Title

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***Abstract*—With the prevailing recognition and implementation of carbon-neutral policies, the proportion of solar photovoltaic (PV) in the energy mix continues to rise. To mitigate the negative impact of variable PV power injection into the power grid, firm solar power generation strategies receive more and more attention. This paper elaborates on a counter-intuitive but effective solution to reduce the firm-generation cost of PV, namely, battery storage, overbuilding, and proactive curtailment. A simulation case study considers a 1-MW PV plant in the cold climate of Harbin, China, whose annual generation equals the annual energy demand from a 0.17 MW constant load. Results show that a 3x-oversized PV plant paired with battery storage and proactive curtailment can reduce its firm-generation cost by 79.67% as compared to a PV plant with no overbuilding but with proactive curtailment and larger battery storage. In a future power grid dominated by variable renewable energy, battery storage, overbuilding, and proactive curtailment are profoundly rewarding.**

Keywords*—*Overbuilding, Curtailment, Firm solar power generation, battery storage, PV plant

I. INTRODUCTION

Once commissioned, solar photovoltaic (PV) plants have a marginal generation cost close to zero [1]. But the initial investment is substantial and constitutes the main factor affecting the economics and financing of solar projects. Since PV power generation depends highly on the weather, irregularity, volatility, and unpredictability are its defining characteristics. These characteristics may bring adverse effects to the power grid, such as increased ancillary service costs, overvoltages, or unreliable protection. At present, power grid stability depends upon conventional thermal power units in providing reserve as to meet the real-time power balancing constraint [2]. Increasing grid penetration level of PV brings about increased cost associated with balancing needs. On this point, if one is to truly evaluate the cost of PV, the ancillary cost of providing backup services must be factored in, and the conventional thinking of PV being a cost-effective solution is no longer valid.

Mitigating PV power fluctuations has been a trending research topic hitherto. Current major ways to address the PV intermittency's challenges include:

- *Electric storage*: Storage devices are of different capacities, response rates, and various types, among which the main ones include battery energy storage, capacitors, and pumped hydro. Generally, storage serves two purposes: storage of excess solar power from over-supply periods, and the provision of deficient energy during under-supply periods. PV plants with storage have become the mainstream solution to PV intermittency, see [3] for a review. Recently, reference [4] described a control strategy based on the battery charging ramp rate, and contrasted distributed and centralized storage solutions for smoothing the variability of PV power.
- *Demand-side management*: It encompasses incentivizing end-users to consume electrical energy when PV power peaks (or net load is low), and discouraging consumption when PV power is low (or net load peaks). In essence, while electrical storage shapes the supply curve, demand-side management aims at shaping the load curve as to match the generation profile [5]. One example of demand-side management is [6], in which the output power of a building heating, ventilation, and air conditioning (HVAC) integrated system was adjusted in response to PV power, while taking advantage of the thermal inertia of the building, thereby alleviating the variation in net load.
- *Geographic smoothing*: As the distances between PV plants increase, the aggregated PV power of a fleet of plants is less variable than that of any single plant, since high-frequency ramps tend to be uncorrelated. This phenomenon is known as geographic smoothing [7]. In other words, when there are multiple PV plants in a large area, the aggregated PV power generation curve flattens due to the compensation of differing local weather conditions. Grid operators are gradually paying more attention to geographic smoothing as the PV penetration continues to increase.
- *Blending with other sources*: Exploiting the spatio-temporal complementarity of multiple renewable energy sources can mitigate the fluctuations of individual power sources. PV can be managed jointly with wind, biomass, and geothermal energy. Wind tends to be uncorrelated or even anti-correlated with solar power, while biomass and geothermal are dispatchable, i.e. they can be forced to be anticorrelated with solar power. Similar to the concept of geographic smoothing, aggregating uncorrelated sources can mitigate the solar variability, which makes the optimization of the power-generation mix highly relevant. For example, reference [8] investigated the optimal sizing

of a hydro–wind–PV hybrid system, in which the output smoothness is taken to be the objective of the minimization problem.

- *Overbuilding and curtailment*: Curtailment is realized by overbuilding PV while fixing its energy production at the load demand. In other words, the PV plant is deliberately oversized, such that the fluctuating top part of the PV generation curve becomes less relevant to scheduled power delivery and thus can be curtailed [9]. Overbuilding increases the curtailment rate, but it also increases the probability of satisfying the local load through the PV plant alone. Overbuilding and curtailment seem like a counter-intuitive strategy, since it implies energy waste. One should however note that the concept of curtailment here differs from the traditional curtailment [10-11]. The traditional curtailment of the PV power often occurs during grid congestion or power imbalances, hence, PV power has to be curtailed to ensure the stable operation of the power grid. In contrast, the curtailment here is proactive, meaning that the PV power is curtailed as to better meet the load demand.

While these mitigation solutions can achieve good results on their own, when two or more ways are applied simultaneously, the effect may be more prominent. That said, a common pitfall of the aforementioned studies is that the cost analysis, insofar as how it was presented, is only partial. Besides, most studies of this sort are only aimed at alleviating but not completely eliminating PV power fluctuations. The law of diminishing returns is well known; it is an economic principle stating that the rate of profit saturates after a certain point as the investment to a particular entity/activity of interest increases. In the present context, the relative economic benefits of leveraging any solution also decrease as the overall variable solar generation approaches complete dispatchability. The trade-off between cost and dispatchability is a question that needs to be settled urgently [12-13].

At this point, it is useful to introduce the recent concept of "firm generation," that is, if the generation is able to meet demand with certainty at all times, it can be regarded as "firm." A conventional thermal plant is, by definition, firm, since it is effectively dispatchable and is able to generate the contracted amount of power. On the other hand, as societal mandates trigger an ever-increasing penetration rate, intermittent PV power must be transformed into firm generation, meeting the changing demand on a 24/365 basis. Of course, achieving firm solar power generation is challenging, especially when the effect of the law of diminishing returns is considered. Thus, how to effectively reduce the firm-generation cost of PV has emerged as a focus of research.

To that end, this paper elaborates on an integrated solution, with the goal of narrowing the gap between the PV plants and traditional thermal units for their ability to provide firm generation. The solution consists of three parts: (1) battery storage, (2) overbuilding the PV plant, and (3) proactive curtailment of PV power. The integrated solution facilitates the transition of PV from its current role of supplementing the power grid to enhancing the power grid in the future. The remaining part of the paper is organized as follows. The evaluation metrics and logic rules of the integrated solution are explained in Section 2. In Section 3, the equivalent annual cost of the PV–battery hybrid system is calculated. Section 4 empirically verifies the proposal with a case study considering a 1-MW PV plant in Harbin, China, which is located in a cold climate. Section 5 analyzes the sensitivity of the PV plant oversizing. In the last section, the findings are concluded with future directions.

II. EVALUATION METRICS AND LOGIC RULES

To gauge the energy economics of the integrated solution, a concept called "firm kWh premium," which further depends upon the familiar measure of levelized cost of electricity (LCOE), is used. In that,

$$\text{Firm kWh premium} = \frac{\text{Firm solar LCOE}}{\text{Unconstrained solar LCOE}}, \quad (1)$$

$$\text{LCOE} = \frac{\text{Equivalent annual cost}}{\text{Equivalent annual electricity produced}}. \quad (2)$$

Recall that LCOE is the ratio of the total equivalent annual cost of installing and operating the PV system over the equivalent annual electrical energy, so it represents the average cost per unit of electricity generated. Firm kWh premium, on the other hand, is the ratio between the LCOE of firm solar generation and that of the unconstrained solar generation, which refers to the natural PV power output of a PV plant without using any variability mitigation solution. The firm kWh premium may be interpreted as the "cost" of converting unconstrained solar power to firm solar power.

Fig. 1 illustrates the logic rules of the integrated solution. The constituents of the solution include just an overbuilt PV plant and some battery storage, which are connected to the local load (such as residential, commercial, and industrial loads). In addition, the PV plant can dynamically curtail the excess PV power based on the actual local demand. More specifically, when the PV power is lower than the local demand, all generated power in injected into the grid, with batteries making up the deficit. When the PV power is higher than the local demand, surplus power from PV is used to charge the battery storage. If the battery storage is fully charged, the surplus PV power can be dynamically curtailed.

III. EQUIVALENT ANNUAL COST OF THE PV–BATTERY HYBRID SYSTEM

A. Objective Function

To compare the economics of different variability mitigation solutions, the equivalent annual cost of that system is defined as follows.

$$\underset{S_2, P_{\text{dis},t}}{\arg\min} \left\langle \xi_1 c_1 X_1 P_1 + l_1 c_1 X_1 P_1 + \xi_2 c_2 S_2 + l_2 c_2 S_2 \sum_{t=1}^{8760} \frac{P_{\text{dis},t}}{S_2} \right\rangle, \quad (3)$$

$$\xi_i = \frac{\tau\left(1+\tau\right)^{T_i}}{\left(1+\tau\right)^{T_i} - 1}, \; i = 1 \,\text{or}\, 2 \,, \quad (4)$$

where ξ_1, c_1, X_1, P_1, l_1 and T_1 are the capital recovery factor, unit cost, oversizing ratio, rated power in kW, O&M factor, and average operating life of the PV plant, respectively; ξ_2, c_2, S_2, l_2 and T_2 are the capital recovery factor, unit cost, rated capacity in kWh, O&M factor, and average operating life of the battery storage, respectively; $P_{\text{dis},t}$ is the discharging power of the battery storage during time *t*; and τ

is the discount rate. The last part of (3) indicates that the O&M cost of the battery storage is related to the number of charging and discharging cycles of the battery storage, that is, a complete cycle consumes l_2 times the investment cost. The capital recovery factor is calculated using the discount rate and the average operating life, as stated in (4).

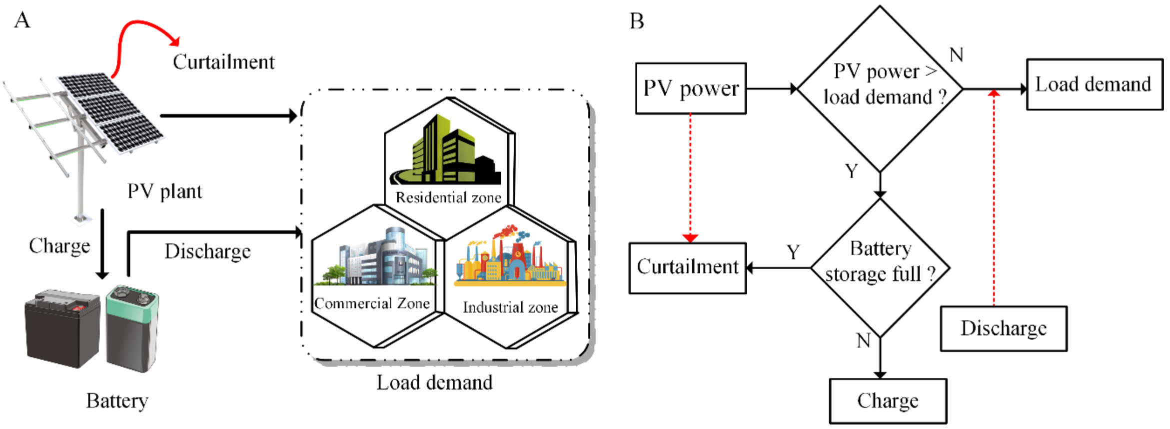

Fig. 1. Overview diagram (A) and logic flowchart (B) of an oversized PV plant with battery storage and a proactive curtailment strategy.

During the operation of the PV–battery hybrid system, some constraints must be satisfied, including the operation constraints of the battery storage, the operation constraint of the PV plant, and the power balance constraint. These are detailed next.

B. Operation constraints of the battery storage

Battery storage stores the electric energy in the daytime when the PV power is high and releases the stored energy to supply the load during cloudy conditions or at night when the PV power is low or zero, thereby guaranteeing that the load demand can be met at all times. The operation constraints of the battery storage are expressed in the following.

$$0 \le P_{\mathrm{ch},t} \le B_{\mathrm{ch},t} P_{\mathrm{ch,max}}, \tag{5}$$

$$0 \le P_{\mathrm{dis},t} \le B_{\mathrm{dis},t} P_{\mathrm{dis,max}}, \tag{6}$$

$$B_{\mathrm{ch},t} + B_{\mathrm{dis},t} \le 1, \tag{7}$$

$$\mathrm{S}_{t+1}^{\mathrm{battery}} = \mathrm{S}_{t}^{\mathrm{battery}} + P_{\mathrm{ch},t}\Delta t - P_{\mathrm{dis},t}\Delta t, \tag{8}$$

$$0 \le \mathrm{S}_{t}^{\mathrm{battery}} \le S_2, \tag{9}$$

$$\mathrm{S}_{1}^{\mathrm{battery}} = \beta S_2, \tag{10}$$

where $P_{\mathrm{ch},t}$ is the charging power of the battery storage during time t; $P_{\mathrm{ch,max}}$ and $P_{\mathrm{dis,max}}$ are the maximum charging and discharging power of the battery storage, respectively; $B_{\mathrm{ch},t}$ and $B_{\mathrm{dis},t}$ are binary variables representing the charging and discharging mode of the battery storage during time t, respectively, in that, if the value is 1, the corresponding mode is activated. $\mathrm{S}_{t}^{\mathrm{battery}}$ and $\mathrm{S}_{t+1}^{\mathrm{battery}}$ are the available energy storage capacity of the battery storage during time t and t+1, respectively. Δt is the unit time interval, which is set to 1 hour; β is the ratio of the initial (i.e., t=1) battery storage capacity to its rated capacity. Equations (5) and (6) prevent the charging and discharging power from exceeding the limit. Equation (7) indicates that the battery storage cannot be simultaneously charged and discharged. The available battery storage capacity in the next period is strictly equal to the available storage capacity in the current period minus the discharging power, or plus the charging power in the current period times the time interval, as revealed in (8). Equation (9) indicates that the energy stored in the battery storage should be lower than its rated capacity. The initial battery storage state of charge in (10), β, is set 0.8 without loss of generality.

C. PV plant operation constraint

The power generated by a PV plant, at any instance t, can be expressed as the sum of three components: the power directly supplied to the load, the curtailed power, and the power charging the batteries:

$$P_{\mathrm{ch},t} + P_{\mathrm{load},t}^{\uparrow} + P_{\mathrm{curt},t} = P_{\mathrm{pv},t} \tag{11}$$

where $P_{\mathrm{pv},t}$ is the PV generated power at time t; $P_{\mathrm{load},t}^{\uparrow}$ is the power directly supplied to the load by the PV plant; and $P_{\mathrm{curt},t}$ is the curtailed power.

D. Power balance constraint

The local demand should be fully satisfied, and this constraint corresponds to:

$$P_{\mathrm{dis},t} + P_{\mathrm{load},t}^{\uparrow} = P_{\mathrm{load},t}, \tag{12}$$

where $P_{\mathrm{load},t}$ is the local demand during time t.

IV. A CASE STUDY: A 1-MW PV PLANT IN HARBIN

In this section, a case study is used to empirically validate the concept of overbuilding and proactive curtailment under a cold climate. The 1-MW PV plant is located in Harbin, China, which has a longitude of 126.64°, a latitude of 45.76°. The PV plant is built to meet an assumed constant baseload with a value of 0.17 MW throughout the year, not just for simplicity, but also to avoid effects of the load shape when interpreting the results. The PV power of the 1-MW PV plant is simulated based on the irradiance-to-power physical model chain as fully illustrated in [14]. The data used in the simulation is a typical meteorological year (TMY) dataset obtained from the National Solar Radiation Database (NSRDB) based on Himawari-8 data [15], including ambient temperature, wind speed, beam normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance. Specifically, the daily global horizontal irradiance is 3.96 kWh/m^2. The tilt angle of the PV panels follows the site's latitude, namely, 45.76°, while the azimuth angle is set to 180°, i.e., south facing. While the PV tilt could be further optimized to align the annual PV generation with the constant load, this paper focuses on the firm power operation strategy. Without loss of generality, 18 Mitsubishi PV-MF185UD4 [2006 (E)] PV modules with a rated power of 185 Wp are placed in series to form a PV string, and 300 such PV strings are connected in parallel to an inverter for a total of 1 MW of DC capacity.

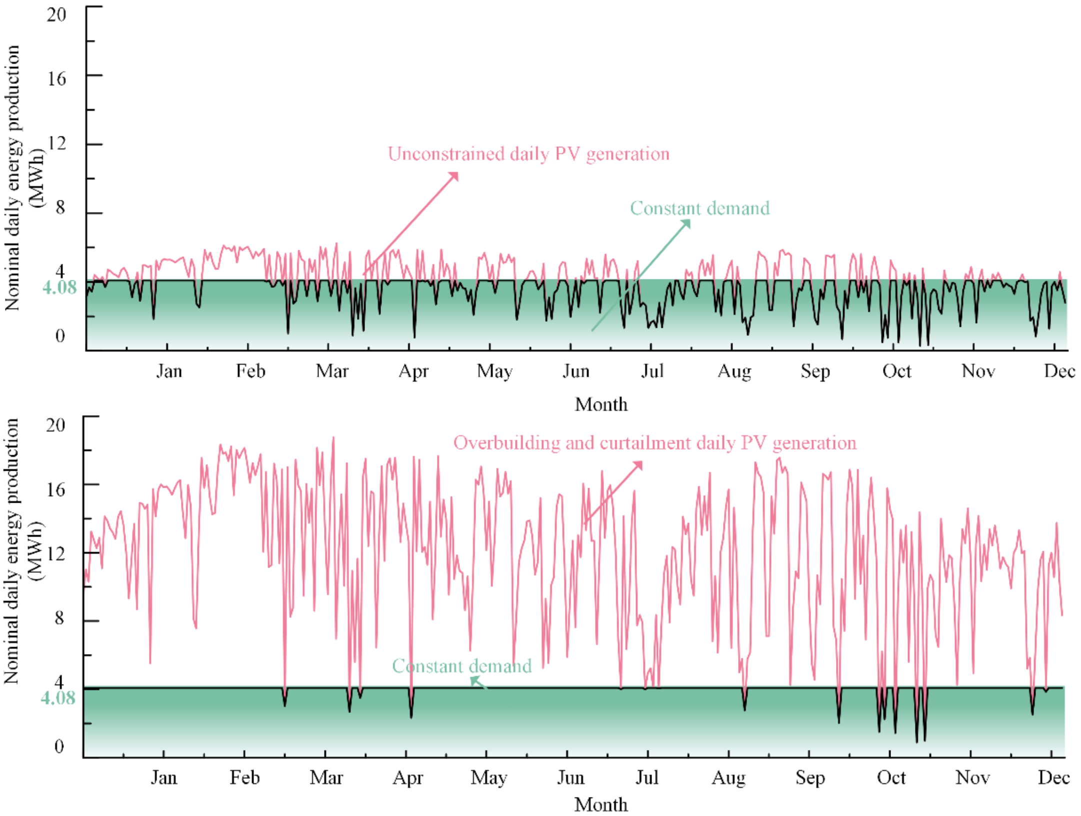

Fig. 2. The actual daily PV power of the PV plant in the typical meteorological year under two scenarios. The daily PV power is acquired by accumulating the hourly PV power simulated from the physical model chain. For scenario A, the PV plant is only equipped with battery storage, while the 3x oversized PV plant uses the battery storage and dynamic curtailment to mitigate the variation of the grid-connected power under scenario B. Both PV plants need to meet 100% of the local constant load with a value of 0.17-MW at all times for a period of one year. The black line presents the PV power directly supplied to the load. The area where the green rectangle intersects the part above the black line indicates a power deficit, which is satisfied by the battery storage.

Considering the standard DC/AC ratio of 1.2 and economics of scale, a TMEIC PVL-L0833GR inverter with a rated capacity of 0.83 MW is chosen. The physical model chain for the modeling of the PV plant is carried out via the convenient Pvlib-python package [16]. The component models in the model chain include the Perez transposition model, the Sandia cell temperature model, the Sandia PV array performance (DC) model, the Sandia inverter (AC) model, and the PVWatts losses model.

The numerical constants required by the optimization are selected next. The average installation cost (c_1) of global PV plants in 2020 is 883 \$/kW [17], while the average global cost (c_2) of lithium batteries is 137 \$/kWh [18]. According to a report published by the National Renewable Energy Laboratory (NREL) in 2021 [19], PV plants have an average life span (T_1) of 30 years, while the service life (T_2) of battery storage is 15 years. The maximum charging $P_{\mathrm{ch,max}}$ and discharging power of the battery storage is set to be 1/4 of its rated energy capacity (S_2). In other words, if the battery is fully charged and discharges at full power it would be able to discharge for 4 hours until reaching zero state of charge. The O&M cost (l_2) of a complete charging and discharging cycle is assumed to be 0.02% of its investment cost. All economic parameters as listed in Table I are fed into the model presented in Section III for calculating the equivalent annual cost of the PV–battery hybrid system.

The cost premium of supplying the constant load is compared for two PV power variability mitigation solutions: A, using battery storage alone; and B, using battery storage together with overbuilding and proactive curtailment. To obtain firm solar power generation, 100% of the local demand should be satisfied. In other words, the PV–battery hybrid system produces the same amount of energy that is used to supply the load under two scenarios. The rated DC power of the PV plant under scenario A is 1-MW, while the rated DC power of the PV plant under scenario B increases to 3-MW, that is, the oversizing ratio of the PV plant is 3. (This multiplier is further optimized below.) The equivalent annual cost of the PV–battery hybrid system and the rated capacity of the battery storage under these two scenarios are acquired by calling the Gurobi solver on a Python development environment, namely, Spyder. Fig. 2 compares the actual daily PV power of the PV plant under scenario A and scenario B.

TABLE I. ECONOMIC PARAMETERS OF THE PV–BATTERY HYBRID SYSTEM

Variables	Values
Discount rate, τ	8%
Unit cost of the PV plant, c_1	883 $/kW
Service life of the PV plant, T_1	30 years
Factor value of the O&M cost of the PV plant, l_1	1.0%
Unit cost of the battery storage, c_2	137$/kWh
Service life of the battery storage, T_2	15 years
Factor value of the O&M cost of battery storage per Cycle, l_2	0.02%

Although both scenarios require battery storage to fulfill the power gaps between the local demand and the PV generation, scenario B needs substantially less battery storage. In scenario A, the PV plant requires battery storage with a rated energy capacity (kWh) of 91.23 times the nameplate power (kW) of the PV plant (Here, only the values are considered, ignoring the unit). The equivalent annual cost of the PV–battery hybrid system using battery storage alone to deliver firm generation is thus 18 times of that of the normal PV plant producing the unconstrained solar power. Stated differently, if the intermittency of the grid-connected power is to be removed by battery storage alone, the firm-generation cost of PV is 18 times the unconstrained-generation cost of PV. However, when the overbuilding and curtailment strategy is employed, the 3x-oversized PV plant is only equipped with the battery storage with a rated energy capacity (kWh) of 5.72 times of the nameplate power (kW) of the PV plant. This can be explained by the smaller duration and magnitude of power deficits by the 3x-oversized PV plant compared to the unconstrained PV plant, as shown in Fig. 2. Correspondingly, the firm-generation cost for this kind of PV plant is only 4.31 times the unconstrained-generation cost of PV, with the additional cost for the PV oversizing included. Therefore, it can be concluded that firm solar power generation can be achieved at a relatively acceptable cost through the integrated solution.

That said, the firm-generation cost of PV is still high due to the large quantity of the battery storage needed. It is also apparent from Fig. 2 that the actual PV energy is much greater (3x) than the local demand under scenario B, which seems to be extreme from the perspective of energy wastage. The simulation results confirm this observation: the curtailment rate of the PV plant is 4.27% under scenario A, while the curtailment rate is 66.54% under scenario B. On this point, if the PV plant could fully utilize the curtailed PV power, such as to produce hydrogen for sale or re-generation, the economic benefits brought by overbuilding and curtailment would further increase, which indicates promising future perspective of the integrated solution.

V. THE EFFECT OF THE OVERSIZING RATIO OF THE PV PLANT

The previous section discussed in detail that overbuilding can reduce the firm-generation cost of PV, but it did not address the question of the best oversizing ratio. Asssuming the oversizing ratio can range from 1 to 5, the corresponding firm kWh premium of a 1-MW PV plant that is used to firmly supply the 0.17-MW constant load is depicted in Fig. 3. The firm kWh premium first decreases and then increases with increasing oversizing ratio. More specifically, the firm kWh premium is 18, when the oversizing ratio is 1; the firm kWh premium is 3.73, when the oversizing ratio is 2; and the firm kWh premium is 4.31, when the oversizing ratio is 3. This is easy to understand, as the installed capacity of the PV plant rises linearly (dark blue line in the figure) and the rated capacity of the battery storage decreases rapidly and then flattens out (light blue line in the figure). When the oversizing ratio increases moderately, the reduced cost of the battery storage exceeds the additional cost of overbuilding PV, leading to a rapid reduction in the firm kWh premium. The battery storage cost reduction gradually weakens when the oversizing ratio increase further. The cost reduction of the battery storage then no longer offsets the increased cost from overbuilding PV.

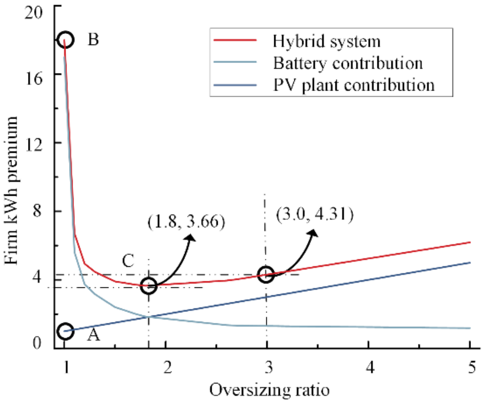

Fig. 3. The firm kWh premium of the PV–battery hybrid system for different oversizing ratios of the PV plant. The light blue line and dark blue line represent the contribution of the battery storage and PV plant, respectively. Compared to the unconstrained PV power (A), the firm solar power to satisfy the constant load with battery storage alone (B) is expensive. When the optimal overbuilding and proactive curtailment strategy is employed, the requirement for the battery storage can be dramatically reduced, resulting in a utopia and nadir point (C) of the firm-generation cost of PV.

To minimize the firm-generation cost of PV, the rated power of the PV plant should be increased to 1.8 MW. Correspondingly, the firm kWh premium is 3.66, which is 79.67% lower than that of the PV plant when only relying on the battery storage. It should be noted that, although the current analysis is carried out for just a single plant, the conclusion drawn can be extended to the case of regional PV generation of multiple PV plants.

VI. CONCLUSION

It is a well-accepted fact that the generation cost of PV power, after the initial commission, is low and close to zero, but what has hitherto been neglected by many is that this refers to unconstrained solar power. Due to environmental benefits and the abundant solar resource, PV penetration in the future power grid may reach an ultra-high value. It is then imperative to assess the performance of the PV plant in terms of its ability to provide firm generation and to analyze the related cost differences. Taking a simulated 1-MW PV plant in Harbin as a case study under a cold climate, the optimal firm kWh premium for the PV plant with battery storage alone is 18, while the optimal value is 3.66 for the PV plant utilizing the integrated solution of battery storage with overbuilding and proactive curtailment. This indicates that the integrated solution must not be ignored when one attempts to reduce the firm-generation cost of PV. In future work, other solutions for reducing the firm-generation cost of PV, such as geographical smoothing and demand-side management, should be studied in conjunction with the current solution.

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