Optimal Design of 24/7 Hybrid-Resource Power Purchase Agreement

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***Abstract*—Power Purchase Agreements (PPAs) are increasingly favored by large energy consumers, such as data centers, for quicker access to reliable and cost-effective electricity. While traditional PPAs typically operate on a pay-as-produced basis with annual supply-demand balancing, emerging needs are driving a shift toward 24/7 hourly matching of supply and demand. Achieving this level of granularity requires integrating flexible resources, such as reservoir hydropower and energy storage, to complement variable renewables like wind and solar. This study presents an integrated optimization framework for designing 24/7 hybrid-resource PPAs that incorporate both dispatchable resources and non-dispatchable renewables. The framework jointly optimizes resource procurement, operational scheduling, and PPA pricing, ensuring economic efficiency while guaranteeing the provider's profitability. Simulation results demonstrate the critical role of flexible resources, such as hydropower, in enabling cost-effective 24/7 energy delivery. Sensitivity analyses further show how the PPA delivery requirement, contract shortfall penalty, and reductions in resource capital cost impact PPA prices and resource procurement decisions.**

I. Introduction

Large electricity loads are growing rapidly in power systems, driven in particular by the expansion of data centers [1]. These facilities require substantial energy to support cloud computing, artificial intelligence (AI) workloads, and digital services [2]. As a result, an increasing number of commercial and industrial (C&I) users are securing affordable and reliable power through bilateral Power Purchase Agreements (PPAs), rather than relying solely on the traditional utility procurement or public electricity pool.

PPAs are long-term bilateral contracts (typically 10–25 years) in which a provider sells energy to a buyer at a pre-determined price [3]. Conventional PPAs typically define delivery obligations on an annual basis, without committing the hourly power supply. To ensure secure and reliable energy supply, a 24/7 PPA structure is gaining more interests from the C&I users, which aims to match the user's electricity consumption on an hourly basis. For example, in 2018, Google announced a 24/7 hourly matching target, shifting from annual net energy balancing to hourly load matching [4].

However, achieving 24/7 delivery introduces substantial challenges. First, without dispatchable or flexible assets, such as reservoir hydropower or energy storage, relying on the non-dispatchable variable renewable energy (VRE) resources for hourly matching can lead to uneconomic outcomes. Second, the PPA design needs to jointly optimize the resource procurement and scheduling as well as PPA pricing. It is important to guarantee the provider's profitability and ensure a cost-effective outcome. Finally, PPA design parameters, e.g., the delivery requirement, contract violation penalty, and resource capital cost, can significantly influence the pricing and resource procurement results, and therefore require careful evaluation. These considerations motivate us to study the following question: *How to design a 24/7 PPA to coordinate flexible resources with VRE and achieve the provider's profit return target while preserving economically efficient outcomes?*

There has been extensive literature on the hybrid-resource PPA design. Most of the work focused on optimizing the procurement and operations of hybrid resource portfolios. The objectives took different perspectives. For example, the works [5]–[7] examined models that allow users to minimize energy costs. The works [8]–[11] examined ways for PPA providers to maximize profits and the [12], [13] illustrated ways to maximize social welfare. For PPA pricing, most of the above literature assumed the given prices from data or existing models. For the single-resource PPA, e.g., solar or wind, the minimum PPA price can be characterized by the levelized cost of energy (LCOE), which reflects the average unit cost of generating electricity from this resource. The National Renewable Energy Laboratory developed LCOE models that typically consider most of the financial parameters [14].

The evolving structure of 24/7 PPAs under hybrid resources requires holistic optimization and assessment for PPA pricing and resource procurement. Although the work [15] proposed a comprehensive LCOE formulation for hybrid-resource 24/7 PPAs, it assumed the given resource capacities without capturing the optimal resource procurement strategies. Jain *et al.* [12] optimized the system cost and characterized the LCOE of 24/7 PPAs as the resulting PPA prices. However, their model did not include hydropower resources, particularly flexible reservoir hydropower. Moreover, their analysis did not capture the effects of PPA delivery requirements, contract violation penalties, and the provider's profit return target.

In contrast to the existing literature, we summarize the main contributions of this work as follows.

Hybrid PPA design framework: This work proposes a 24/7 PPA design framework that integrates hybrid energy resources, leveraging the flexibility of reservoir hydropower

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and energy storage. It explicitly accounts for hourly PPA delivery requirements and contract shortfall penalties. The framework jointly optimizes resource procurement and PPA pricing, ensuring cost-effective outcomes while guaranteeing the provider's profit return target.

Hydropower role: We analyze the role of hydropower in 24/7 PPAs. Simulation results show that reservoir hydropower alone can economically meet the 24/7 PPA requirement when no capacity constraint is imposed. Pairing pumped storage hydropower (PSH) with solar and wind significantly lowers the PPA price compared with solar-and-wind-only portfolios. Moreover, if solar and wind capital costs are reduced by about 50%, the resulting PPA price becomes comparable to that of reservoir hydropower.

Sensitivity analysis: We perform detailed sensitivity analysis on the PPA delivery requirement, contract violation penalty, and solar and wind capital costs. A higher PPA delivery requirement, contract shortfall penalty, or capital cost will increase the break-even PPA price for resource portfolios. However, the roles and relative positions of different resources within the portfolio can shift as the parameters change.

II. System Model

We consider a PPA provider designs PPA contracts to serve users' electricity demand based on an optimally procured portfolio of selected types resources. In this study, we focus on a single provider and a single user. The framework can be extended to multiple providers and multiple users in future work. We next present the models for the PPA provider and the user, along with the overall decision-making process.

A. PPA Provider and User

Figure 1 illustrates the interaction between the PPA provider and the user. The PPA provider can procure different resources to form PPAs. Particularly, in the portfolios, we model VRE (e.g., solar, wind, and run-of-river (RoR) hydropower), reservoir hydropower, and energy storage (e.g., batteries and PSH).[1] We denote the resource sets of VRE, reservoir hydropower, and storage by $\mathcal{R}_{vre}$, $\mathcal{R}_{rv}$, and $\mathcal{R}_{sto}$, respectively. We let $\mathcal{R} = \mathcal{R}_{vre} \bigcup \mathcal{R}_{rv} \bigcup \mathcal{R}_{sto}$.

Under the agreement, the buyer and the provider specify an hourly delivery requirement, such as a minimum PPA delivery share of the buyer's hourly load. We assume that any shortfall of the commitment will incur a high penalty cost for the provider. We assume that the provider can sell surplus energy back into the grid and receive incentives or revenues with a low price, ensuring that PPA delivery is a priority. In addition to the PPA deliveries, the buyer can procure energy from other sources to meet its demand. The detailed models are presented in Section III.

B. Timescale of Decision-Making

This work considers two stages of decision-making with a long-term planning horizon (e.g., 20 years) and a short-term operational horizon (24 hours for one day). At the beginning of an investment horizon of days, the PPA provider

[1]Resources like nuclear and thermal units can be added in future work.

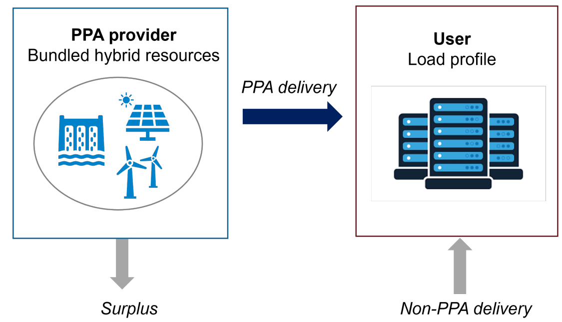

Fig. 1: PPA trading digram

determines the optimal capacities of different resources as well as the flat PPA price. The investment horizon is divided into operational horizons, i.e., each day corresponds to one operational horizon, which is further divided into many time slots $\mathcal{T} = \{1, 2, ..., T\}$ (e.g., 24 hours).[2] At the beginning of each operational horizon, the provider decides the optimal scheduling of hybrid resources to serve the user's demand, considering the PPA delivery requirement.

To facilitate the formulation and calculation, we scale the long-term resource investment/procurement costs to one day and calculate the daily expected operational costs and revenues. We build a stochastic optimization problem later and use historical data to construct a scenario set Ω that represents all the days in the investment horizon. These scenario sets empirically model the joint distribution of renewable energy generation profiles and load profiles. For each operational horizon d, scenario $\omega \in \Omega$ occurs with a probability ρ^{ω}. Next, we introduce the hybrid resource modeling over the planning and operational horizons.

III. Hybrid Resources Modeling

We will first present the decision variables, followed by the resource planning and operational constraints. Then, we formulate the cost and profit functions from the perspectives of the system and the PPA provider, respectively.

A. Decision Variables

We define the decision variables over the planning and operational horizons, respectively.

Over the planning horizon, we denote the PPA price by π^{PPA}. For any unit $i \in \mathcal{R}$, we denote by X_i^P the power capacity. For the unit i of reservoir hydropower or energy storage, i.e., $i \in \mathcal{R}_{rv} \bigcup \mathcal{R}_{sto}$, it also comes with storage capacity denoted by X_i^S. We let $\boldsymbol{X}$ be the vector of power and storage capacity decisions for all resource units.

Over the operational horizon at hour t of scenario ω, for any unit $i \in \mathcal{R}$, we denote the supply power by $g_{i,t}^{\omega}$, PPA delivery by $p_{i,t}^{\omega,PPA}$, feeding-back amount by $p_{i,t}^{\omega,sur}$. For non-storage unit $i \in \mathcal{R} \setminus \mathcal{R}_{sto}$, the provider can decide the power $p_{i,j,t}^{\omega,ch}$ charged into any storage unit $j \in \mathcal{R}_{sto}$. For storage unit i, we denote the charge power by $g_{i,t}^{\omega,ch}$, the discharge power by $g_{i,t}^{\omega,dis}$, the state-of-charge (SOC) by $e_{i,t}^{\omega}$. In terms

[2]Future work can extend the operational horizon to multiple days to capture the operations of long-duration storage and reservoir hydropower.

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of demand balance, we let $p_t^{\omega,nonPPA}$ be the non-PPA power delivery for the user and $p_t^{\omega,vio}$ be the shortfall of the PPA delivery requirement. We let $\boldsymbol{x}$ be the vector of all the decision variables over the operational horizon.

B. Planning and Operational Constraints

We formulate the planning and operation constraints for the supply and demand.

1) PPA requirement and demand balance:

$$D_t^{\omega} = p_t^{\omega,nonPPA} + \sum_{i\in\mathcal{R}} p_{i,t}^{\omega,PPA}, \forall\omega\in\Omega, \forall t\in\mathcal{T} \quad (1)$$

$$\sum_{i\in\mathcal{R}} p_{i,t}^{\omega,PPA} + p_t^{\omega,vio} \geq \gamma\cdot D_t^{\omega}, \forall\omega\in\Omega, \forall t\in\mathcal{T} \quad (2)$$

$$p_t^{\omega,nonPPA} \geq 0, \forall\omega\in\Omega, \forall t\in\mathcal{T} \quad (3)$$

Constraint (1) enforces the demand balance, where D_t^{ω} is the user's demand at hour t of scenario ω. The demand is served by the non-PPA delivery and the total PPA delivery from all the units. Constraint (2) enforces the PPA delivery requirement. The parameter γ regulates the share of hourly demand served by the PPA delivery,[3] where $p_t^{\omega,vio}$ is the shortfall of the delivery obligation. Constraint (3) ensures that the non-PPA delivery quantity is nonnegative.

2) VRE and reservoir hydropower:

$$0 \leq g_{i,t}^{\omega} \leq a_{i,t}^{\omega}\cdot X_i^P, \forall i\in\mathcal{R}\setminus\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (4)$$

$$\sum_{t\in\mathcal{T}} g_{i,t}^{\omega} \leq B_i^{\omega}\cdot X_i^S, \forall i\in\mathcal{R}_{rv}, \forall\omega\in\Omega, \quad (5)$$

$$g_{i,t}^{\omega} = p_{i,t}^{\omega,PPA} + p_{i,t}^{\omega,sur} + \sum_{j\in\mathcal{R}_{sto}} p_{i,j,t}^{\omega,ch}, \quad \forall i\in\mathcal{R}\setminus\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (6)$$

$$X_i^P \geq 0, \ \forall i\in\forall i\in\mathcal{R}\setminus\mathcal{R}_{sto}, \quad (7)$$

$$X_i^S \geq 0, \ \forall i\in\mathcal{R}_{rv}. \quad (8)$$

In Constraint (4), the parameter $a_{i,t}^{\omega}$ denotes the capacity factor of VRE. The supply power[4] is constrained by the output power $a_{i,t}^{\omega}\cdot X_i^P$ at hour t of scenario ω. Constraint (5) is the daily water budget constraint for reservoir hydropower. The parameter B_i^{ω} adjusts the daily water budget based on the storage size for scenario ω, which can capture the seasonal variations. Constraint (6) shows how the supply power $g_{i,t}^{\omega}$ is scheduled, including the PPA delivery, the surplus feedback amount, and the charged energy into the storage units. Constraints (7) and (8) ensure non-negative capacities.

3) Energy storage: We consider general energy storage operation models that can include batteries and PSH.

$$0 \leq g_{i,t}^{\omega,ch} \leq X_i^P, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (9)$$

$$0 \leq g_{i,t}^{\omega,dis} \leq X_i^P, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (10)$$

$$e_{i,t}^{\omega} = e_{i,t-1}^{\omega} + \eta_i^c\cdot g_{i,t}^{\omega,ch} - g_{i,t}^{\omega,dis}/\eta_i^d, \quad \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (11)$$

$$0 \leq e_{i,t}^{\omega} \leq X_i^S, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}\bigcup 0 \quad (12)$$

$$e_{i,0}^{\omega} = e_{i,T}^{\omega}, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \quad (13)$$

$$g_{i,t}^{\omega,dis} = p_{i,t}^{\omega,PPA} + p_{i,t}^{\omega,sur}, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T}, \quad (14)$$

$$g_{i,t}^{\omega,ch} = \sum_{j\in\mathcal{R}\setminus\mathcal{R}_{sto}} p_{j,i,t}^{\omega,ch}, \forall i\in\mathcal{R}_{sto}, \forall\omega\in\Omega, \forall t\in\mathcal{T} \quad (15)$$

$$X_i^P \geq 0, \ \forall i\in\mathcal{R}_{sto}, \quad (16)$$

$$X_i^S \geq 0, \ \forall i\in\mathcal{R}_{sto}. \quad (17)$$

Constraints (9)-(10) are the power-capacity limits for the charge and discharge, respectively. Constraint (11) is the SOC change over time due to the charge and discharge, where η_i^c and η_i^d denote the charge and discharge efficiency, respectively. Constraint (12) ensures the SOC is bounded by the storage capacity. Constraint (13) makes the initial SOC equal to the final SOC, which decouples the storage operation across different days. In Constraint (14), part of the discharge will be be used for PPA delivery and the rest will be fed back to the grid. Constraint (15) requires the charge power from all other non-storage resource units. Constraints (16) and (17) ensure the non-negative capacities.

C. Cost and Profit

We present the system cost and the provider's profit based on the defined variables. Due to page limits, we omit detailed formulations that readers can find in the online appendix [16].

1) System cost: The system cost is defined as the total cost of the provider and user. It is the sum of the procurement cost $CO^{inv}(\boldsymbol{X})$, the operational cost $CO^{op}(\boldsymbol{x})$, the contract violation penalties $CO^{vio}(\boldsymbol{x})$, and non-PPA resource costs CO^{nonPPA}, less the revenue $RV^{sur}(\boldsymbol{x})$ from feeding surplus energy back to the grid.

$$CO^{Sys}(\boldsymbol{x},\boldsymbol{X}) = CO^{inv}(\boldsymbol{X}) + CO^{op}(\boldsymbol{x}) + CO^{nonPPA}(\boldsymbol{x}) + CO^{vio}(\boldsymbol{x}) - RV^{sur}(\boldsymbol{x}). \quad (18)$$

2) PPA provider's profit: The provider's profit is the revenue from the PPA contract $RV^{PPA}(\boldsymbol{x},\pi^{PPA})$ and surplus generations $RV^{sur}(\boldsymbol{x})$, less the procurement cost $CO^{inv}(\boldsymbol{X})$, the operational cost $CO^{op}(\boldsymbol{x})$, and the violation penalty $CO^{vio}(\boldsymbol{x})$.

$$PF^{Prv}(\boldsymbol{x},\boldsymbol{X},\pi^{PPA}) = RV^{PPA}(\boldsymbol{x},\pi^{PPA}) + RV^{sur}(\boldsymbol{x}) - CO^{inv}(\boldsymbol{X}) - CO^{op}(\boldsymbol{x}) - CO^{vio}(\boldsymbol{x}), \quad (19)$$

where the expected PPA revenue RV^{PPA} is calculated by

$$RV^{PPA}(\boldsymbol{x},\pi^{PPA}) = \sum_{\omega\in\Omega}\rho^{\omega}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{R}}\pi^{PPA}\cdot p_{i,t}^{\omega,PPA}. \quad (20)$$

IV. Optimization Models for PPA design

We formulate a risk-neutral stochastic optimization problem that minimizes the expected system cost to achieve economic efficiency, satisfying the provider's profit return target. Note that minimizing the system cost is equivalent to maximizing the total surplus of the provider and user.

[3] While this delivery requirement is treated as an exogenous parameter in this model, it could be modeled as a buyer's decision variable in future work. Besides, the PPA delivery requirement can also be defined using absolute delivery quantities or by imposing annual or monthly delivery obligations.

[4] We allow the curtailment in this constraint. However, since the provider can always sell back energy, the curtailment will not occur.

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Problem-*PPA*: Optimal PPA Design

$$\min_{\boldsymbol{x},\boldsymbol{X},\pi^{PPA}} \ CO^{Sys}(\boldsymbol{x},\boldsymbol{X})$$
$$\text{s.t. } (1)-(17),$$
$$PF^{Prv}(\boldsymbol{x},\boldsymbol{X},\pi^{PPA})=\xi. \quad (21)$$

The constraint (21) ensures the profit return target $\xi \geq 0$. We show the solution to *Problem-PPA* as follows.

Proposition 1. *The optimal planning and scheduling results of Problem-PPA are equivalent to optimal solution $\boldsymbol{x}^*, \boldsymbol{X}^*$ to the following Problem-Sys that minimizes the system cost.*

$$min_{\boldsymbol{x},\boldsymbol{X}} \ CO^{Sys}(\boldsymbol{x},\boldsymbol{X})$$
$$s.t. \ (1)-(17).$$

Problem-Sys is a linear program and the optimal PPA price π^{PPA*} is given as follows.

$$\frac{CO^{inv}(\boldsymbol{X}^*)+CO^{op}(\boldsymbol{x}^*)+CO^{vio}(\boldsymbol{x}^*)-RV^{sur}(\boldsymbol{x}^*)+\xi}{\sum_{\omega\in\Omega}\rho^{\omega}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{R}}p_{i,t}^{\omega,PPA*}}. \quad (22)$$

This proposition result is because of inelastic PPA demand from the user. Based on the system optimal results, the provider can always set a sufficiently high price to guarantee its profit target. Also, when the provider's profit target is given as the fixed value ξ, *Problem-Sys* is equivalent to minimizing the users' cost. The value ξ reflects how the benefits are allocated between the provider and the user.

V. Numerical Studies

We simulate different portfolios to show the role of flexible resources, particularly the reservoir hydropower and PSH in the 24/7 PPA design. Furthermore, we demonstrate how the PPA delivery requirement, resource procurement cost, and contract violation impact the PPA pricing and resource procurement results.

A. Simulation setup

We simulate the following four portfolios, where each resource type has one unit. Note that we optimize the capacities of resources in each portfolio.

- *S+W*: Solar and wind energy
- *H*: Reservoir hydropower
- *S+W+H*: Solar, wind, and reservoir hydropower
- *S+W+PSH*: Solar, Wind, and PSH

For solar and wind resources, we use hourly capacity factor data from ERCOT for the full year 2024 [17], resulting in 366 scenarios, each assigned an equal probability in the scenario set.[5] We present the financial parameters of all the resources in Table I, where we use the capital cost for the procurement cost. We set the user's non-PPA price at a flat rate 80$/MWh, the surplus feed-in tariff at a low flat rate 5$/MWh.

[5]This approach preserves the joint temporal and cross-variable correlations in the historical data. Scenario reduction techniques can also be applied to reduce the number of scenarios while retaining representative characteristics.

TABLE I: Resource Financial Parameters

Parameter	Solar (utility-PV)	Wind (on-shore)	Hydro (reservoir)	PSH
Power CAPEX ($/kW)	1491	1632	3700	1100
Storage CAPEX ($/kW)	–	–	50	50
FOM ($/kW-yr)	20	33	74	22
VOM ($/MWh)	0	0	0	1
Discount Rate (%)	6%	6%	6%	6%
Project Life (yr)	30	30	40	40
Efficiency (%)	–	–	85%	75%

B. Simulation Results

We present the results of break-even PPA prices in Figure 2. The subfigures (a,b,c) show the impact of PPA delivery requirement, violation penalty, and solar and wind capital cost reduction, respectively. Different curves in each figure show different portfolios. Figure 3 illustrates the capacity of each resource in the portfolio under varying PPA delivery requirements. Each subfigure corresponds to a specific portfolio. Due to page limits, we only present the impact of PPA delivery requirement on capacity outcomes as an example.

1) The role of hydropower: We show that reservoir hydropower alone can economically meet the 24/7 PPA requirement when no capacity constraint is imposed. Pairing PSH with solar and wind can significantly lower the PPA price compared with solar-and-wind-only portfolios.

As shown in Figure 2(a)(b), the *S+W* portfolio always leads to the highest break-even PPA price. The price can be higher than 200$/MWh when the PPA delivery requirement is higher than 80%. The *H* portfolio alone can already achieve a reasonable PPA price. Adding the solar and wind into reservoir hydropower can further reduce the price, but the reduction is limited when we can optimize the hydropower capacities without limits. The *S+W+PSH* portfolio can significantly reduce the PPA price compared with the *S+W* portfolio. However, as PSH can only store energy and requires support from generators, its price is still much higher than the portfolios with reservoir hydropower.

Figure 2(c) shows that reducing the solar and wind capital costs can significantly reduce the PPA prices of the portfolios that contain solar and wind. Particularly, when the costs are reduced around 50%, the *S+W+PSH* portfolio can achieve a comparable price to the reservoir hydropower portfolio.

2) Sensitivity analysis results: As shown in Figure 2, a higher PPA delivery requirement, contract shortfall penalty, or capital cost will increase the break-even PPA price.

However, the roles and relative positions of different resources within the portfolio can shift as the parameters change. As shown in Figure 3, a higher PPA delivery requirement will overall increase the capacities of resources in the portfolio. However, it may also reduce the capacity due to the competition from other resources. For example, in Figure 3(c), when paired with reservoir hydropower, wind energy is preferred under low PPA delivery requirements, while solar energy becomes more advantageous as the delivery requirement increases. This can be because, although wind energy is less variable than solar, the expanded hydropower capacity

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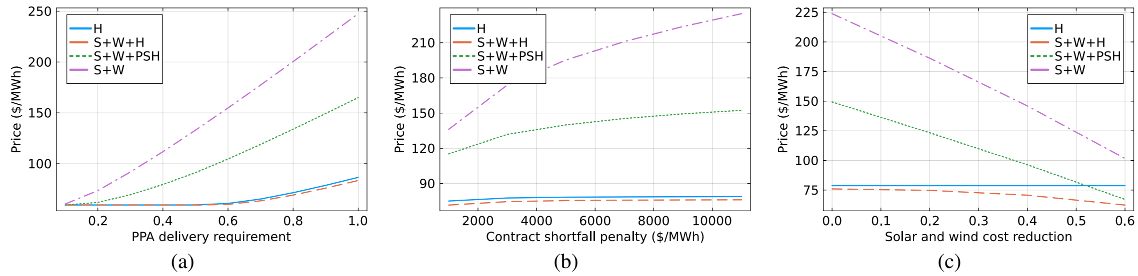

Fig. 2: PPA break-even price with (a) PPA delivery requirement (contract penalty 9000$/MWh; no cost reduction); (b) Contract shortfall penalty (PPA delivery requirement 90%; no cost reduction); (c) Solar and wind capital cost reduction (contract penalty 9000$/MWh; PPA delivery requirement 90%).

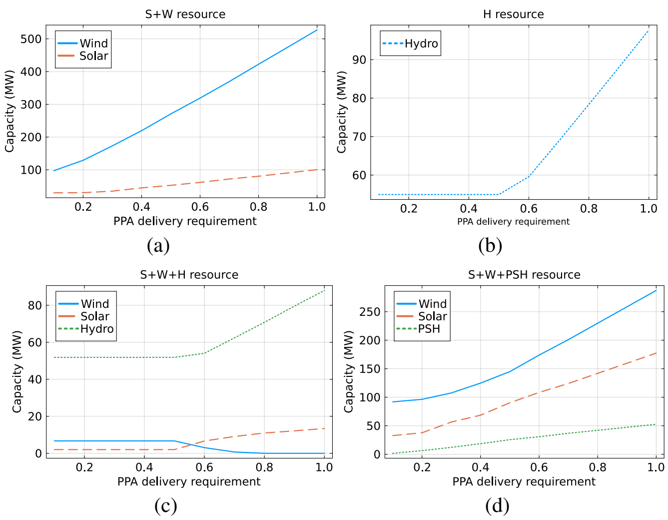

Fig. 3: Resource capacity with PPA delivery requirement (contract penalty 9000$/MWh; no cost reduction).

reduces the need for wind while making the lower-cost solar resource more favorable to better align with the load shape.

VI. Conclusion

This study presents an optimization framework for designing 24/7 hybrid-resource PPAs that incorporate flexible resources (e.g., reservoir hydropower and energy storage) and VRE. The framework jointly optimizes resource procurement, operational scheduling, and PPA pricing, which maximizes the total surplus of the provider and user while guaranteeing the provider's profitability. Simulation results indicate that reservoir hydropower alone can economically satisfy the 24/7 PPA requirement when capacity constraints are not imposed. Pairing PSH with solar and wind substantially lowers the PPA price compared with solar-and-wind-only portfolios. Sensitivity analysis further shows that increasing the PPA delivery requirement, contract shortfall penalty, or capital cost increases the break-even PPA price, while it may also shift the relative roles of resources within the portfolio.

The future work can further consider the risk-averse decisions, variable pricing structures, more detailed hydropower operation models, and network representations.

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