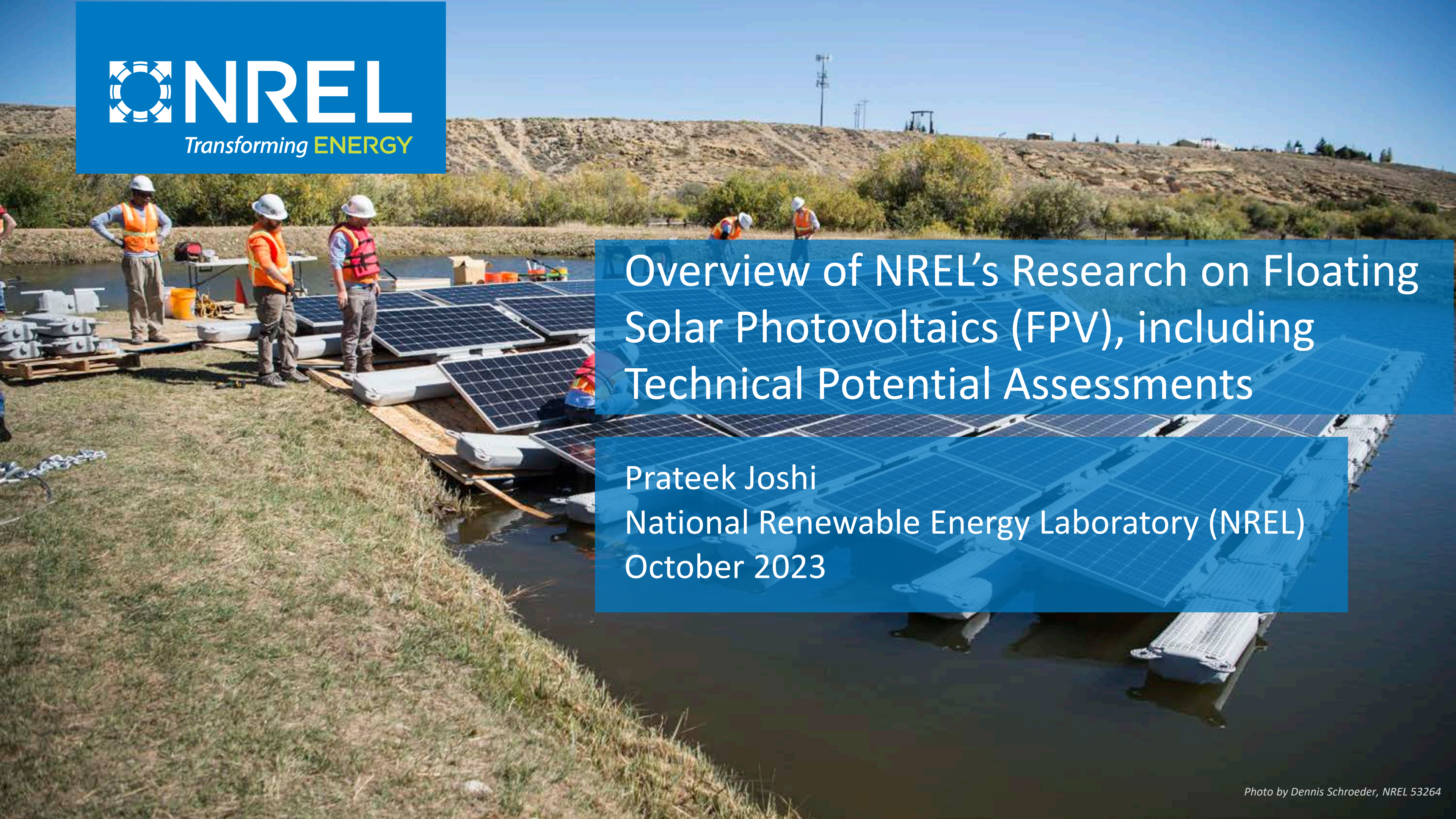


NREL Transforming ENERGY

Overview of NREL’s Research on Floating Solar Photovoltaics (FPV), including Technical Potential Assessments

Prateek Joshi
National Renewable Energy Laboratory (NREL)
October 2023

Photo by Dennis Schroeder, NREL 53264

NREL at a Glance

3,702 workforce, including:

- 2,721 regular/limited term
- 503 contingent workers
- 205 postdoctoral researchers
- 179 graduate student interns
- 94 undergraduate student interns

—as of 8/21/2023

World-class research expertise in:

- Renewable Energy
- Sustainable Transportation & Fuels
- Buildings and Industry
- Energy Systems Integration

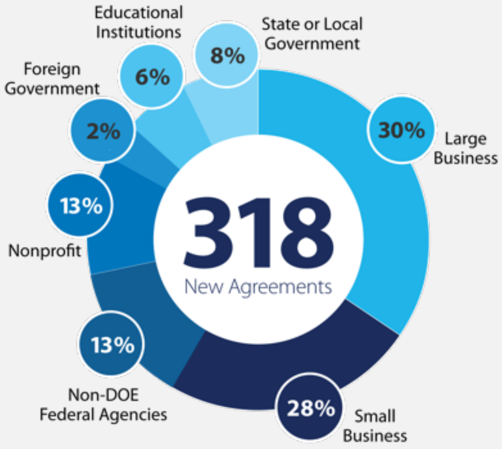
Partnerships with:

- Industry
- Academia
- Government

4 campuses operate as living laboratories

Photo by Werner Slocum, NREL 71582

More Than 1,000 Active Partnerships in FY 2022



Agreements by Business Type

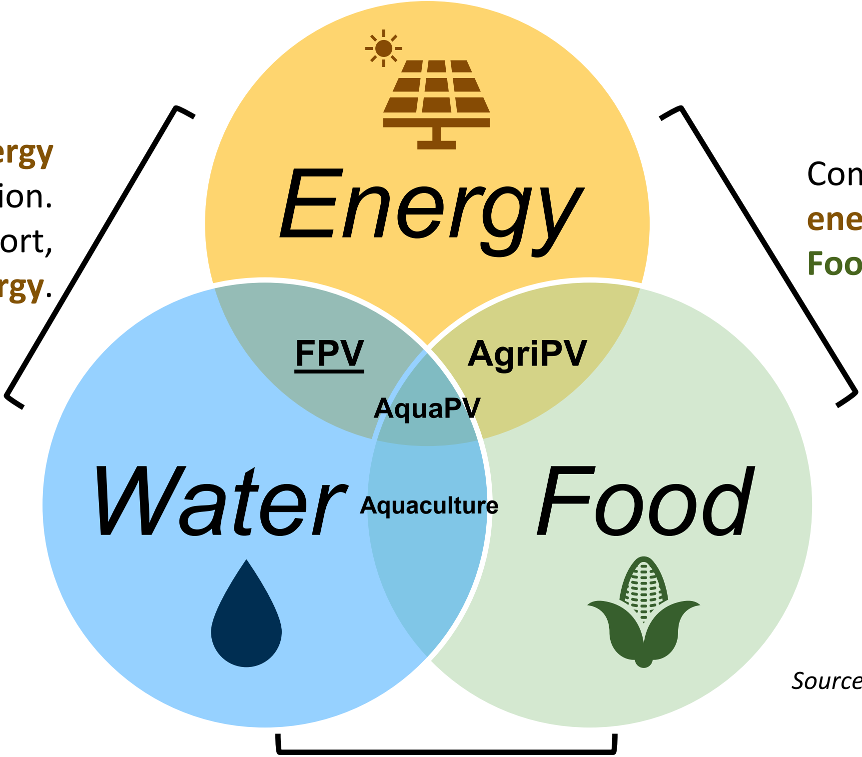
Funding by Business Type

Presentation Outline

FPV Overview

Energy-Water-Food Nexus for Solar PV

Water shortages could limit **energy** production.
Water infrastructure (transport, treatment, etc.) requires **energy**.



Competing land use for **food** and **energy** production.
Food production requires **energy**.

Source: Joshi (2023)

Food production could impact **water** quality and availability.
Water shortages and contamination could limit **food** production.

Overview of FPV Systems

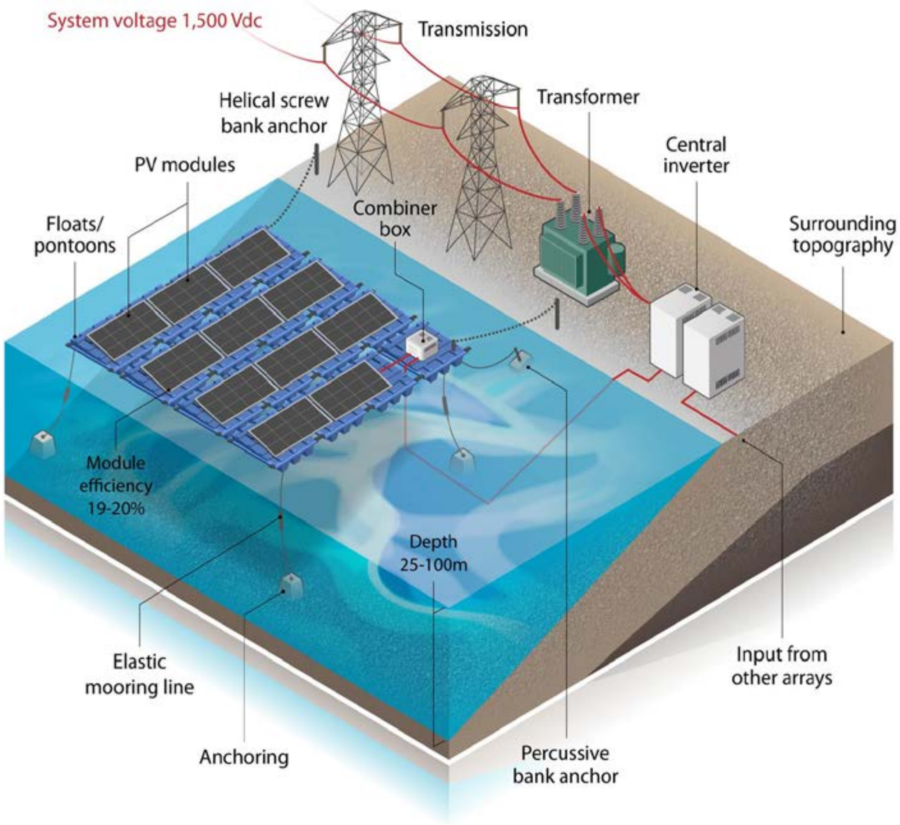


Figure. Schematic of Typical FPV System

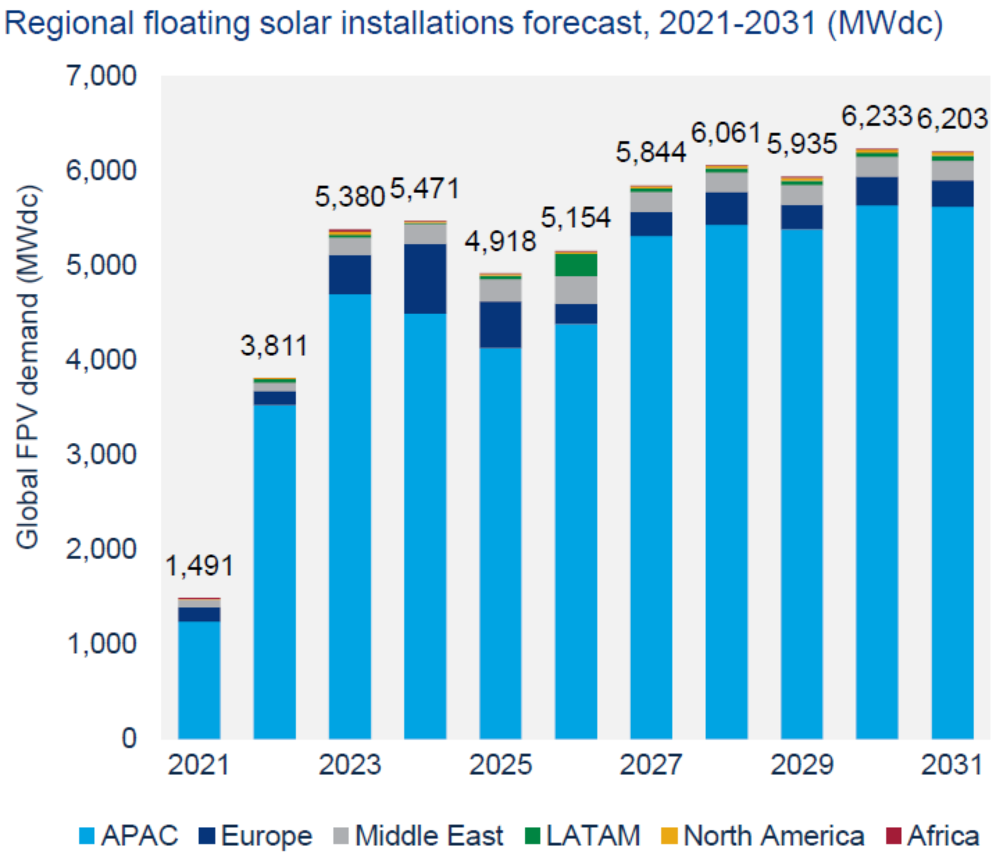
- **Modules:** Same PV technology as ground-mount or rooftop PV, with the emerging potential for tracking and/or bifacial panels.
- **Site:** Typically sited on artificial waterbodies (e.g., reservoirs, retention ponds, etc.), with emerging applications on natural waterbodies, both inland and offshore.
- **Structure:** Platforms consist primarily of high-density polyethylene (HDPE) floats, with potentially different considerations for offshore sites. Anchors and mooring lines minimize lateral movement of the system. Racking material is similar to land-based PV (e.g., stainless steel).
- **Electrical Components:** Similar equipment as a land-based PV installation, with some different considerations for freshwater or marine environments (e.g., electrical cables connecting the modules to each other, and connecting the modules to the central inverter).

Source: Ramasamy and Margolis (2021)

Figure: Alfred Hicks, NREL 65944

FPV Market Growth

Figure. FPV Annual Installations Forecast by Region (2021-2031)



Source: Chopra and Sagardoy (2022)

FPV Cost Comparison

Modeled FPV system has a higher installed cost, \$0.26/W_{DC} (25%) greater than the cost per W_{DC} of ground-mounted PV.

- *Higher cost is largely due to higher structural costs related to the floats and anchoring/mooring system.*

Levelized cost of electricity (LCOE) estimated to be 20% higher for FPV system compared to ground-mount PV.

- *Accounts for higher installed cost, higher energy production, and lower operating and maintenance costs for FPV (but does not account for other FPV co-benefits).*

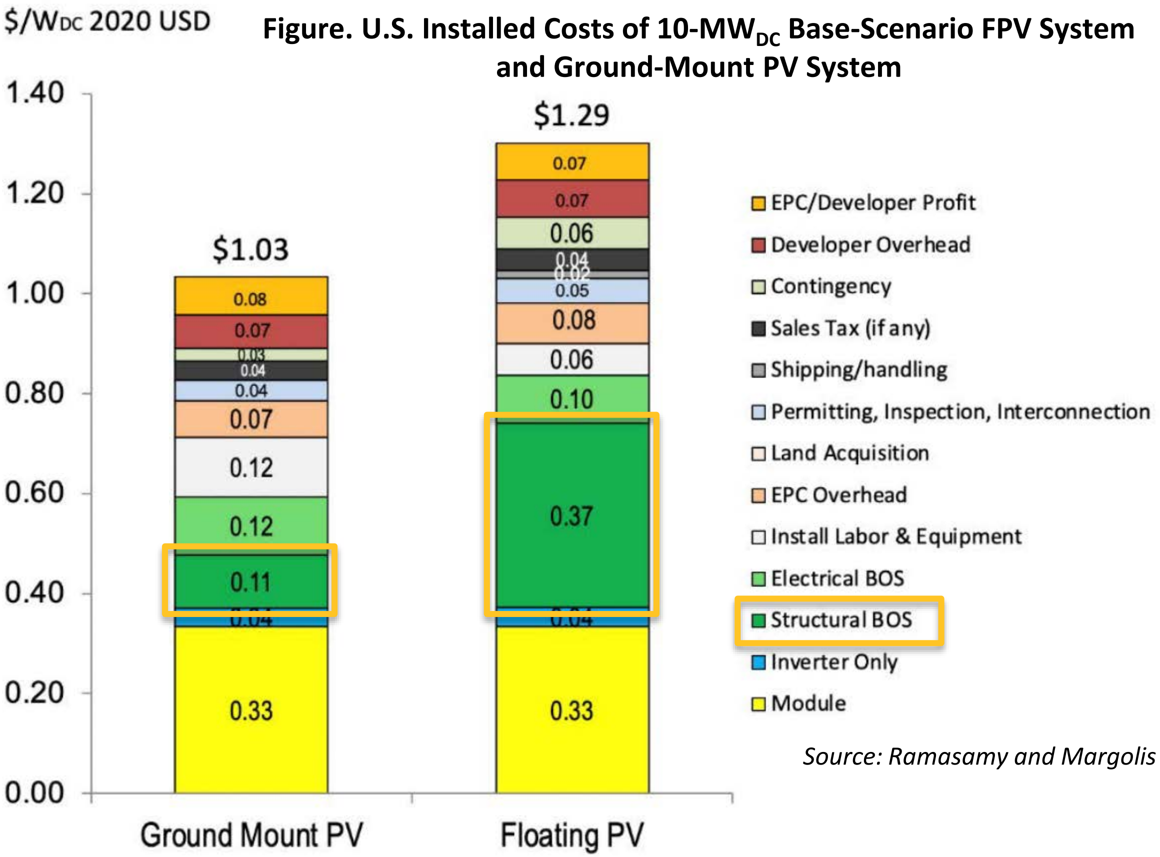
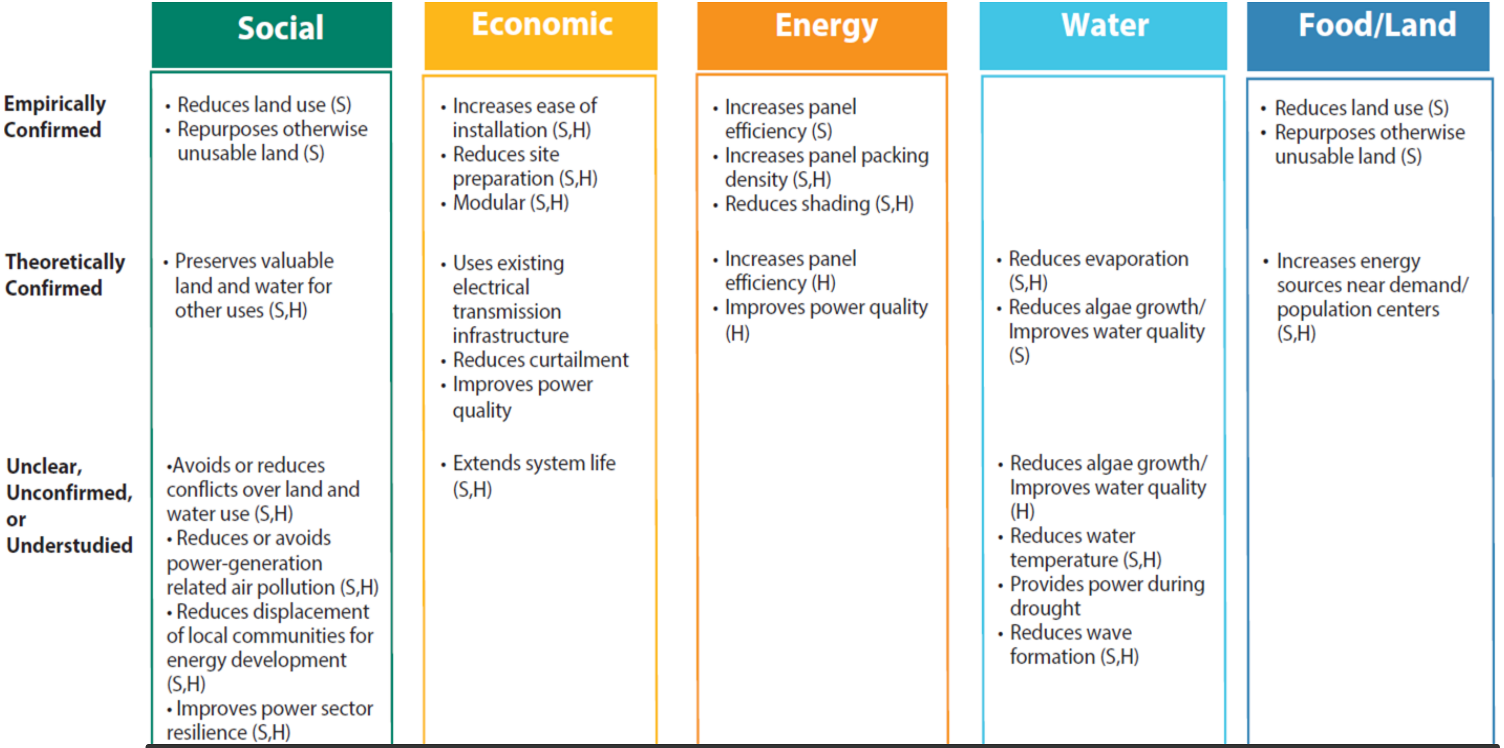


Figure. U.S. Installed Costs of 10-MW_{DC} Base-Scenario FPV System and Ground-Mount PV System

Source: Ramasamy and Margolis (2021)

Research Activities

Potential Co-Benefits of FPV Systems



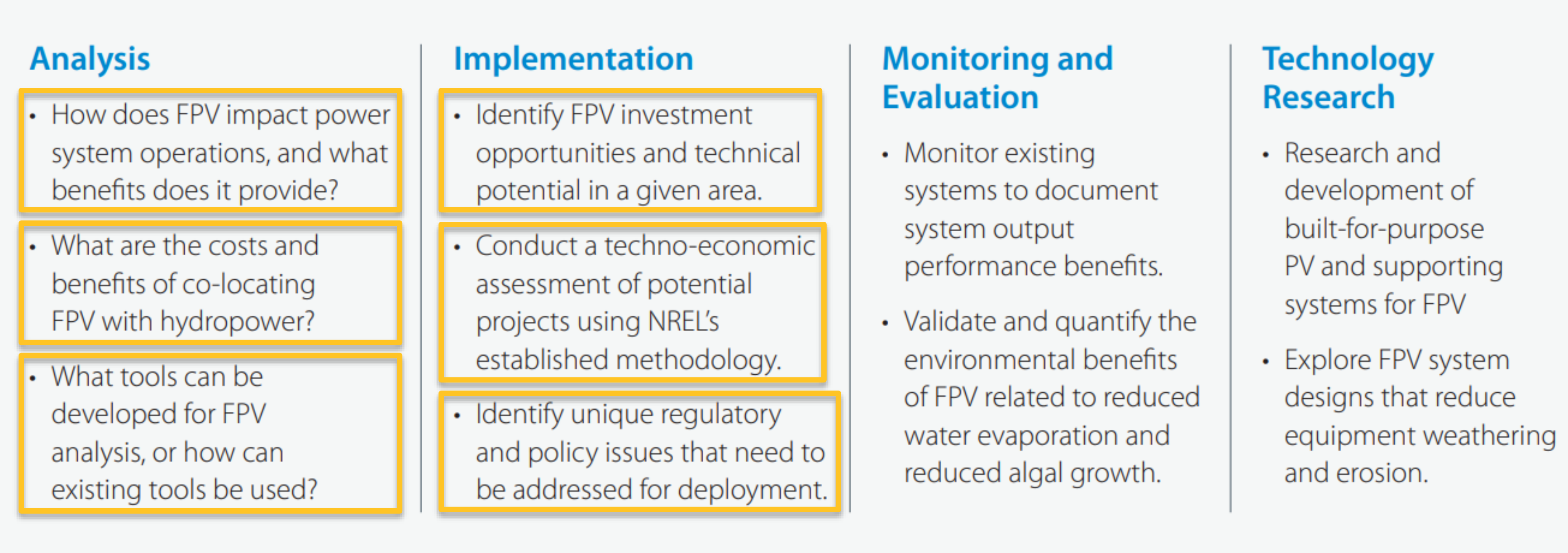
	Social	Economic	Energy	Water	Food/Land
Empirically Confirmed	Reduces land use (S) Repurposes otherwise unusable land (S)	Increases ease of installation (S,H) Reduces site preparation (S,H) Modular (S,H)	Increases panel efficiency (S) Increases panel packing density (S,H) Reduces shading (S,H)		Reduces land use (S) Repurposes otherwise unusable land (S)
Theoretically Confirmed	Preserves valuable land and water for other uses (S,H)	Uses existing electrical transmission infrastructure Reduces curtailment Improves power quality	Increases panel efficiency (H) Improves power quality (H)	Reduces evaporation (S,H) Reduces algae growth/ Improves water quality (S)	Increases energy sources near demand/ population centers (S,H)
Unclear, Unconfirmed, or Understudied	Avoids or reduces conflicts over land and water use (S,H) Reduces or avoids power-generation related air pollution (S,H) Reduces displacement of local communities for energy development (S,H) Improves power sector resilience (S,H)	Extends system life (S,H)		Reduces algae growth/ Improves water quality (H) Reduces water temperature (S,H) Provides power during drought Reduces wave formation (S,H)	

Social and water-related co-benefits remain understudied.

Figure. Summary of FPV Co-Benefits (S = stand-alone, H = hybrid system with hydropower)

Source: Gadzanku et al. (2021a)

FPV Research Areas



Analysis

- How does FPV impact power system operations, and what benefits does it provide?
- What are the costs and benefits of co-locating FPV with hydropower?
- What tools can be developed for FPV analysis, or how can existing tools be used?

Implementation

- Identify FPV investment opportunities and technical potential in a given area.
- Conduct a techno-economic assessment of potential projects using NREL's established methodology.
- Identify unique regulatory and policy issues that need to be addressed for deployment.

Monitoring and Evaluation

- Monitor existing systems to document system output performance benefits.
- Validate and quantify the environmental benefits of FPV related to reduced water evaporation and reduced algal growth.

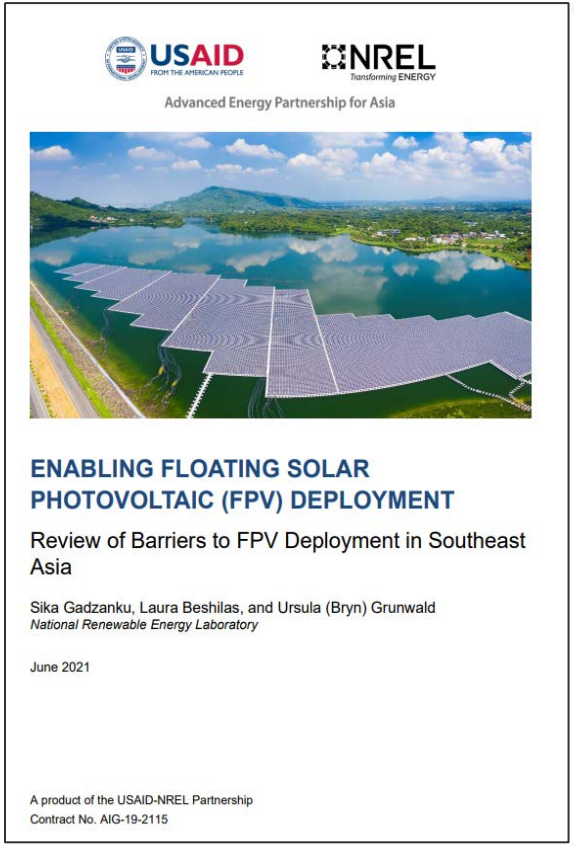
Technology Research

- Research and development of built-for-purpose PV and supporting systems for FPV
- Explore FPV system designs that reduce equipment weathering and erosion.

▭ Activities completed or underway at NREL

Source: Gadzanku (2022)

FPV Policy Barriers and Best Practices (1/2)



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NREL Transforming ENERGY

Advanced Energy Partnership for Asia

ENABLING FLOATING SOLAR PHOTOVOLTAIC (FPV) DEPLOYMENT

Review of Barriers to FPV Deployment in Southeast Asia

Sika Gadzanku, Laura Beshilas, and Ursula (Bryn) Grunwald
National Renewable Energy Laboratory

June 2021

A product of the USAID-NREL Partnership
Contract No. AIG-19-2115

Considerations Covered

- Cultural
- Environmental
- Economic
- Regulatory
- Technical
- Hybrid Systems

FPV Policy Barriers and Best Practices (2/2)

Regulatory

Barriers

Uncertainty about water rights may delay FPV project development and increase costs.

Lack of interagency cooperation and coordination may stall FPV deployment.

Lengthy, expensive, and unclear environmental approval processes for FPV systems can make projects less financially appealing.

Best Practices to Consider

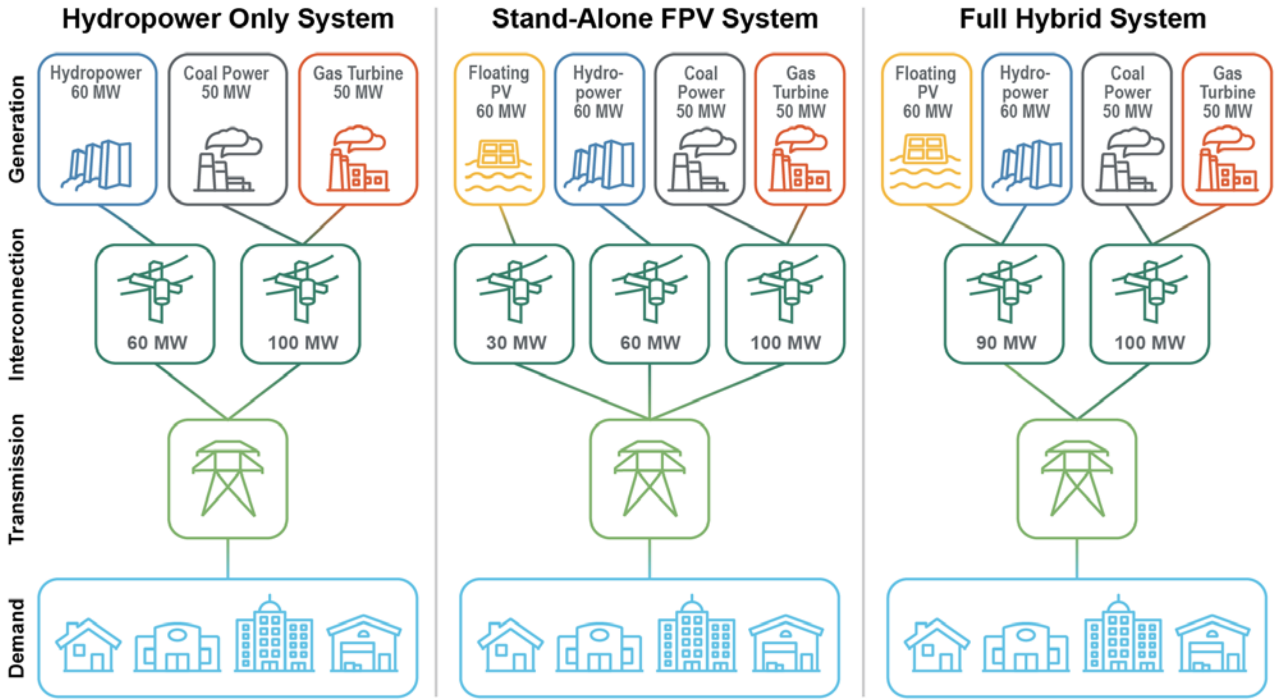
Clear policies around water rights for FPV projects could reduce uncertainty during the project development process.

Develop interagency processes for installing solar PV on waterbodies, along with clear environmental approval processes.

Source: Gadzanku et al. (2021b)

FPV Hybrid Operational Modeling (1/2)

Research Question: What are the operational benefits of hybridizing FPV with hydropower?



Source: Gadzanku et al. (2022)

Figure. Example System Configurations for the Hydro-Only (left), FPV Stand-Alone (middle), and Hybrid FPV-Hydropower (right) Systems

FPV Hybrid Operational Modeling (2/2)

Key Findings:

Compared to a Stand-Alone FPV system, hybridizing FPV with hydropower helps:

- Conserve water by shifting hydropower generation to other periods of the year (top graph).
- Lower PV curtailment when transmission constraints cause curtailment (bottom graph).
- Reduce dependence on other types of generation, such as gas-fired generation, by reducing PV curtailment.

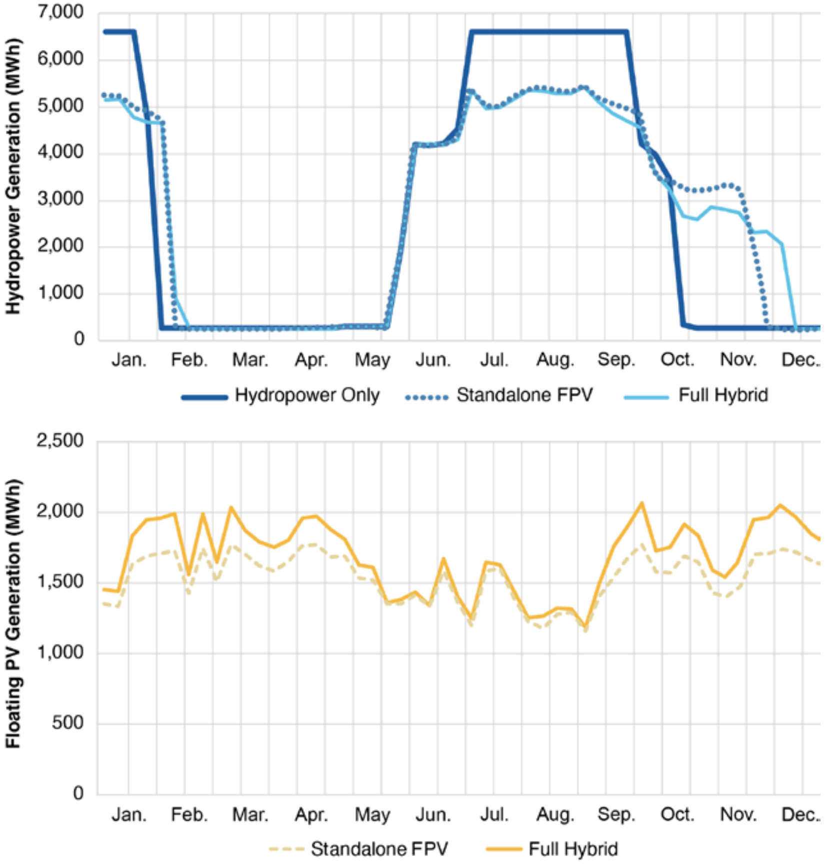


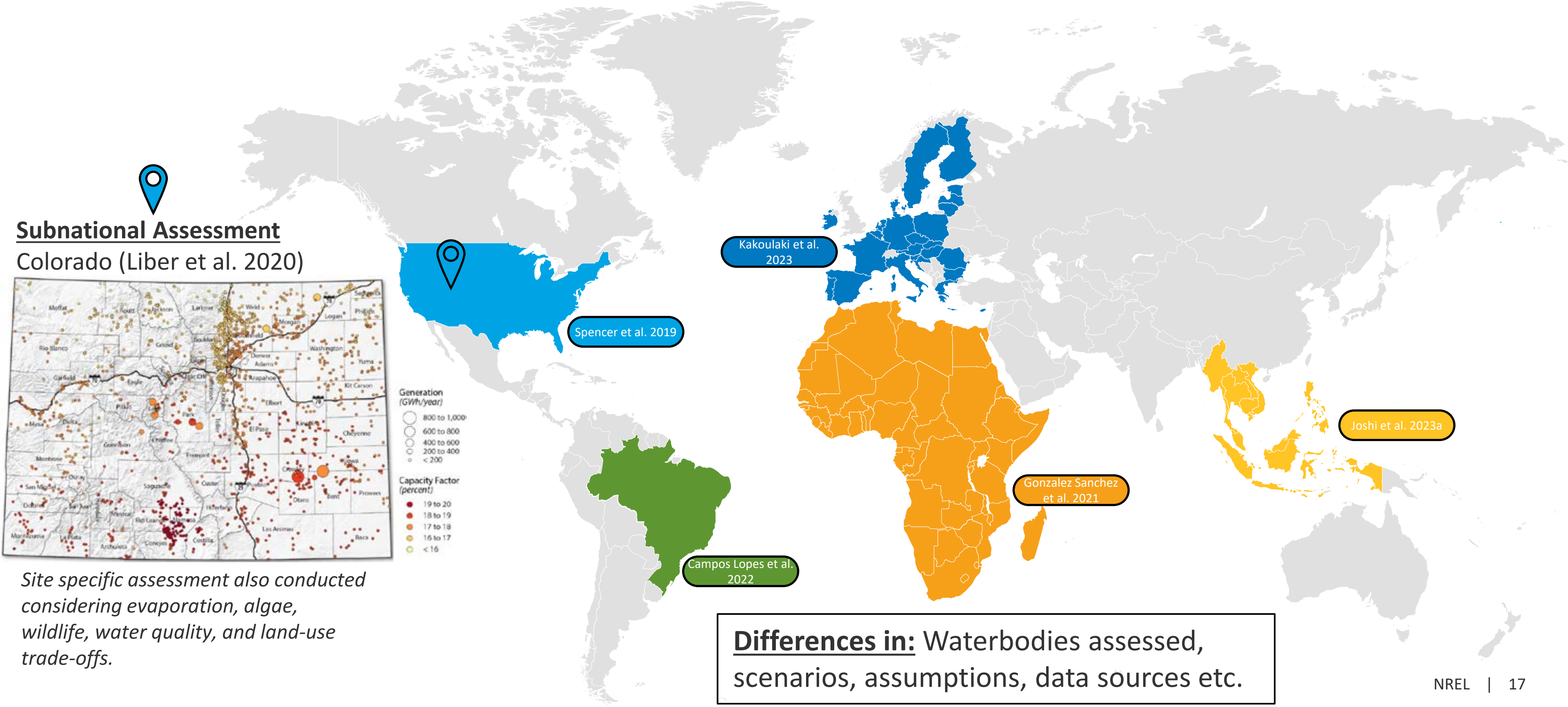
Figure. Annual Hydropower (Top) and FPV Generation (Bottom) in Different Scenarios

Source: Gadzanku et al. (2022)

Technical Potential Assessments

Select FPV Technical Potential Assessments

Global Assessments:
- ❖ Lee et al. 2020
- ❖ Jin et al. 2023



Subnational Assessment

Colorado (Liber et al. 2020)

Site specific assessment also conducted considering evaporation, algae, wildlife, water quality, and land-use trade-offs.

Differences in: Waterbodies assessed, scenarios, assumptions, data sources etc.

Southeast Asia FPV Study: Data Collection

Waterbodies

Reservoirs (hydropower and non-hydropower)

Global Reservoir and Dam Database (GRanD)

Natural Waterbodies (e.g., inland lakes, ponds, etc.)

HydroLAKES Database

Infrastructure

Transmission lines, major roads, and protected areas

RE Data Explorer

Stimson Mekong Infrastructure Tracker

Solar Energy Resource

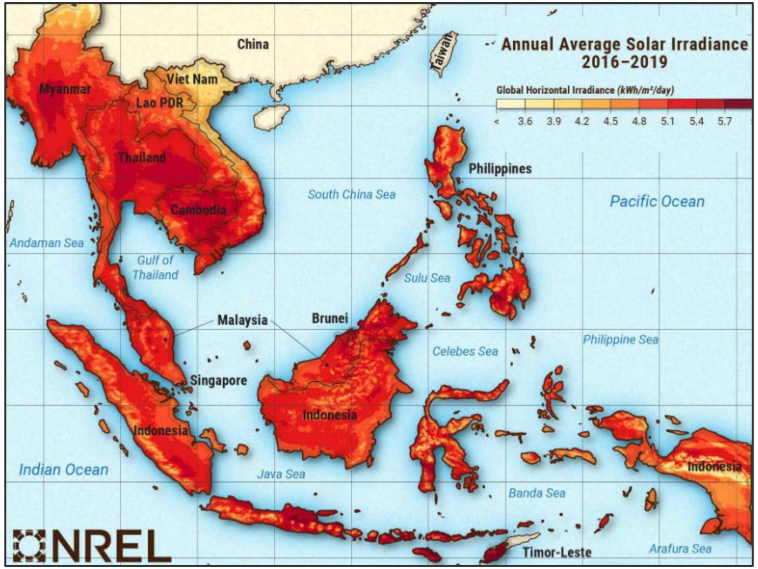
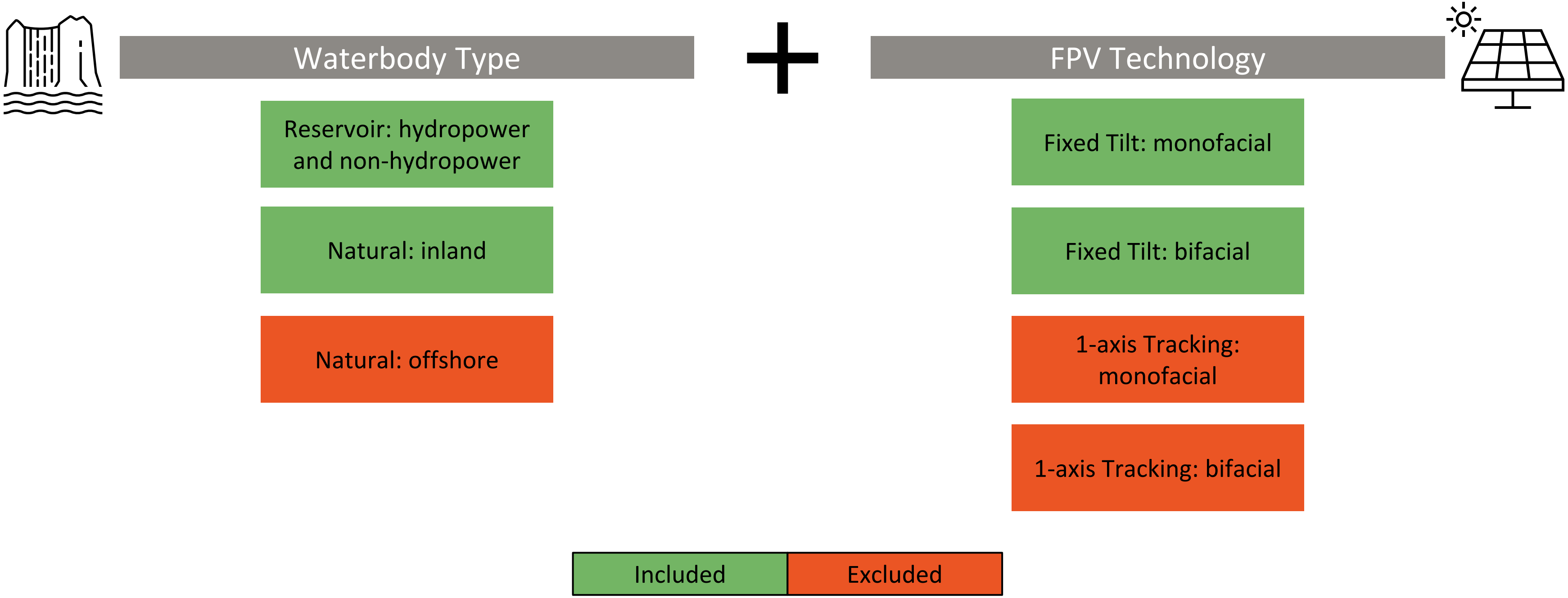


Figure. High-Resolution Solar Resource Data Available for Southeast Asia

Source: Joshi et al. (2023b)

Southeast Asia FPV Study: Analysis Scenarios



Waterbody Type + **FPV Technology**

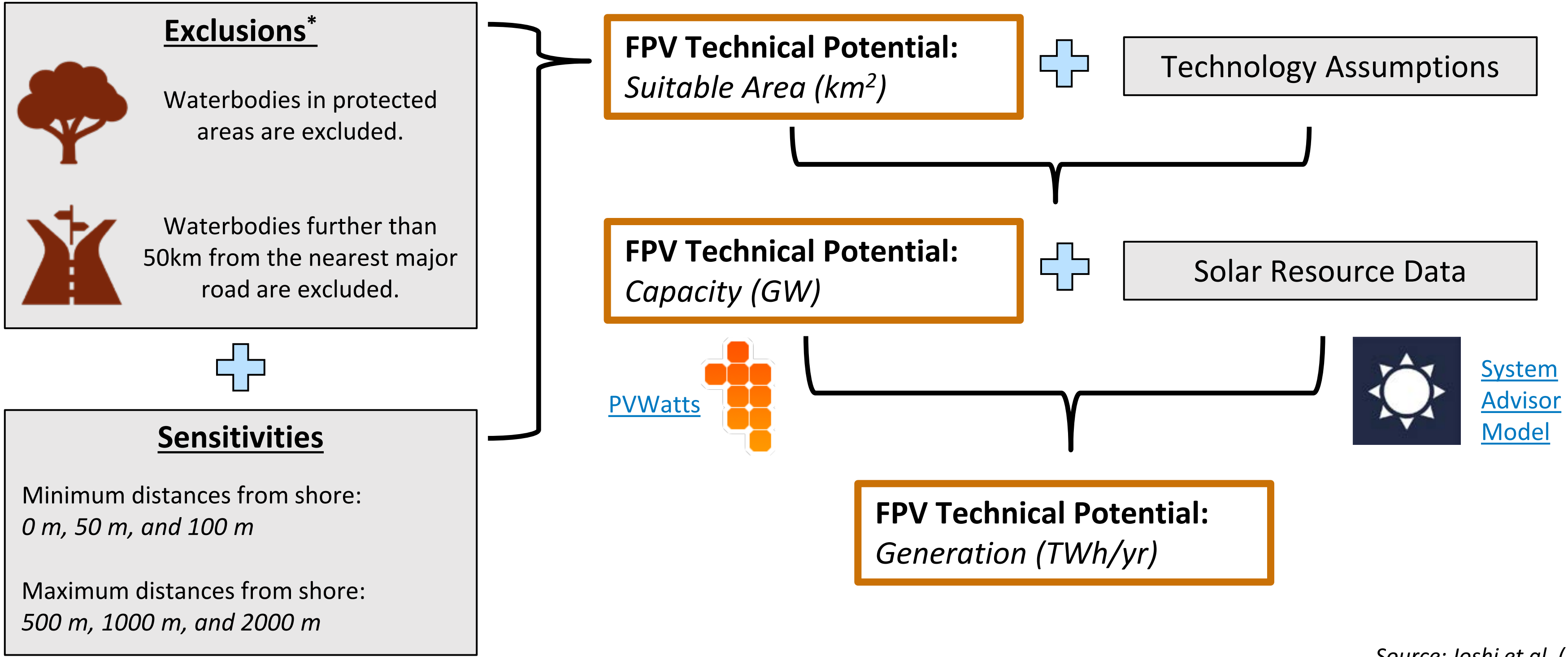
Waterbody Type:
- 🟩 Reservoir: hydropower and non-hydropower
- 🟩 Natural: inland
- 🟥 Natural: offshore

FPV Technology:
- 🟩 Fixed Tilt: monofacial
- 🟩 Fixed Tilt: bifacial
- 🟥 1-axis Tracking: monofacial
- 🟥 1-axis Tracking: bifacial

🟩 Included 🟥 Excluded

Source: Joshi et al. (2023b)

Southeast Asia FPV Study: Technical Potential Calculation



Exclusions*

Waterbodies in protected areas are excluded.

Waterbodies further than 50km from the nearest major road are excluded.

Sensitivities

Minimum distances from shore:
0 m, 50 m, and 100 m

Maximum distances from shore:
500 m, 1000 m, and 2000 m

FPV Technical Potential: *Suitable Area (km^2)*

Technology Assumptions

FPV Technical Potential: *Capacity (GW)*

Solar Resource Data

PVWatts

System Advisor Model

FPV Technical Potential: *Generation (TWh/yr)*

Source: Joshi et al. (2023b)

*A distance-from-transmission exclusion was included for certain results, but not the default results, because this data was only available for certain countries (Cambodia, Laos, Myanmar, the Philippines, Thailand, and Vietnam).

Southeast Asia FPV Study: Results – Reservoirs

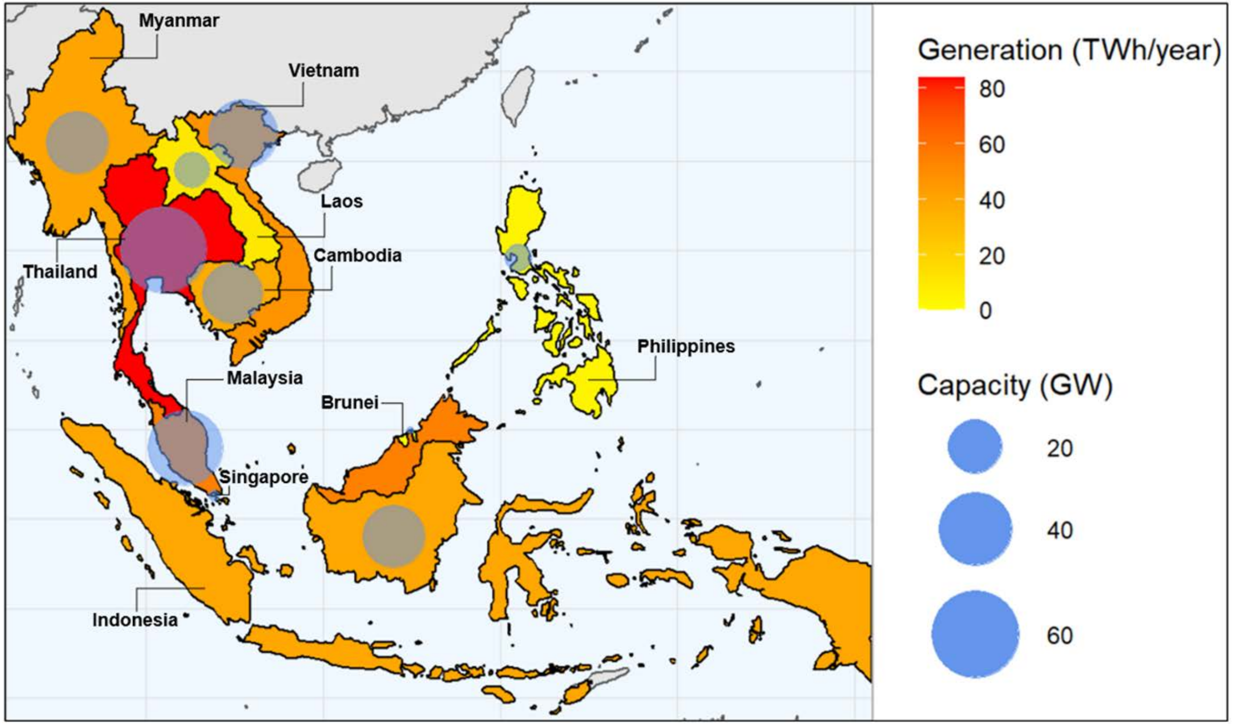


Figure. FPV Generation and Capacity Technical Potential for Reservoirs in Southeast Asia

Note: These results assume fixed-tilt monofacial FPV panels, with a 50 m minimum distance-from-shore and 1000 m maximum distance-from-shore buffer. The dataset excludes waterbodies that are more than 50 km from major roads and waterbodies that are within protected areas. These results do not reflect a filter for distance-from-transmission.

Southeast Asia Regional Results:

Waterbodies: 88

Area: ~1,343 – 2,784 km^2

Capacity: ~134 – 278 GW

Generation: ~187 – 389 TWh/yr

Ranges in results are due to different distance-from-shore assumptions.

Source: Joshi et al. (2023b)

Southeast Asia FPV Study: Results – Natural Waterbodies

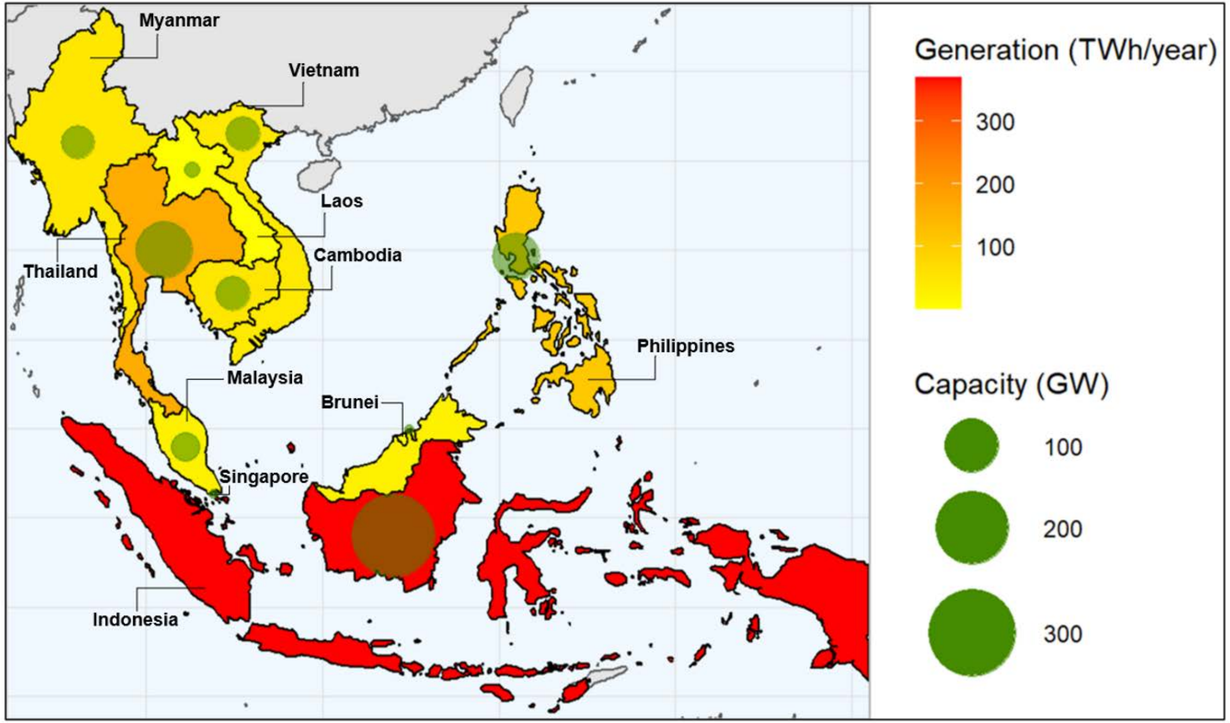


Figure. FPV Generation and Capacity Technical Potential for Natural Waterbodies in Southeast Asia

Note: These results assume fixed-tilt monofacial FPV panels, with a 50 m minimum distance-from-shore and 1000 m maximum distance-from-shore buffer. The dataset excludes waterbodies that are more than 50 km from major roads and waterbodies that are within protected areas. These results do not reflect a filter for distance-from-transmission.

Southeast Asia Regional Results:

Waterbodies: 7,213

Area: ~3,427 – 7,676 km^2

Capacity: ~343 – 768 GW

Generation: ~476 – 1,062 TWh/yr

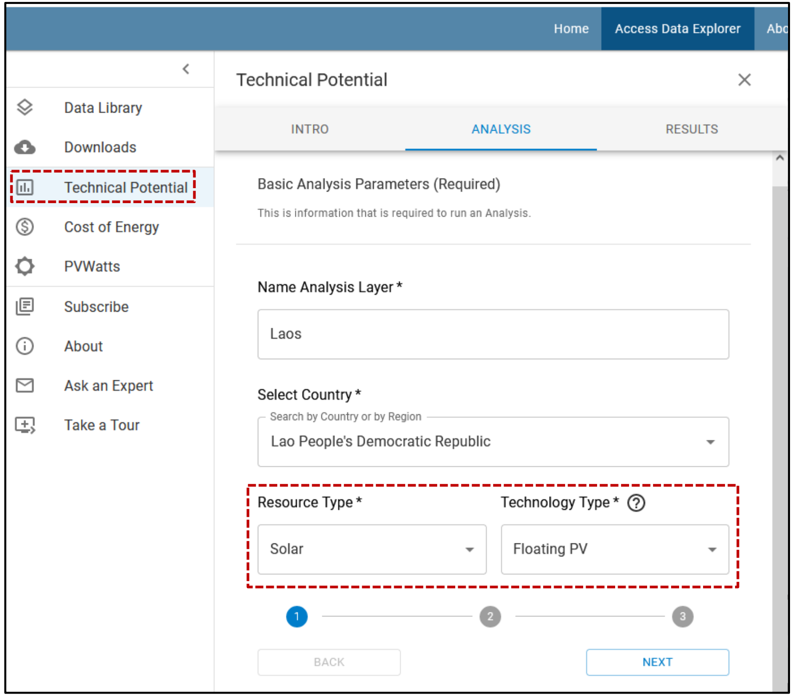
Ranges in results are due to different distance-from-shore assumptions.

Source: Joshi et al. (2023b)

Southeast Asia FPV Study: Open Access Data

https://www.re-explorer.org/home

Technical Potential Tool



Technical Potential

Basic Analysis Parameters (Required)

This is information that is required to run an Analysis.

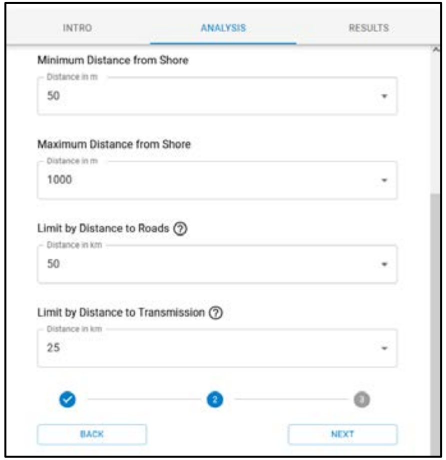
Name Analysis Layer *: Laos

Select Country *: Search by Country or by Region: Lao People's Democratic Republic

Resource Type *: Solar

Technology Type *: Floating PV

Inputs

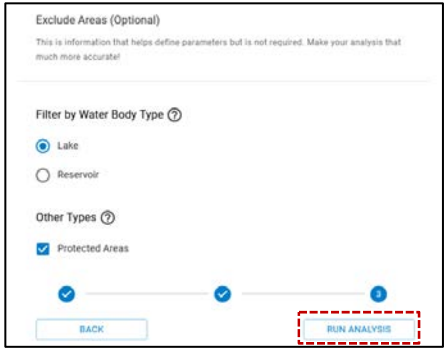


Minimum Distance from Shore: Distance in m: 50

Maximum Distance from Shore: Distance in m: 1000

Limit by Distance to Roads: Distance in km: 50

Limit by Distance to Transmission: Distance in km: 25



Exclude Areas (Optional)

This is information that helps define parameters but is not required. Make your analysis that much more accurate!

Filter by Water Body Type

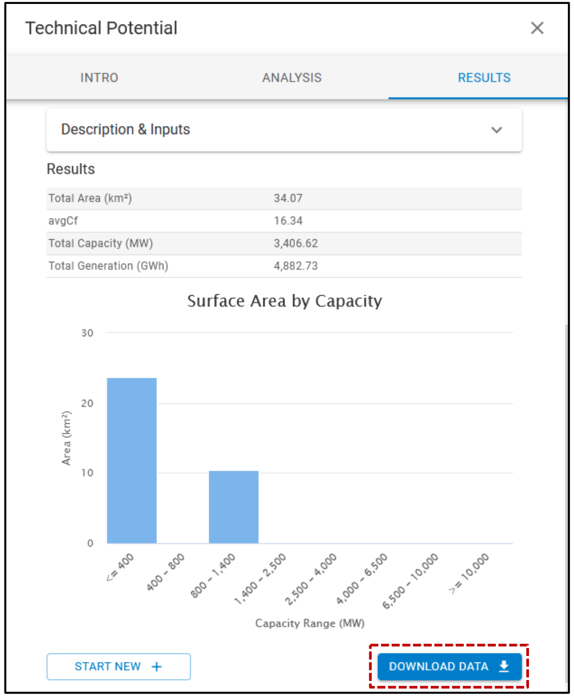
● Lake

○ Reservoir

Other Types

☑ Protected Areas

Results



Technical Potential

Results

Total Area (km²)	34.07
avgCf	16.34
Total Capacity (MW)	3,406.62
Total Generation (GWh)	4,882.73

Thank You!

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NREL/PR-5R00-87698

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Transforming ENERGY

References (1/2)

Campos Lopes, Mariana Padilha, Tainan Nogueira, Alberto José Leandro Santos, David Castelo Branco, and Hamid Pouran. “Technical Potential of Floating Photovoltaic Systems on Artificial Water Bodies in Brazil.” *Renewable Energy* 181 (January 2022): 1023–33. https://doi.org/https://doi.org/10.1016/j.renene.2021.09.104.

Gadzanku, Sika. “Enabling Floating Solar (FPV) Deployment: Policy and Operational Considerations.” Presented at the Asia Clean Energy Forum (ACEF), National Renewable Energy Laboratory (NREL), June 17, 2022. https://www.nrel.gov/docs/fy22osti/83228.pdf.

Gadzanku, Sika, Heather Mirletz, Nathan Lee, Jennifer Daw, and Adam Warren. “Benefits and Critical Knowledge Gaps in Determining the Role of Floating Photovoltaics in the Energy-Water-Food Nexus.” *Sustainability* 13, no. 4317 (April 13, 2021a). https://doi.org/https://doi.org/10.3390/su13084317.

Gadzanku, Sika, Laura Beshilas, and Ursula (Bryn) Grunwald. “Enabling Floating Solar Photovoltaic (FPV) Deployment - Review of Barriers in Southeast Asia (NREL).” Golden, CO: National Renewable Energy Laboratory (NREL), June 2021b. https://www.nrel.gov/docs/fy21osti/76867.pdf.

Gadzanku, Sika, Nathan Lee, and Ana Dyreson. “Enabling Floating Solar Photovoltaic (FPV) Deployment: Exploring the Operational Benefits of Floating Solar-Hydropower Hybrids.” Golden, CO: National Renewable Energy Laboratory (NREL), June 2022. https://www.nrel.gov/docs/fy22osti/83149.pdf.

Gonzalez Sanchez, Rocio, Ioannis Kougias, Magda Moner-Girona, Fernando Fahl, and Arnulf Jäger-Waldau. “Assessment of Floating Solar Photovoltaics Potential in Existing Hydropower Reservoirs in Africa.” *Renewable Energy* 169 (May 2021): 687–99. https://doi.org/https://doi.org/10.1016/j.renene.2021.01.041.

Jin, Yubin, Shijie Hu, Alan D. Ziegler, Luke Gibson, J. Elliott Campbell, Rongrong Xu, Deliang Chen, et al. “Energy Production and Water Savings from Floating Solar Photovoltaics on Global Reservoirs.” *Nature Sustainability*, March 13, 2023. https://doi.org/10.1038/s41893-023-01089-6.

Joshi, Prateek. “Enabling Floating Solar Photovoltaic (FPV) Deployment in Southeast Asia: Overview with Considerations for Aquaculture PV.” Presented at the Renewable Energy Buyers Vietnam Working Group, National Renewable Energy Laboratory (NREL), February 2023. https://www.nrel.gov/docs/fy23osti/85264.pdf.

References (2/2)

Joshi, Prateek, Evan Rosenlieb, and Sika Gadzanku. “Enabling Floating Solar Photovoltaic (FPV) Deployment: FPV Technical Potential Assessment for Southeast Asia.” Golden, CO: National Renewable Energy Laboratory (NREL), May 2023a. https://www.nrel.gov/docs/fy23osti/84921.pdf.

Joshi, Prateek, Evan Rosenlieb, and Sika Gadzanku. “Enabling Floating Solar Photovoltaic (FPV) Deployment: FPV Technical Potential Assessment for Southeast Asia.” National Renewable Energy Laboratory (NREL), June 2023b. https://www.nrel.gov/docs/fy23osti/86321.pdf.

Kakoulaki, Georgia, Rocio Gonzalez Sanchez, Ana Maria Gracia-Amillo, Sándor Szabó, Matteo De Felice, Fabio Farinosi, Luca De Felice, et al. “Benefits of Pairing Floating Solar Photovoltaics with Hydropower Reservoirs in Europe.” *Renewable and Sustainable Energy Reviews* 171 (January 2023). https://doi.org/https://doi.org/10.1016/j.rser.2022.112989.

Lee, Nathan, Ursula Grunwald, Evan Rosenlieb, Heather Mirletz, Alexandra Aznar, Robert Spencer, and Sadie Cox. “Hybrid Floating Solar Photovoltaics-Hydropower Systems: Benefits and global assessment of technical potential.” *Renewable Energy* 162 (August 24, 2020): 1415–27. https://www.sciencedirect.com/science/article/pii/S0960148120313252.

Liber, William, Chris Bartle, Robert Spencer, Jordan Macknick, Alexander Cagle, and Taylor Lewis. “Statewide Potential Study for the Implementation of Floating Solar Photovoltaic Arrays.” Colorado Energy Office, Ciel & Terre, National Renewable Energy Laboratory (NREL), December 2020. https://energyoffice.colorado.gov/press-release/colorado-energy-office-releases-study-on-floating-solar-potential-in-the-state.

Ramasamy, Vignesh, and Robert Margolis. “Floating Photovoltaic System Cost: Q1 2021 Installations on Artificial Water Bodies.” Golden, CO: National Renewable Energy Laboratory (NREL), October 2021. https://www.nrel.gov/docs/fy22osti/80695.pdf.

Spencer, Robert S., Jordan Macknick, Alexandra Aznar, Adam Warren, and Matthew O. Reese. “Floating Photovoltaic Systems: Assessing the Technical Potential of Photovoltaic Systems on Man-Made Water Bodies in the Continental United States.” *Environmental Science and Technology* 53 (December 2018): 1680–89. https://doi.org/https://doi.org/10.1021/acs.est.8b04735.

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