Advanced Energy Partnership for Asia

ENABLING FLOATING SOLAR PHOTOVOLTAIC (FPV) DEPLOYMENT

Exploring the Operational Benefits of Floating Solar-Hydropower Hybrids

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List of Acronyms

FPV	floating solar photovoltaic
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
NREL	National Renewable Energy Laboratory
PV	photovoltaic
SAM	System Advisor Model
USAID	United States Agency for International Development

Key Takeaways

Southeast Asian countries are taking significant steps to meet growing energy needs while reducing the carbon footprints of their power sectors. The adoption of renewable energy, including floating solar photovoltaic (FPV) systems, can help diversify power generation mixes and strengthen energy security. FPV systems offer a renewable option to help meet demand and lessen land-use conflicts, as well as other oft-cited co-benefits. Additionally, Southeast Asia is still experiencing some of the fastest electricity demand growth rates in the world even with a reduction in overall electricity demand due to the ongoing COVID-19 pandemic (International Energy Agency 2020).

This report explores the potential value that hybrid FPV-hydropower systems can provide for power systems. We model an example hybrid FPV-hydropower system to quantify the operational benefits that hybridization may provide. Using hourly time-series solar resource and seasonal resource data for a typical hydropower plant, we quantify the potential curtailment reduction, transmission utilization, and changes in seasonal and diurnal electricity generation for the hybrid FPV system. Results (summarized in Table ES 1) suggest that depending on the seasonality of hydropower resources, FPV system size, and transmission capacity, hybridizing FPV with hydropower could reduce PV curtailment and lead to more optimal use of limited water resources.

Table ES 1. Summary of Key Takeaways

Literature review	• The limited research on PV-hydropower hybrids indicates that PV and hydropower can complement each other on an interannual basis, but their complementarity at shorter time scales is less understood. ● There is a gap in literature on modeling potential hybrid FPV-hydropower operational benefits, specifically reduced solar PV curtailment, improved system operation at different time scales, improved transmission utilization, and water resource conservation.
What are the broad, system-level benefits of hybridization?	Compared to a Stand-Alone FPV system, hybridizing FPV with hydropower helps: • Lower PV curtailment when transmission constraints cause curtailment • Reduce dependence on other types of generation, such as gas-fired generation, by reducing PV curtailment. • Conserve water by shifting hydropower generation to other periods of the year in order to maximize use of zero marginal cost generation from PV.
What are the benefits of hybridization at different time scales?	• Hybridizing FPV with hydropower offers benefits on a daily and seasonal scale because of the complementarity of solar and hydropower and the flexibility of hydropower. • At the diurnal scale, results suggest that full hybridization could lower operations and maintenance costs, namely, generator wear and tear and reduce cycling for gas fired generation, by taking advantage of more hydropower flexibility. • At the seasonal scale, results suggest that hybridizing FPV leads to more optimal use of water resources with hydropower generation reduced in the wet season to conserve water for use during the dry season. This could be an important resilience measure in countries or regions that are dependent on hydropower generation but vulnerable to droughts and general declines in hydropower output. • Future research is needed to explore system costs benefits as well as plant and system level benefits at the sub-hourly scale.
How does the PV system size impact benefits?	• Our results suggest that the size of the FPV system relative to the hydropower system in a hybrid plant drives a trade-off between seasonal smoothing of hydropower generation and PV curtailment. A larger FPV system allows more seasonal smoothing of hydropower but increases curtailment during peak solar hours.

The findings presented in this analysis offer some potential applications to the Southeast Asia context. Given Southeast Asia's abundant solar PV resources, the complementarity of solar with hydropower, and the region's significant hydropower assets, hybridizing FPV with hydropower could help meet the region's growing electricity demand and provide a measure of resilience against future decline and changes in hydropower generation.

The primary intended audiences for this work include:

1. Energy sector decision makers within energy ministries and utilities that may consider the potential for hybrid FPV-hydropower system integration to support broader energy and development goals.
2. Energy system modelers tasked with exploring and quantifying the potential value that hybrid FPV-hydropower systems may provide within a specific energy system.

Although this work focuses on applications of FPV-hydropower in the Southeast Asia region, the results and takeaways may also be applicable to countries in other regions, with adaptations.

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1. Overview: Hybrid Floating Solar Photovoltaic-Hydropower Systems

The Southeast Asia region is undergoing rapid energy sector transitions and exploring the potential role of renewables—including solar photovoltaics (PV)—as it becomes increasingly competitive as a result of technological advances and falling capital costs.[1] Low-cost solar PV provides countries in the region with an option to meet increasing energy demand and diversify generation portfolios, complementing hydropower and thermal-dominant systems and strengthening energy security throughout the region. Floating solar PV (FPV) has emerged as an attractive application of solar PV that allows for systems to be floated on water bodies. Pairing FPV in hybrid systems with hydropower may also provide significant value for power systems in the region, beyond oft-cited co-benefits of stand-alone FPV (Lee et al. 2020; Gadzanku et al. 2021).

Despite growing interest in FPV systems, few applications of hybrid FPV-hydropower systems exist in Southeast Asia, and limited information is available about the co-benefits these systems may provide for potential adopters. This work, funded by the U.S. Agency for International Development (USAID) through the Advanced Energy Partnership for Asia, explores the value that hybrid FPV-hydropower systems may provide to the power systems of Southeast Asian countries. This work on the value of hybrid FPV-hydropower systems is accompanied by a recent report, *Creating an Enabling Policy and Regulatory Environment for Floating Solar Photovoltaics: Review of Barriers to FPV Deployment in Southeast Asia*, also focused on Southeast Asia (Gadzanku, Beshilas, and Grunwald 2021).

Figure 1 depicts representative stand-alone and hybrid FPV-hydropower systems and key components. Detailed descriptions of these systems are available in the literature (World Bank, ESMAP, and SERIS 2019; Lee et al. 2020). Stand-alone FPV systems are generally located on artificial inland water bodies, such as ponds, lakes, and reservoirs, and are operated independently, or not connected or operated in hybridization with other generation types. In hybrid FPV-hydropower systems, the FPV is co-located on a hydropower reservoir and coupled with the hydropower generator, allowing for co-optimized planning and operation.

a. Why Consider FPV in Southeast Asia?

Globally, FPV deployment has risen from 6 megawatts (MW) to 2,579 MW of installed capacity from 2013 to 2021, respectively (Reindl and Paton 2020). Asia leads the world in FPV deployment, with over 85% of installed systems (Reindl and Paton 2020). A few significant co-benefits have contributed to this regional growth, specifically in Southeast Asia, where land-constrained countries with growing populations and economies seek innovative solutions to sustainably balance energy, agriculture, and other needs. FPV systems offer a renewable option to help meet demand and lessen or avoid land-use conflicts, in addition to other oft-cited co-benefits (Gadzanku et al. 2021).

The potential co-benefits of complementing existing and planned hydropower in Southeast Asia with FPV as part of hybrid systems may be significant. When paired with reservoir-based hydropower, hybrid FPV-hydropower systems may also provide additional co-benefits such as reduced capital costs through use of existing grid connections, reduced solar PV curtailment, improved system operation at different time scales, additional energy storage opportunities, improved transmission utilization, and water resource conservation, among others (Hernandez et al. 2014; Teixeira et al. 2015; Hoffacker, Allen, and Hernandez 2017; Ibeke et al. 2017; Cazzaniga et al. 2018; Rosa-Clot and Tina 2018; Spencer et al. 2019; Liu et al. 2019; Lee et al. 2020; Gadzanku, Beshilas, and Grunwald 2021; Gadzanku et al. 2021; Ramasamy and Margolis 2021).

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[1] Southeast Asia in this document refers to the 10 countries of the Association of Southeast Asian Nations: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam.

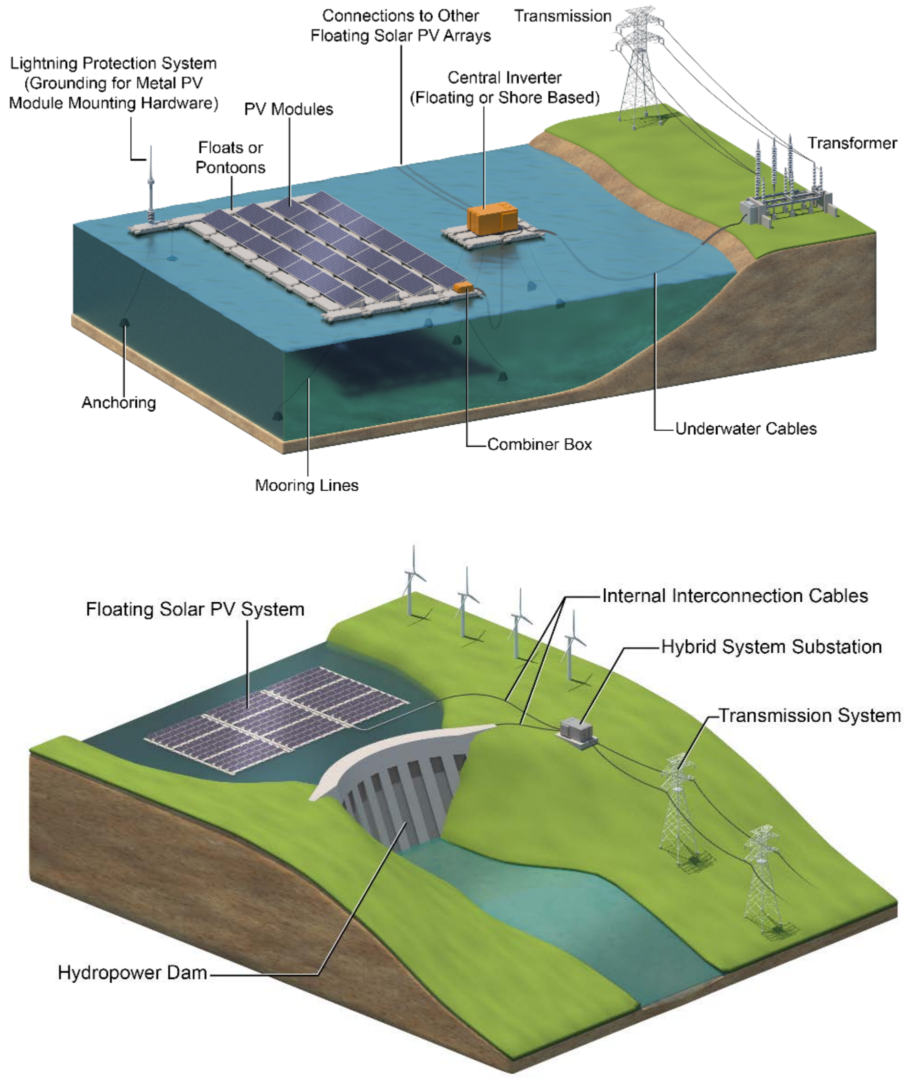

Figure 1. Representative configurations of (a) stand-alone FPV and (b) hybrid FPV-hydropower systems

Source: (Lee et al. 2020)

b. What Is the Purpose of This Report and Intended Audience?

This report explores the potential value that hybrid FPV-hydropower systems can provide for power systems. We model an example hybrid FPV-hydropower system to quantify the operational benefits that hybridization may provide.

The primary intended audiences for this work include:

1. **Energy sector decision makers** within energy ministries, public utility commissions, and utilities that may be considering the potential for hybrid FPV-hydropower system integration to support broader energy and development goals.
2. **Energy system modelers** tasked with exploring and quantifying the potential value that hybrid FPV-hydropower systems may provide within a specific energy system.

Although this work focuses on applications of FPV-hydropower in Southeast Asia, the results and takeaways may also be applicable to countries in other regions, with adaptations.

c. How Do We Model Hybrid FPV-Hydropower Systems?

To explore the potential value of hybrid FPV-hydropower systems, we modeled three example systems. The configurations for these three systems are shown in Figure 2.

- The **Hydropower Only** system assumes generation consists of hydropower, and coal- and natural gas-fired thermoelectric power and does not include land-based PV or FPV in the generation mix. The hydropower and thermal (coal and natural gas) generation are separately interconnected to the main transmission system, which then leads to the distribution system and demand.
- The **Stand-Alone FPV** system assumes that generation includes a stand-alone FPV system co-located, but not hybridized, with the hydropower. In this configuration, each generation type (thermal generation, hydropower generation, FPV generation) is separately interconnected to the grid.
- The **Full Hybrid FPV-Hydropower** system assumes that FPV is hybridized with the hydropower and interconnected at the same substation, allowing for optimal operation of the system by fully utilizing the available transmission.

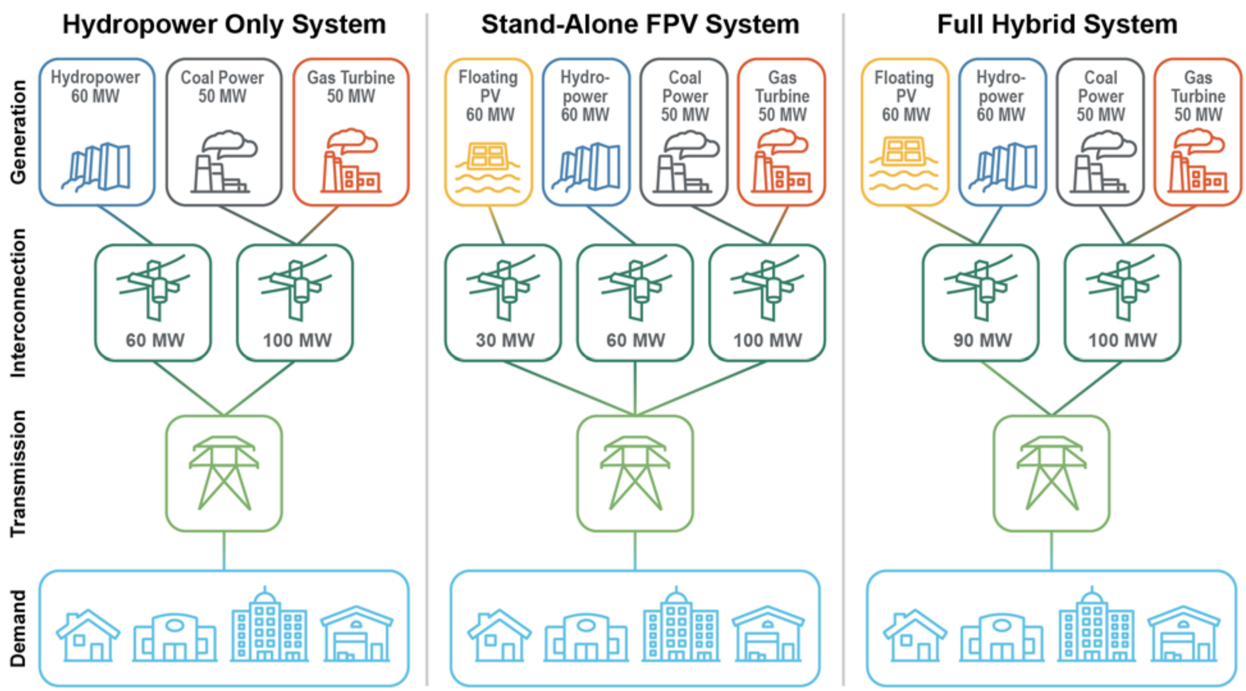

Figure 2. Example system configurations for the Hydropower Only (left), Stand-Alone FPV (middle), and Full Hybrid FPV-Hydropower (right) systems

Generation capacities for these example systems are 60 MW for each of FPV and hydropower, and 100 MW for the total thermal generation (with the share of thermal capacity in each system's power generation mix ranging from 50 – 60%). The generation mix considered is roughly based on the average mix in Southeast Asia (IEA 2019). The technology system sizes considered are based on literature, size range of existing and announced FPV projects, and the size range of existing hydropower plants in Southeast Asia. As of 2020, the majority of FPV installations are in the 1-10 MW range; however, Asia tends to host larger FPV projects (in the range of 10-50 MW), with some projects exceeding 100 MW

(Cox 2021; Tractebel Engie 2021). An NREL review of 115 existing hydropower systems in Southeast Asia found hydropower capacity ranging from 0.02 – 1,920 MW, with 30 MW the most common system size, and an average project size of 190 MW.

Hydropower is assumed to have a grid interconnection capacity equal to its installed capacity (i.e., 60 MW).[2] Thermal generation consists of coal and natural gas-fired generation, which are each equal to 50 MW. The interconnection connected to both thermal plants is assumed to be 100% (or 100 MW) of installed coal and natural gas-fired plant capacities. FPV interconnection is equal to 30 MW, which is 50% of the nameplate capacity and is sufficient transmission capacity for most hours of the plant's operation. This is partly due to how FPV was modeled. We use the System Advisor Model (SAM) to estimate hourly solar production and assumed an 11° tilt (based on numbers reported in the literature, which is lower than typical land-based PV systems) (NREL 2019; Spencer et al. 2019). This lower tilt would result in relatively lower solar generation from the FPV system; as such, the maximum output from the 60-MW FPV facility would be 43 MW (which is 72% of maximum plant output), making a 30-MW transmission interconnection reasonable at this site.

Ramping rates of 60% per hour and 100% per hour were used for the hydropower generator and thermal generators, respectively, with production costs set at $0.008 per kilowatt hour (kWh) for coal generation and $0.01 per kWh for combustion turbine natural gas generation (reflecting fuel costs and variable costs) and $0.001 per kWh for hydropower (an arbitrary cost that reflects our assumption that hydropower has a lower generation cost than all thermal generators but more than the zero marginal cost of solar).[3] A representative hourly demand profile was assumed for the model.

To explore dispatch and curtailment due to transmission constraints when FPV is added to the system, the transmission connected to the main demand substation is lower than the total generation capacity in the Stand-Alone and Full Hybrid systems:

- In the **Hydropower Only** system, total transmission capacity is 160 MW, as hydropower and thermal generation are the only generation available.
- In the **Stand-Alone FPV** system, total transmission capacity is 190 MW: 60 MW for the hydropower system, 30 MW for the FPV system, and 100 MW for thermal generation.
- In the **Full Hybrid** system, total transmission capacity is also 190 MW: 100 MW for thermal generation, with the FPV and hydropower plants sharing an interconnection with capacity set at 90 MW, which is the total hydropower capacity plus 50% (or 30 MW) of FPV capacity.

To model our example energy system, we utilized the NREL-developed Engage model.[4] Engage is built around Calliope, a widely used and tested open-source modeling framework for energy system simulation and planning.[5] We utilized the economic dispatch model capabilities of Engage to model the three system configurations (Figure 2) at an hourly temporal resolution for a single year.

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[2] The representative hydropower plant is modeled after an unspecified hydropower plant in a Southeast Asian country with significant hydropower capacity for this modeling exercise. The plant is located close to the capital and the border of a neighboring country for potential export. The hydropower plant was chosen purely as an example, and all modeling assumptions and inputs are from publicly available sources or hypothetical, to allow for exploration of FPV value to an example system. This work does not encourage development of FPV at this site, and the respective government and utilities were not involved in the study.

[3] Bloom et al. have the least flexible thermal generator type, coal, use a 2% per minute, which is more flexible than our 100% per hour assumption for thermal fleet (Bloom et al. 2016). Brinkman et al. assume variation in hydropower flexibility, ranging from 0.2% per minute to 1.6% per minute, so we use an intermediate value here that makes hydropower less flexible than thermal generation (Brinkman et al. 2021).

[4] Engage is a publicly available, flexible, web-based energy planning model for rapid multisectoral scenario exploration. For additional information on Engage, see: https://engage.nrel.gov/.

[5] More information on Calliope is available online: https://calliope.readthedocs.io/en/v0.6.6-post1/index.html.

To complement this report, we will share the example FPV-hydropower system model presented in this work. Making this model publicly available allows readers to explore further and adapt this base model for specific hybrid system applications.

For additional information on the modeling approach and accessing this model in Engage, see the appendix.

d. What Is Covered in This Report?

We first provide context for our modeling activity with a review of previous hybrid FPV-hydropower modeling work in Section 2. Modeling results are presented in Section 3, and Section 4 discusses implications for countries in the Southeast Asia region. We conclude with key takeaways and potential next steps for research and application of these hybrid systems.

2. Review: Hybrid FPV-Hydropower System Modeling

Key Takeaways	
	• The limited research on PV-hydropower hybrids indicates that PV and hydropower can complement each other on an interannual basis, but their complementarity at shorter time scales is less understood. • There is a gap in literature on modeling potential hybrid FPV-hydropower operational benefits.

This section presents a concise review of previous hybrid FPV-hydropower modeling work. The review is not limited to FPV hybrids, as, operationally, there are many similarities between land-based and FPV systems that are interconnected at a common substation with hydropower generation. The initial literature review identified 21 papers; however, after reviewing general hybrid literature, we focus on seven papers that included modeling of the combined operation (either co-optimization and/or coordination) of utility-scale hydropower and PV plants (Table 1).

Table 1. Hybrid Solar-Hydropower System Literature

Reference	Solar PV Capacity (MW)	Ratio of Hydropower to Solar PV Capacity	Treatment of Grid	Consideration of Hydropower Flexibility	Temporal Resolution	Location of Modeled System
An et al. (2015)	320	4	Other generators have lower merit order.	-	Hourly	Longyangxia Dam, Qinghai Province, China
Li, F. and Qiu (2016)	320	4	-	Min/max levels Min/max releases	Monthly	Longyangxia Dam, Qinghai Province, China
Ming (2018a)	320	4	Hybrid plant output must load-follow.	Ramp rates Spare capacity for reserve provision Min/max releases Minimum turbine up times	15 Minute	Longyangxia Dam, Qinghai Province, China
Yang et al. (2018)	850	1.5	-	Min/max releases	Monthly	Longyangxia Dam, Qinghai Province, China
Li, F et al. (2018)	850	1.5	Fixed demand	Min/max releases	Monthly	Longyangxia Dam, Qinghai Province, China
Li, H. et al. (2019)	850[6]	1.5	Hydro is implemented preferentially.	Min/max releases	Monthly	Longyangxia Dam, Qinghai Province, China
Liu et al. (2019)	2,000	0.5	Hybrid plant is implemented preferentially.	-	15 Minute	Jinan, China

[6] The Longyanxia power plant originally had 320 MW of solar but was increased to 850 MW while the hydropower capacity remained constant.

Hybrids with ground-mount PV, FPV, and wind that utilize battery energy storage are the focus of significant research (Denholm, Margolis, and Eichman 2017; Gorman et al. 2020; DOE, NREL, and LBNL 2021; Murphy, Schleifer, and Eurek 2021; Gorman et al. 2022). An important distinction from hybrid FPV-hydropower systems is that wind-PV systems are typically inverter-based power plants, while FPV-hydropower combines inverter and synchronous generation.[7] The cost-effectiveness of battery storage-based hybrids depends on the cost and lifetime of batteries, while the cost-effectiveness of hybrids without batteries depends much more on understanding the operational complementarity of the technologies. Hydropower modeling has unique challenges because power generation is only one of many competing priorities in plant operation, including water management, recreation, and environmental regulations (Stoll et al. 2017). Because of these competing priorities, existing hybrid modeling tools may not fully capture the potential value of hydropower hybrids. Modeling of hydropower hybrids is also complicated by the fact that hydropower resource availability is subject to interannual variability and climate-driven uncertainty in future precipitation.

Turning to hybrid PV-hydropower systems, most of the available literature focuses on the Longyangxia hydropower plant and solar park located in Qinghai Province, China. This is a well-known system that consists of a 1,280-MW hydropower plant completed in 1992 and an 850-MW PV system completed in 2017, one of the largest PV systems globally (NASA Earth Observatory 2017). An et al. (2015) describe the combined operation of this hybrid system as complementary, and provide an algebraic formulation of a PV and hydropower generation model that meets an hourly load curve, assuming that other generation sources are only used when these resources are exhausted. The work quantifies the amount of hydropower resources used to meet minimum hydropower production requirements—compensating for the diurnal PV generation profile—and the additional hydropower generation necessary to meet peak demand. This formulation is made under varying daily hydropower availability that accounts for seasonal reservoir levels. The authors test the complementary operation of PV and hydropower for three different solar resource profile days and demonstrate how the combined plant can provide more energy for morning demand on sunnier days.

Li and Qui (2016) formulate a multi-objective optimization problem for long-term operation (multiple years) of the Longyangxia system to maximize combined power output and minimize the monthly variance of the combined power output. Ming et al. (2018) optimize the operation of the Longyangxia system for maximum energy production and compare to actual operational data and find that optimized operation generates 1.9% more energy, while also reducing the time that the hydropower generator is online. Constraints on the optimization were: (1) require the generation profile to closely mirror the load profile, (2) maintain expected daily water consumptions, (3) reservoir mass balance, storage levels, reservoir release limits and other water use requirements, and (4) turbine generation limits, available capacity for reserves, ramp rate limitations, minimum turbine up times, and vibration limits. Ming et al. (2018) is closely related to this paper and uses the inner two stages of the described optimization process with an objective to minimize water usage under uncertain PV conditions. Li et al. (2019) determine operating rules for a hydropower-PV hybrid considering long-term uncertainties in stream flow and solar resource. The optimization is a maximization of energy production and guaranteed power output. Constraints account for reservoir storage capacity, water release limits, hydropower generation limits, and grid transfer constraints (including transmission limits). Yang et al. (2018) develop operating rules for the Longyangxia hybrid plant, which they believe can apply to other hydropower-PV hybrid plants. Their work focuses on long-term plant operation. The derivation of operating rules (which describe to operators how and when to release water depending on conditions) begins with a deterministic optimization for maximized energy production and reliability. Reliability is defined based on the number of time periods in which the total output meets the "firm" requirement. Constraints are for reservoir capacity, release

[7] Perhaps the closest analog to hybrid FPV-hydropower in the literature is hybrid PV-concentrated solar power, in which solar PV with battery energy storage is integrated with concentrated solar power plants with thermal energy storage. Similar to hybrid FPV-hydropower, hybrid PV-concentrated solar power includes energy storage, PV, and a synchronous generator, and like hydropower, concentrated solar power is charged by a natural inflow (solar radiation).

limits, and transmission constraints. Li et al. (2018) optimize the monthly release from hydropower in hybrid PV-hydropower for maximum energy generation and minimum water and PV curtailment. Curtailment is simply determined by using a fixed demand profile (no information about the demand is provided). Hydropower minimum and maximum releases and storage levels are constraints.

Beyond modeling analysis, installing hybrid systems requires considerations of different hydropower plant technologies, types, and typical uses. Roughly one-third of installed hydropower plants are multipurpose installations, serving additional functions that include flood protection, drought mitigation, irrigation, and water supply (Dzenan Malovic et al. 2015; U.S. Department of Energy 2018). Hydropower systems can be classified according to the size, head availability, operation regime, and purpose of the plant. Size classifications typically fall under micro (under 0.1 MW), small (between 0.1 and 10 MW), medium (between 10 and 100 MW), and large (over 100 MW) (Dzenan Malovic et al. 2015).

The core classification of hydropower systems, however, lies according to their operation regime, with run-of-river, storage, and pumped storage as the main types:

- **Run-of-river hydropower plants** typically have limited or no storage capacity, so electricity generation is dependent on reservoir inflow and subject to weather and seasonal changes (Dzenan Malovic et al. 2015).
- **Storage hydropower plants** generate electricity from dammed or impounded reservoirs, creating some storage capacity for use during periods of low rainfall.
- In **pumped storage hydropower plants**, water is stored during periods of low electricity demand and low electricity prices by pumping from a lower reservoir to a higher reservoir, and then released to generate electricity during periods of high demand and high electricity prices (U.S. Department of Energy 2018; Dzenan Malovic et al. 2015).

The primary uses of hydropower plants may therefore inform whether an FPV system can be installed and the extent of hybridization benefits that can be realized. Most FPV-hydropower hybrids have been installed on storage hydropower systems due to the logistical challenges of installing FPV on a pumped storage and run-of-river hydropower systems, as water levels may fluctuate too often.

Additionally, full hybridization of FPV with hydropower may occur under a few different ownership and operation configurations, which may also inform how hybrid systems operate in practice. Dobrotkova et al. (2019) identified three potential ownership and operation configurations:

- An all-publicly owned model where both the FPV and hydropower plants are owned and operated by public entities.
- A public-private partnership model in which the FPV and hydropower plants are owned and operated by a mix of public and private entities. This model, especially in the case where the FPV and hydropower plant are owned by different entities, could create a case of split incentives, as optimal operation of the hybrid plant may lead to lower output from one of the plants (likely the hydropower plant) during certain periods in the year.
- An all or almost 100% privately owned model in which both the FPV and hydropower plants are owned and operated by private entities (typically the same company).

Our literature revealed a gap in literature on modeling potential FPV-hydropower operational benefits. As noted, a majority of the available literature focuses on the Longyangxia hydropower plant and solar park, which is functionally similar to an FPV-hydropower system, but the PV system is not floating solar. The analysis detailed here aims to contribute to the growing literature on hybrid FPV-hydropower benefits by modeling the potential operational benefits of stand-alone FPV compared to a hydropower only and fully hybridized FPV-hydropower systems. Our modeling results would apply to PV-hydropower or FPV-hydropower hybrids, as we do not physically model the floating system other than by assuming low tilt angles that are typical in FPV installations.

3. Results: Value of Hybrid FPV-Hydropower Systems

This section presents a summary of the modeled results and insights from these results. We modeled the three example systems, **Hydropower Only**, **Stand-Alone FPV,** and **Full Hybrid** in the Engage modeling tool to quantify the potential reduction in curtailment, transmission utilization, and changes in diurnal and seasonal electricity generation for the various systems.

a. What Are the Broad, System-Level Benefits of Hybridization?

Key Takeaways	Compared to a stand-alone FPV system, hybridizing FPV with hydropower helps: • Lower PV curtailment when transmission constraints are the cause of curtailment • Reduce dependence on other types of generation, such as gas-fired generation, as a result of reduced PV curtailment. • Conservation of water in the reservoir by shifting hydropower generation to other periods of the year.

The following section presents modeling results based on production cost modeling conducted in Engage. Hybridization could provide benefits from the plant level to the system level. Using hourly time-series solar resource and seasonal resource data for a typical hydropower plant, we quantified the potential curtailment reduction, transmission utilization, and seasonal and diurnal electricity generation changes for the hybrid FPV system.

To consider potential curtailment reduction, we considered the difference in solar production for the Stand-Alone FPV and Full Hybrid example systems. Curtailment refers to a difference between generation dispatched and the resource available (Lau 2019). It can often be a measure of system flexibility (i.e., the ability to shift energy production to better match system demand and vice versa (Frew et al. 2021), but curtailment increases system cost because higher-cost generators are used instead of full PV utilization. Curtailment, specifically PV curtailment, is an increasingly common occurrence, with levels of curtailment depending on a host of factors, including operational parameters like transmission constraints, level of PV penetration, and system flexibility (Frew et al. 2021). In this study, we examined potential curtailment reduction as a function of system type and transmission capacity.

To explore this, we limited the transmission capacity available to the FPV and hydropower plants in the Stand-Alone FPV and Full Hybrid example systems. We did this by comparing two cases, **the Full Hybrid** and **Stand-Alone FPV** systems, that had the same transmission, representing equal transmission investments. This constraint informed how the model optimizes dispatch of FPV, hydropower, and/or thermal generation and allowed us to study potential curtailment impacts as transmission was constrained in the Stand-Alone FPV case. Additionally, given that the major focus of this work was on how solar interacts with hydropower, we considered PV curtailment at multiple time scales: hourly, daily, and on a seasonal basis. Hydropower is the main generation source in the base scenario across all modeled systems, which allows for a high-level exploration of how changes in solar curtailment could lead to shifts in hourly, daily, and seasonal hydropower generation.

Given this modeling context, our calculations estimated 8.55% PV curtailment for the Stand-Alone FPV system and zero curtailment in the Hybrid system (shown in Table 2).[8] The estimated curtailment in the

[8] Based on estimated annual curtailment. We estimated maximum power production across all hours of the year based on production modeled in SAM. Using this hourly production profile, we calculated the hourly potential curtailed PV (which is a difference between the capacity factor and transmission constraint). For example, on January 1, 2019, at 7 a.m., the expected curtailed PV is 0 because the hour's capacity factor (i.e., the total amount of energy produced over the nameplate capacity) is less

Stand-Alone FPV system would be any generation greater than the available transmission, whereas the FPV system in the Full Hybrid system would not have this transmission constraint as long as the hydropower was flexible enough to ramp down during peak solar hours. Actual hydropower plant flexibility can vary significantly by reservoir size, number of generator units and their characteristics, environmental constraints, and within seasons. For the purpose of our study, we assumed that hydropower was only constrained by available water and a ramp rate. Previous studies suggest that depending on the seasonality of hydropower resources and the ratio of the size of the FPV system to hydropower plant, a fully hybridized FPV-hydropower system could reduce curtailment and lead to more optimal use of limited water resources. Our modeling results corroborated this hypothesis as we observe that hybridizing FPV with hydropower reduces (in our case, eliminates) PV curtailment caused by limited transmission. At a system level, the cost optimal operational decision is to maximally utilize low-to-zero marginal cost resources by dispatching solar and conserving hydropower resources for later in the year if the hydropower is flexible enough to do so.

Table 2. Estimated PV Curtailment for Stand-Alone and Hybrid FPV Systems

System	Maximum Theoretical Plant Output (MW per MW capacity)	Maximum Actual Plant Output (MW per MW capacity)	Total Annual Curtailed Generation (megawatt hour (MWh) per MW capacity)	Total Curtailed at 60-MW Plant (MWh)	Available Generation at 60-MW Plant (MWh)	Total Curtailment (%)
Stand-Alone FPV	0.7182	0.500	125.2	7,514	87,850	8.55%
Full Hybrid FPV-Hydropower	0.7182	0.7182	0	0	87,850	0%

Our results show that the FPV system in the Full Hybrid system has a higher annual generation compared to the Stand-Alone FPV system. The difference is the avoided curtailment due to hybridization with the hydropower plant. Additionally, the hydropower generation across all systems is the same (not shown in Table 2) because our model requires all available water resource be dispatched during each calendar year.

Furthermore, without FPV in the generation mix (as seen for the Hydropower Only system in Figure 3), there is increased reliance on thermal generation because there are limited hydropower resources throughout the year. For our modeled systems, coal-fired generation remains unchanged across the Hydropower Only and Stand-Alone FPV systems, with generation slightly lower in the Full Hybrid System (specifically a 0.01% decrease in annual coal-fired generation translating to reduced output at noon during a handful of days in the dry season) but there are substantial differences in gas-fired generation.

The Hydropower Only system recorded the highest natural gas-fired generation because this system had no solar capacity at all, followed by the Stand-Alone FPV system (which curtailed 8.55% of FPV generation) and the Full Hybrid system, which had the lowest annual natural gas generation because it did not curtail any FPV generation. Natural gas generation changes are due to marginal cost dispatch rules, with gas displaced when solar is available because it is more expensive than coal generation.

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than the transmission constraint (which is 0.5, that is, 50% of the nameplate capacity). Whereas, on January 1, 2019, at 12 p.m. (when solar resource availability is close to its peak availability), the expected curtailed PV is 0.09124 MW per MW of capacity because the available solar resource is equal to a 0.59124 capacity factor, which is 0.09124 higher than the transmission constraint. Then this hourly potential PV curtailment is aggregated over the year, totaling 7,514 MWh for a 60-MW FPV plant, which is 8.55% of the maximum solar generation from this plant.

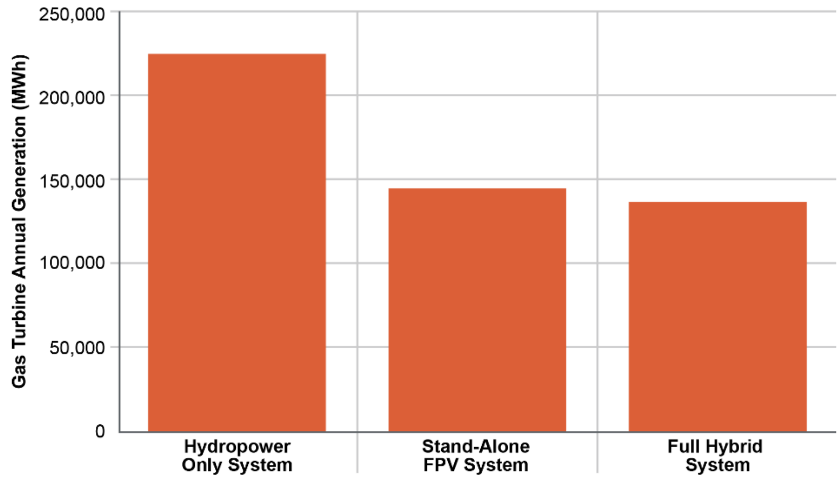

Figure 3. Gas-fired generation for all three model systems

To explore the temporal aspects of these results, we considered these benefits at different time scales and assess how FPV system size impacts the observed curtailment benefits.

b. What Are the Benefits of Hybridization at Different Time Scales?

Key Takeaways	• Hybridizing FPV with hydropower offers benefits on a daily and seasonal scale because of the complementarity of solar and hydropower. • At the diurnal scale, results suggest that Full Hybridization could lower generator operations and maintenance costs and reduce cycling for gas-fired generation by taking advantage of more hydropower flexibility. • At the seasonal scale, results suggest that hybridizing FPV leads to more optimal use of water resources with hydropower generation reduced in the wet season to conserve water for use during the dry season. This could be a very important resilience measure in countries or regions that are very dependent on hydropower generation but vulnerable to droughts and general declines in hydropower output. • Future research is needed to explore system costs benefits as well as plant and system level benefits at the sub-hourly scale.

To assess the benefits of hybridization at different time scales, we considered hourly, daily, and seasonal time scales, in addition to the annual results presented above. Figure 4 shows the seasonal shape of the annual hydropower resource used in this analysis. We explored whether the modeled hydropower reservoir conserved water resources into the dry season when coupled with FPV. There are some limits with the modeling approach used, which has some simplifying assumptions when modeling hydropower, including assuming that seasonal storage can shift completely and that all water resources must be used in a calendar year, which may not be realistic in an actual operational setting.

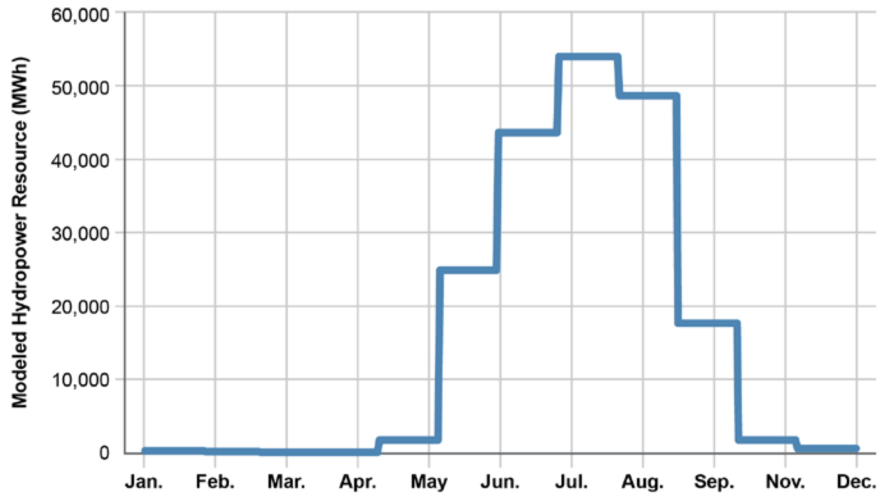

Figure 4. Modeled hydropower resource (MWh)

Results (as seen in Figure 5) indicate that, on average, increased FPV generation correlated to lower wet-season (or shifted) hydropower generation.

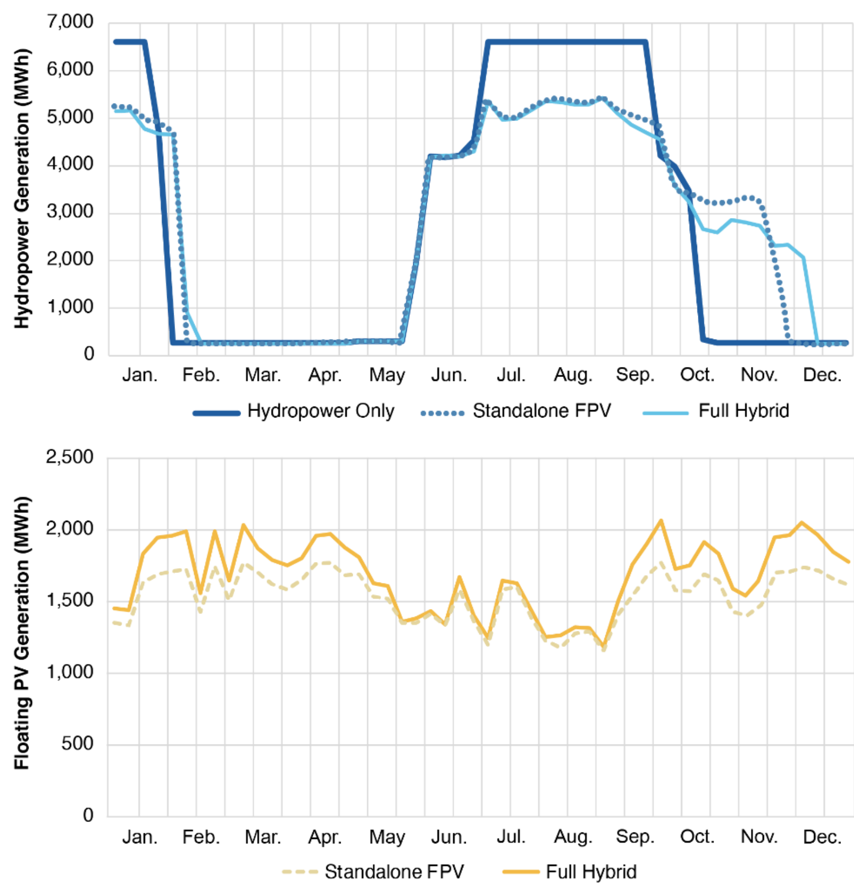

Figure 5. Floating PV (FPV) generation (top) and hydropower generation (bottom) for all model systems, with results aggregated on a weekly basis

Looking at hydropower generation for one year during two time periods of the year—July 1 through September 28 and October 1 through December 29—shows average generation output during the wet season and dry season, respectively (see Figure 6). Full hybridization allows hydropower operation to be optimized across seasons. The Full Hybrid system chooses to reduce hydropower output during the wet season, leading to higher FPV generation (due to reduced PV curtailment), conserving water for use during the dry season (October through December) when reservoir levels are lower. The opposite is observed for the Hydropower Only system. Here, the maximum hydropower resource available during the wet season is used, and, during the dry season, there is increased reliance on thermal generation because the system has no FPV resources available to dispatch; there is also less hydropower available due to low reservoir levels. Hydropower generation in the Stand-Alone FPV system is a medium between the two extremes, indicating that having some FPV capacity available, even if not hybrid, helps conserve hydropower resources and reduce dependence on thermal generation.

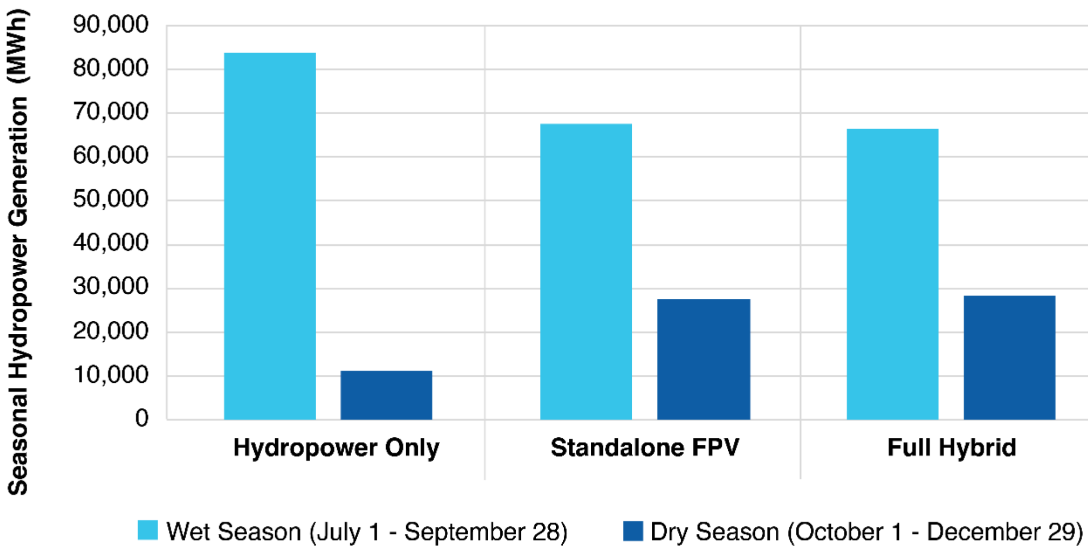

Figure 6. Seasonal hydropower generation in wet season (light blue) and dry season (deep blue) for all example systems

As seen in Figure 6 as well, the difference between seasonal hydropower generation in the Full Hybrid and Stand-Alone FPV systems is small, equal to the amount of FPV curtailed when the systems are uncoupled and are transmission constrained. Additionally, the size of the FPV system modeled in this example is quite small, limiting how much hydropower and resources could be conserved on an hourly basis. We explore the potential impact of FPV system size on the scale of these benefits in the next section.

At the hourly or daily scale, we explored the dispatch profile to understand how hybridization shaped the use of FPV, hydropower, and thermal generation. To do this, we show dispatch for FPV, hydropower, and thermal generation for three days in the wet and dry seasons. The wet and dry seasons in this hypothetical setting run from July to September, and October to December, respectively. This suggests that the shift in hydropower generation conserved water resources during peak PV production for use at a later time in the day, month, or season. To explore trends at the diurnal, monthly, and seasonal levels, we looked at dispatch over July 1–3 and October 1–3 (Figure 7 and Figure 8). The trends observed during those six days are not necessarily representative of the entire dry and wet season; however, they provide some insight as to potential dispatch trends during those time periods.

Some operational benefits of hybridization may be observed at a diurnal (daily) time scale in Figure 7. For both three-day periods, the Full Hybrid system dispatches more solar compared to the Stand-Alone FPV system due to reduced curtailment (as discussed in the previous section). For example, in the dry season Figure 7 (right), curtailed PV above 30 MW in the Stand-Alone FPV system is replaced by hydropower or natural gas. The reduced curtailment can save water resources for use during other periods of the day or later in the season. This trend demonstrates the flexibility of the modeled hydropower system, as well as the complementarity of the solar and hydropower resources, with increases in PV generation typically translating to decreases in hydropower generation. Similarly, the Hydropower Only system generates more with hydropower in the daytime because there is no solar compared to the Stand-Alone FPV system (Figure 8).

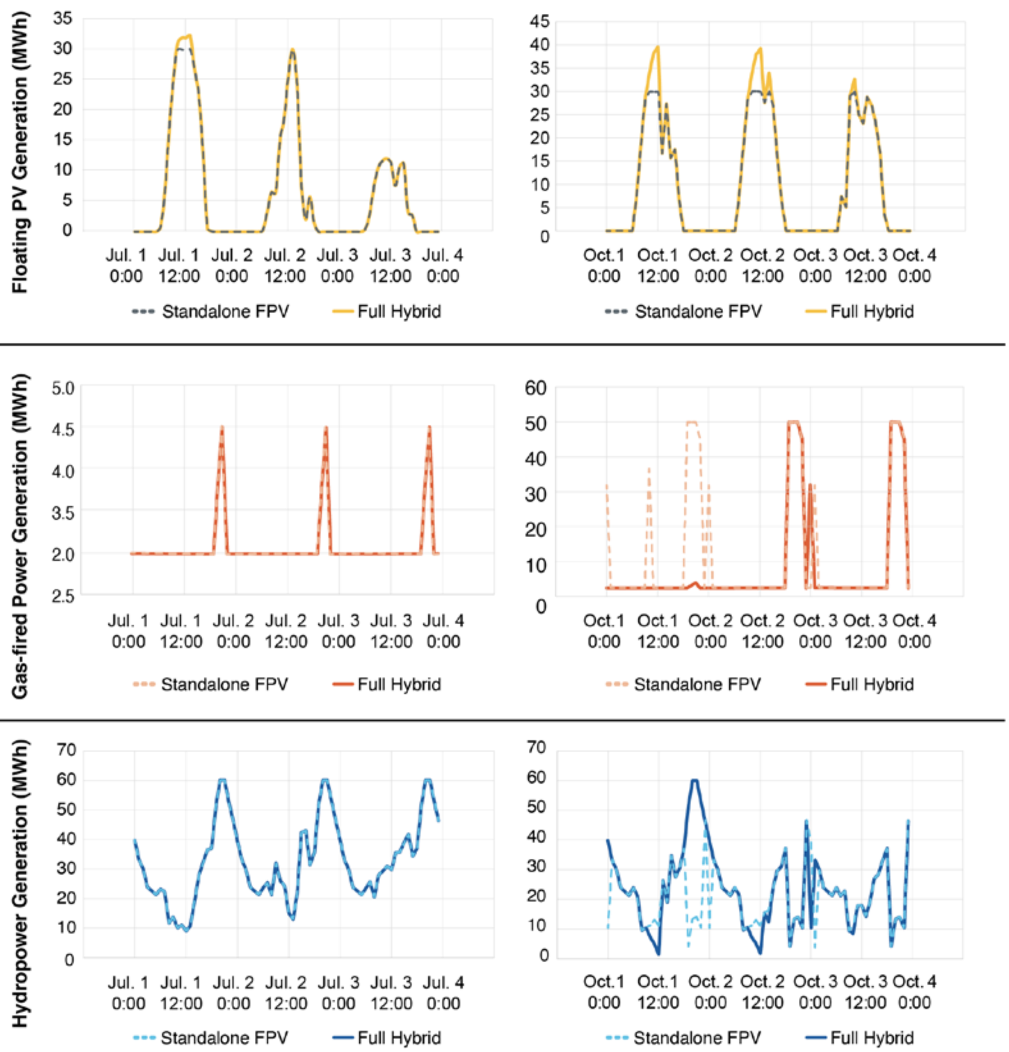

Figure 7. Floating PV (FPV) generation (top), gas-fired generation (middle), and hydropower generation (bottom) for Stand-Alone FPV and Full Hybrid systems with results aggregated on an hourly basis in the rainy season (July 1–3) (left) and dry season (October 1–3) (right).

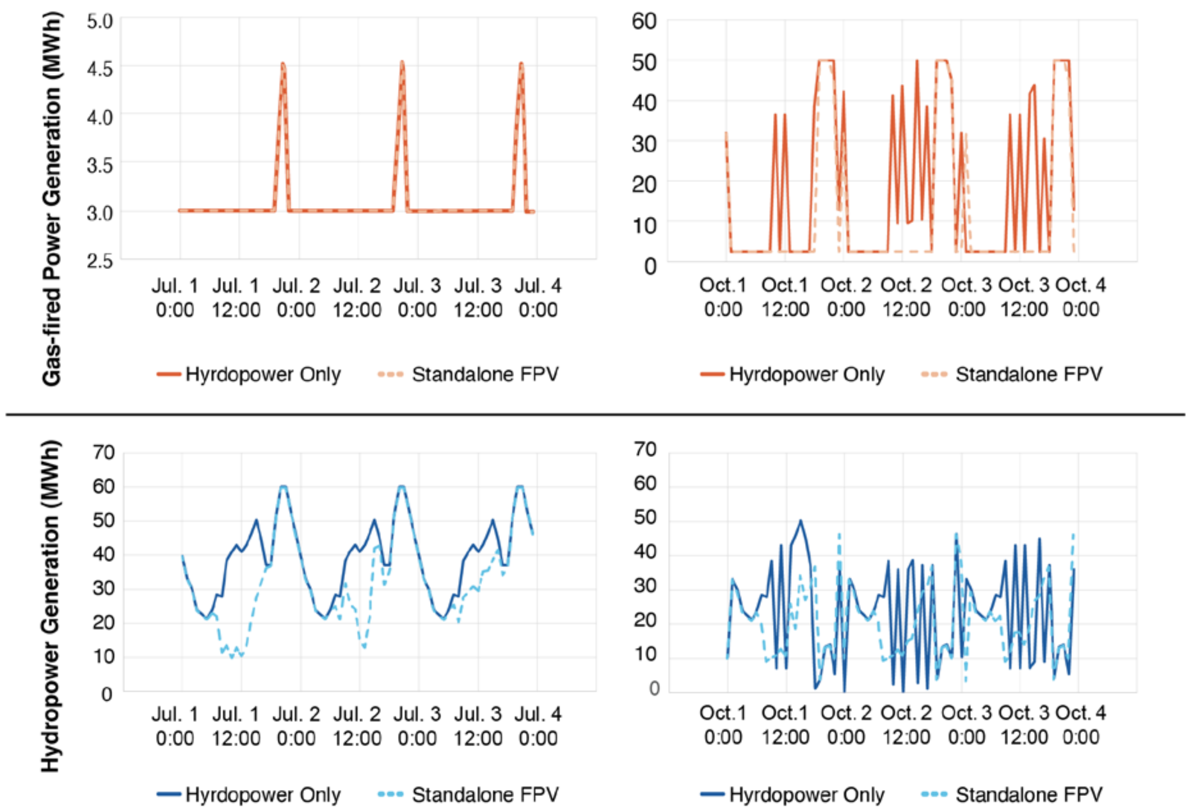

Figure 8. Gas-fired generation (top) and hydropower generation (bottom) for Hydropower Only and Stand-Alone FPV systems with results aggregated on an hourly basis in the rainy season (July 1–3) (left) and dry season (October 1–3) (right). Coal generation did not change.

The hydropower that is not used during peak solar hours either due to the Stand-Alone FPV system (Figure 8) or due to reduced curtailment in the Full Hybrid (Figure 7) is then available later in the day or season. In our simulations, we observed that this hydropower provided flexibility during key periods, often displacing gas turbine generation, which can operate as a flexible generator to quickly ramp up and down to match variability from load or PV generation. This is particularly observable in the dry season when the Hydropower Only system uses gas for ramping up and down. When the Stand-Alone FPV plant is added, the system tends to only need gas-fired generation for evening peaks, and finally the Full Hybrid system on one day (October 1 in this case) can eliminate the need for cycling the gas-fired generation at all. While these results are based on observations of a sample of days that may not represent the entire year, these results suggest that hybrid FPV can reduce not only fuel costs but also wear-and-tear costs on gas-fired generation.

Here we see that, as was noted in the literature review, PV/FPV-hydropower hybridization allows system operators to leverage the asynchronous nature of solar and hydropower resources (high-quality solar resources are generally available in dry seasons, with lower quality solar resources available in the rainy seasons). This operational benefit can directly translate to increased dependence on solar during the dry season (reducing reliance on hydropower) and then reducing dependence (and increasing reliance on hydropower) during the rainy season (Lee et al. 2020).

c. How Does the PV System Size Impact Benefits?

Key Takeaways	Our results suggest that the size of the FPV system relative to the hydropower system in a hybrid plant drives a trade-off between seasonal smoothing of hydropower generation and PV curtailment. A larger FPV system allows more seasonal smoothing of hydropower but increases curtailment during peak solar hours.

The literature reviewed suggests that the ratio of hydropower to FPV capacity could impact PV curtailment, hydropower dispatch, and water resource use. To explore this, we first used a range of hydropower to FPV size ratios ranging from 0.17 to 4 (Table 3). The range of FPV sizes considered also emphasize that FPV systems can take up very little space on a reservoir and still be able to match hydropower capacity (Bui 2019). The only variable in the runs was FPV system size.

Table 3. Sensitivity Analysis To Explore Impact of FPV Sizing on Solar Curtailment

Scenario	Solar PV Capacity (MW)	Hydropower Capacity (MW)	Ratio of Hydropower to Solar PV Capacity	Transmission Capacity (MW)
Reference: Standard Full Hybrid System	60 MW	60 MW	1	90 MW
Full Hybrid System with 4 hydropower: PV capacity ratio	15 MW	60 MW	4	90 MW
Full Hybrid System with 2% reservoir coverage	25.6 MW	60 MW	2.3	90 MW
Full Hybrid System with 1.5 hydropower: PV capacity ratio	40 MW	60 MW	1.5	90 MW
Full Hybrid System with 27% reservoir coverage	345.6 MW	60 MW	0.17	90 MW

Next, we explored scenarios with larger FPV systems by maximizing utilization of transmission capacity (see Table 4) to calculate potential FPV system sizes. The second analysis involved varying the FPV system size based on transmission utilization assumptions and the seasonal capacity factors of the hydropower plant (see Table 4). The hydropower and transmission capacities remain unchanged (at 60 MW and 90 MW, respectively), but the FPV system was sized assuming: (1) the FPV system could use all the excess hydropower transmission over the course of the year; and (2) the FPV system could use all the excess hydropower transmission in the wet season (July to September wet season capacity factor was 0.8135 compared to 0.2714 in the baseline year).[9] The rationale for the latter sizing is based on potential hybridization benefits reported in literature.

[9] The "Max Tx" scenario FPV capacity of 288 MW was determined by assuming the transmission capacity of 60 MW could be fully utilized at every hour of the year by a combination of the 60-MW hydropower plant having an annual capacity factor of 0.2714 and the solar power plant having a capacity factor of 0.1517. The "Max Tx Wet" scenario FPV capacity of 88 MW was determined by assuming the transmission capacity of 60 MW could be fully utilized at every hour of the wet season (July-September) by a combination of the 60-MW plant with a 0.8135 wet season capacity factor and the solar power plant having a wet season capacity factor of 0.1263. The calculated FPV capacity assumes a very flexible hydropower plant and does not account for curtailment, though in the simulations we ran there were limits to the flexibility, and FPV was curtailed as needed. See the appendix for more details on these scenarios.

Table 4. Sensitivity Analysis To Explore Impact of Transmission Availability on Solar Curtailment

Scenario	Solar PV Capacity (MW)	Hydropower Capacity (MW)	Ratio of Hydropower to Solar PV Capacity	Transmission Capacity (MW)
Standard Full Hybrid System	60 MW	60 MW	1	90 MW
Full Hybrid System with maximum transmission use (‘Max Tx’)	288 MW	60 MW	0.20	90 MW
Full Hybrid System with maximum transmission use during wet season (‘Max Tx-Wet’)	88 MW	60 MW	0.68	90 MW

As noted in (Lee et al. 2020), high-quality hydropower and solar PV resources may often be located far from load centers; thus, high-voltage transmission lines are often required to transport electricity from these plants to load centers. As such, during times of low production from these plants (e.g., hydropower generation during dry seasons), there is a risk of underutilizing these transmission lines. Hybridizing hydropower with FPV may offer the opportunity to maximize the use of these expensive transmission assets. In this sensitivity case, we sized the FPV system to maximize transmission use, even though some peak period curtailment would result. Our modeling results showed that the sensitivities tested in Table 4 had some impact on hydropower generation. The main impact, as shown in Figure 9, is higher hydropower generation in the dry season and lower hydropower generation in the wet season compared to the standard Full Hybrid system, with the largest seasonal smoothing provided by the Max Tx scenario because the Max Tx scenario had a larger FPV system.

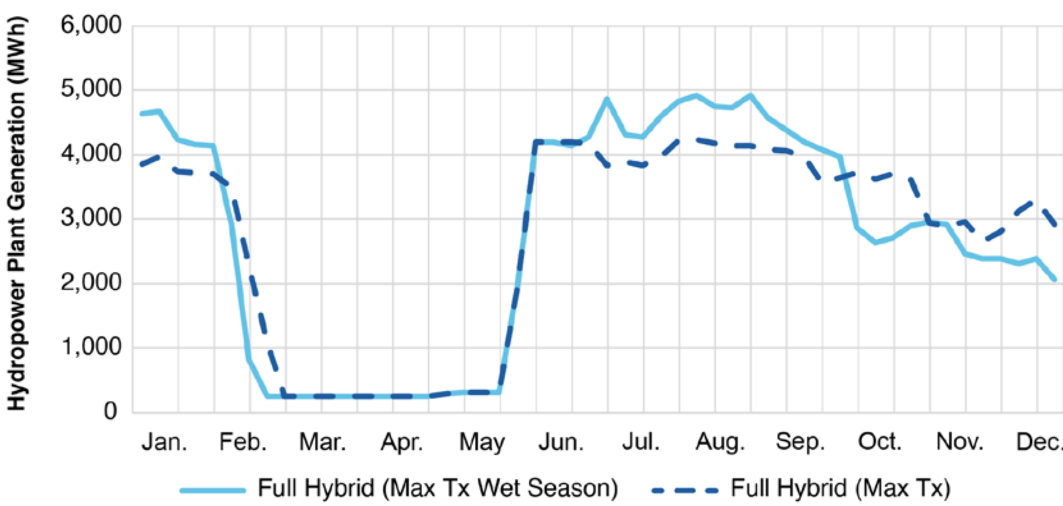

Figure 9. Sensitivity analysis: Hydropower generation, assuming varied transmission utilization and wetter hydrological cycles for Full Hybrid FPV-hydropower system

Our sensitivity analysis revealed additional trends between FPV system sizing, curtailment, and water use. First, we expect to see a similar trend in terms of how transmission capacity impacts curtailment. Namely, the Full Hybrid systems with FPV systems sized lower than the available transmission capacity (i.e., 90 MW) would have no curtailment, as long as the hydropower is able to fluctuate along with PV. Looking at Figure 10, this suggests that curtailment would be expected in the Full Hybrid (Max Tx) and Full Hybrid (27% coverage) sensitivity cases (in addition the Stand-Alone FPV system).

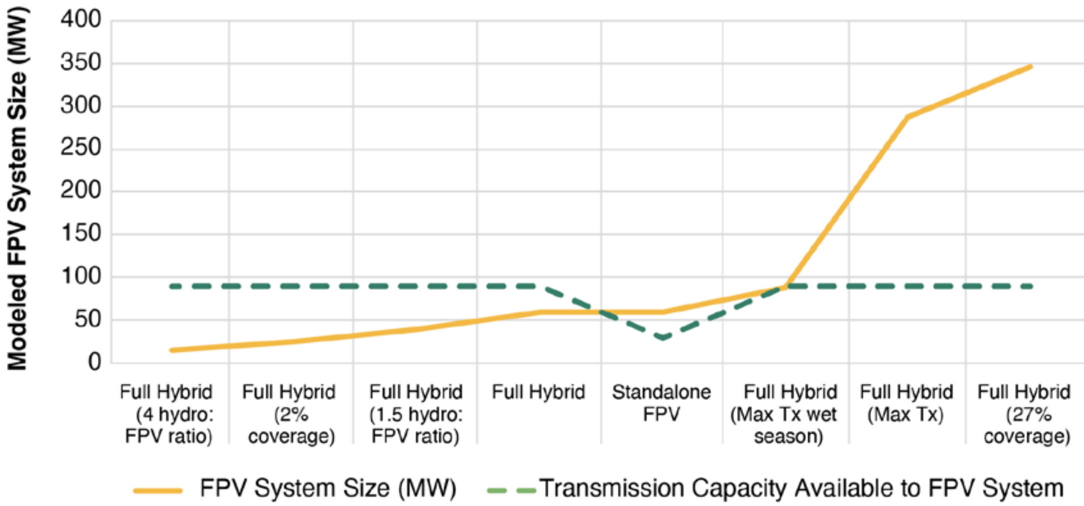

Figure 10. Comparison of available transmission to modeled FPV system size. Transmission capacity for the Stand-Alone FPV system was 30 MW (i.e., 50% of its nameplate capacity), whereas all FPV systems in the full hybrid systems shared a joint interconnection of 90 MW with the hydropower system

We see (in Figure 11) that this is the case, with curtailment observed in the Full Hybrid (Max Tx) and Full Hybrid (27% coverage) cases in addition to the Stand-Alone FPV system case. An economic assessment would determine if this level of curtailment was acceptable to maximally utilize transmission (Max Tx) or leverage a large extent of the reservoir surface area (27% Coverage). We also considered how hydropower production and water use by extension could be impacted by FPV system size. In Figure 11, the wet and dry season hydropower generation are in light blue and deep blue, with the three reference model systems (i.e., the Hydropower Only, Stand-Alone FPV and Full Hybrid systems) in lighter shades with FPV system sizing going from the smallest at 15 MW for the Full Hybrid system with a hydropower: FPV size ratio of 4 to 345.6 MW for the Full Hybrid system with 27% reservoir coverage (0.17 hydropower: FPV size ratio).

Our modeling results show that, in general, as the relative size of the FPV system increases in the hybrid power plant, the seasonal fluctuations in hydropower are reduced, with more hydropower available in the dry season. Annual hydropower generation will be equal across all scenarios, but the Hydropower Only system case has the highest hydropower generation in the wet season because it does not have FPV in its generation mix. Additionally, as FPV system size increases, there is more of a shift of hydropower generation (i.e., conservation of water resources) from the wet season for use later in the year during the dry season.

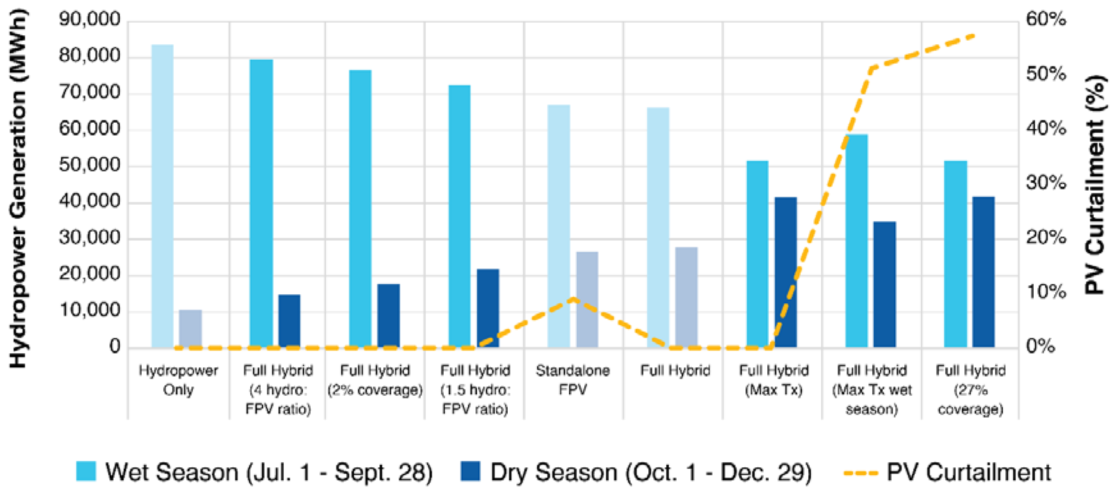

Figure 11. Sensitivity analysis: Impact of FPV system size on PV curtailment, seasonal hydropower generation, and water use. Results for the sensitivities are in light blue and deep blue, with the three reference systems in lighter shades.

Overall, our modeling results suggest that, depending on the seasonality of hydropower resources, FPV system size, and transmission capacity, hybridizing FPV with hydropower could reduce PV curtailment and lead to more optimal use of limited water resources. The two effects must be evaluated together because leveling out seasonal hydropower generation with a larger FPV system tended to lead to significant PV curtailment.

4. Discussion

Hydropower generation in Southeast Asia has quadrupled in the last 20 years (IEA 2019), with a majority of this growth occurring in the Mekong region. Total installed hydropower capacity in the Mekong stood at ~42 GW in 2020, with an additional 22 GW planned in the coming decades (Siala et al. 2021). For example, as of 2019, hydropower supplied 45% of Cambodia's electricity and recent droughts impacted hydropower generation, driving some power plant production down to 10% of its normal output (Cheang 2018; Hutt 2019). Hydropower installations here range from 30 MW to 400 MW. Laos sources most of its electricity from hydropower and has historically depended on imports from Thailand during the dry season when hydropower generation is unable to meet growing demand, and due to its mountainous and forested geography, utility-scale solar is not as viable (hydropower plants range from 36 MW to 540 MW). Other countries in the Southeast Asia region, namely Indonesia, Myanmar, the Philippines, Thailand, and Vietnam, also have significant hydropower capacity. The range of hydropower dependence varies but nevertheless, this growing dependence on hydropower presents some climate risks, including the need for measures to counteract the expected decline in hydropower generation due to more intense rainfall and droughts and overall inconsistent rainfall (International Energy Agency 2021). Despite this growing climate risk and other drawbacks of hydropower (including the disturbance of natural ecosystems, displacement of communities, and the associated carbon emissions), large-scale hydropower remains an affordable clean energy option (Siala et al. 2021; International Energy Agency 2021).

In countries with very hydropower-dependent grids—that is, grids where hydropower is a significant or the main electricity generation source—the benefits of diversifying generation are on display. Often, during dry seasons, saving any amount of hydropower resource for use later is ideal; thus, the marginal hydropower conservation shown in the difference between the Stand-Alone FPV, and Full Hybrid systems could: (1) save generation output for use later, helping to avoid power outages; and (2) optimize the use of solar resource when it is available during the day. This is especially important in Southeast Asia, a region with abundant solar resources and ambitious renewable energy goals that could help meet its growing electricity demand, which remains one of the fastest growing in the world (International Energy Agency 2020). As such, there is a need to develop resilience measures that could reduce these vulnerabilities to overall country and regional power grids. The modeling results suggest that hybridizing FPV with hydropower could provide operational benefits that could help mitigate the decline of existing hydropower assets while providing clean electricity that furthers the region's sustainability goals.

Our analysis of potential operational benefits at multiple time scales shows that full hybridization allows hydropower operation to be optimized across days and seasons. The hypothetical system modeled in this study shows that during some hours in the wet season, the Stand-Alone FPV system used FPV instead of hydropower, conserving water stored in the reservoir for use during the dry season when reservoir levels are lower, and the system also used less thermal generation overall. When the same transmission capacity is used as part of a Full Hybrid system, hydropower can be spread even further into the dry season for the same transmission investment. The opposite was observed for the Hydropower Only system. Here, the maximum hydropower resource available during the rainy season was used, and, during the dry season, there was increased reliance on thermal generation because the system had no FPV resources available to dispatch, and there is also less water available due lower reservoir levels.

5. Conclusions

This work uses an electricity production cost model to explore the potential operational benefits of hybridizing FPV with hydropower. This analysis focused on operational benefits on a daily to seasonal basis and the potential impact of FPV system size and transmission capacity on the scale of benefits. The analysis used highly spatially and temporally resolved solar resource data (available through the Renewable Energy (RE) Data Explorer); however, we could not conduct hybrid benefits analysis on a shorter time scale due to modeling limitations and the lack of spatially and temporally resolved data for the hypothetical hydropower power plant.[10]

Future work could examine the benefits of FPV hybridization at shorter time scales (at a sub-hourly scale) and at a broader geographic level (considering potential benefits to a country or region's grid). This kind of analysis would require more spatially and temporally resolved data (i.e., generation resource and demand data on a sub-hourly level), as well as a production cost model that can model at a sub-hourly timescale. Other areas of study could involve examining the impacts of hybridization on system costs, as well as the operational benefits using actual data from existing FPV-hydropower hybrid plants and comparable hydropower only and stand-alone FPV systems. A techno-economic analysis for a particular location would be necessary to weigh the trade-offs between transmission utilization and curtailment. Additionally, continued research on potential ecological impacts of FPV installations across different geographical contexts remains important.

Nevertheless, our findings suggest that, given Southeast Asia's abundant solar resources, the complementarity of solar with hydropower, and the region's significant hydropower assets, hybridizing FPV with hydropower could help meet the region's growing electricity demand and strengthen energy security in the region.

[10] The RE Data Explorer is a user-friendly geospatial analysis tool for analyzing renewable energy potential and informing decisions. It performs visualization and analysis of renewable energy potential that can be customized for different scenarios. RE Data Explorer can support prospecting, integrated planning, policymaking, and other decision-making activities to accelerate renewable energy deployment.

6. Appendix

The Engage Energy Modeling Tool (Engage) is a publicly available, highly accessible, and flexible and free web-based energy planning model for rapid multisectoral scenario exploration. Its cloud-based shared data model, intuitive interface, and visualization capabilities facilitate collaboration and communication among diverse stakeholder groups, teams, and experts modeling systems from district energy or microgrids to national scales. For this work, we employed Engage to model different configurations of stand-alone FPV and hybrid FPV-hydropower systems. This tool was developed in collaboration with the Hawaii State Energy Office with funding from the Department of Energy's Energy Transitions Initiative and Solar Energy Technologies Office.

Engage supports both capacity expansion and production cost modeling. As a capacity expansion model, it simulates and optimizes generation and transmission capacity costs given assumptions about future electricity demand, fuel prices, technology cost and performance, and policy and regulation. As an economic dispatch model or production cost model, it takes a given generation and transmission system and determines the lowest-cost way to operate it, while maintaining reliability under uncertainty and other types of constraints.

Engage is built around Calliope, a tested and well-documented open-source modeling framework for energy system planning. The model allows the user to define a technology sited at a given location and uses a resource to introduce or remove energy from the system. Calliope defines a location as a site which can contain multiple technologies, and which may contain other locations for energy balancing purposes. Technologies are aggregated based on their carriers such as electricity or heat. As it is a generally constrained optimization model, the objective function consists of various parameters, variables, and constraints as defined by the user or based on the model defaults.

Interested individuals can access models by creating an Engage account. Public models can then be accessed by all users, with closed models available to users with access.

Table A 1. Modeled PV Curtailment for Stand-Alone and Hybrid FPV Systems

System	FPV System Size (MW)	Maximum theoretical plant output (MW per MW capacity)	Maximum actual plant output (MW per MW capacity)	Total curtailed capacity factor (MWh per MW capacity)	Total curtailed at 60 MW plant (MWh)	Available generation at FPV plant (MWh)	Total curtailment (%)
Full Hybrid (sizing ratio of 4)	15	0.7182	0.7182	0	0	21,962	0%
Full Hybrid (2% FPV coverage)	25.6	0.7182	0.7182	0	0	37,483	0%
Full Hybrid (sizing ratio of 1.5)	40	0.7182	0.7182	0	0	58,566	0%
Full Hybrid (Max Tx Wet Season)	88	0.7182	0.6818	0	0	128,846	0%
Full Hybrid (Max Tx)	288	0.7182	0.2083	746.9	215,098	412,678	51.01%
Full Hybrid (27% FPV coverage)	345.6	0.7182	0.1736	849.6	293,627	506,014	58.03%

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