental Systems Research Institute (ESRI) living atlas transportation dataset.[95] We defined utility-scale FPV as systems with a nameplate capacity of $\geq$1 MW, consistent with the United States EIA data collection process for electricity generators.[46] Additional details regarding the suitability analysis are provided in the supplemental methods and Table S7.

Estimation of FPV-electricity generation

Using the filtered dataset of suitable FPV locations, we estimated annual FPV generation for each waterbody in the Northeast by leveraging the National Renewable Energy Lab's System Advisor Model (SAM)[96] and the Physical Solar Model (PSM) version 3 of the National Solar Radiation Database (NSRDB).[97] This approach captured temporal and spatial variability in FPV resources (see Habte et al.[98] for details). Compared with terrestrial utility-scale solar systems, FPV systems differ in two key parameters affecting annual generation: power density and panel tilt. We adapted SAM to account for these FPV-specific factors, ensuring more robust generation estimates. Based on prior research and industry trends, we assumed FPV systems operate at power densities of ~1 ha/MW,[22,33,54] which is higher than terrestrial systems due to their ability to support lower tilt angles. For instance, FPV systems typically use an 11° tilt angle,[33,54,99] compared with the 20°–30° common in terrestrial systems.[100] Accordingly, we adopted an 11° tilt for our FPV generation estimates.

System capacity was defined with a minimum threshold of 1 MW, consistent with the United States EIA criteria for measuring total power plant capacity.[46] Waterbodies smaller than ~1 ha were excluded from analysis due to their inability to meet this minimum threshold. We allowed the model to determine maximum system capacity based on waterbody area and surface-area coverage (i.e., percentage of coverage). Surface-area coverage plays a critical role in FPV system configurations and has a linear relationship with annual generation.[33] Previous research identified 27% as the median percentage of coverage for FPV systems at the time[33]; however, more recent studies suggest higher percentages of coverage are more likely on smaller waterbodies to achieve the 1-MW threshold.[22] Therefore, we scaled the percentage of coverage to range from >27% to 100% for smaller waterbodies, while capping coverage at 27% for larger waterbodies capable of supporting systems larger than 1 MW. Aside from adjustments to panel tilt and system capacity, we retained the default SAM settings for estimating annual FPV generation, reflecting the most recent standards for solar energy systems in the United States, including system efficiencies and losses.[33] We expressed technical potential as estimated annual FPV generation in GWh.

FPV-buildout scenario formation and comparisons

We defined four buildout scenarios to assess trade-offs between FPV-electricity generation, freshwater biodiversity conservation, and the preservation of social benefits. The climate crisis scenario reflects the full technical potential of FPV solar energy by including all suitable waterbodies without exclusions. This scenario is designed to model an aggressive climate mitigation strategy,[48] where maximizing FPV development takes precedence over other considerations. The biodiversity crisis scenario incorporates The Nature Conservancy's freshwater resilient and connected network data (Figure S5; Nobre et al.[22,40]), which include biodiversity areas and highlight variably resilient waterbody connectivity in the region. To avoid potential conflicts between FPV development and biodiversity, we excluded waterbodies that spatially overlapped with this network. The social benefits scenario accounts for the social values of freshwater ecosystems by excluding waterbodies that provide nature's contributions to people,[23–25] particularly thorough recreational activities such as swimming, fishing, and boating, among others.[33] To identify these waterbodies, we leveraged data from the NID, which links recreational use to specific waterbodies across the Northeast. We further supplemented this analysis with a USGS dataset of boat ramp locations, capturing additional recreational sites beyond those identified in the NID. Waterbodies with a listed recreational use in either dataset were excluded to minimize potential FPV-recreation conflicts. Finally, the precautionary scenario takes the most conservative approach by removing all waterbodies identified as potential conflicts in both the biodiversity crisis and social benefits scenarios. This scenario reflects a cautious strategy where FPV deployment is minimized to safeguard biodiversity and social values. To evaluate the implications of each scenario, we quantified trade-offs by comparing differences in potential FPV-electricity generation, biodiversity preservation, and social benefits. Additional methodological details related to the suitability analysis are provided in the supplemental materials.

Water and land sparing and net emission offset

To estimate the land-sparing potential of FPV solar energy across the Northeast for each scenario, we used the median energy density estimate of 2.03 ha/MW, derived from terrestrial utility-scale solar energy data in the United States large-scale photovoltaic database.[101] Given an energy density of ∼1 ha/MW for FPV systems,[33,54] we calculated land-sparing as the area that would be required to generate the same capacity as FPV systems on water. Similarly, we estimated water-sparing potential as the difference in total FPV-covered areas between scenarios and the area covered in our climate crisis scenario. To establish potential emission offsets from FPV systems, we conducted an emission rate analysis using established life cycle emission estimates for solar panels. We used a life cycle emission rate of 0.046 metric tonnes (MT) of CO_2e/MWh, based on the median of 41 estimates from the National Renewable Energy Lab's Life Cycle Assessment Harmonization project for crystalline silicon solar panels.[102,103] After calculating total emissions from FPV systems during the first year of electricity generation, we estimated potential offsets by comparing FPV system emissions to those of non-baseload generating units across the Northeast. We collected data on non-baseload generation (MWh) and emission rates (MT CO_2e/MWh) from 2018 to 2022 using the United States Environmental Protection Agency's (EPA) Emissions and Generation Resource Integrated database (eGRID).[104] Non-baseload-generating units are used to compared the emission benefits of energy efficiency programs or renewable energy integration,[104] such as the development of FPV. Total average non-baseload emissions for the Northeast were calculated as a baseline (Table S9). Using this baseline rate, we calculated FPV-related emission offsets by multiplying the rate with total FPV generation for each scenario (Figure S1; see Gallaher et al.[18] for additional details). Our emission rate analysis is summarized by the following equation:

$$\begin{aligned} FPV_{emission\ offsets} &= \left(nonbaseload_{Gen} * nonbaseload_{rate}\right) \\ &\quad - \left(\left(FPV_{gen} * nonbaseload_{rate}\right) + FPV_{emissions}\right). \end{aligned}$$

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to, and will be fulfilled by, the lead contact, Adam Gallaher (adam.gallaher@cornell.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data that support the findings of this study are publicly available and sources are provided within the paper and its supplementary information files. Code developed to process datasets and estimate annual FPV generation can be found at the following GitHub repository, https://github.com/GallaherAdam/Northeast_FPV. A citable Zenodo repository, https://doi.org/10.5281/zenodo.15283135, has also been added to ensure accurate code attribution. Correspondence about the data and code should be directed to adam.gallaher@cornell.edu.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.G., E.L.K., and S.M.G.; methodology, A.G.; formal analysis, A.G.; investigation, A.G., E.L.K., and S.M.G.; writing – original draft, A.G., E.L.K., and S.M.G.; writing – review and editing, A.G., E.L.K., and S.M.G.; and funding acquisition, S.M.G. and E.L.K.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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