Battery Capacity Planning for Grid-Connected Solar Photovoltaic Systems

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***Abstract*—With the steady increase of grid-connected solar photovoltaic (PV) power generation in many parts of the world, management of solar generation intermittency becomes a key challenge for power system operators. A widely considered approach to addressing this issue is to install battery energy storages together with solar PV sources. This paper discusses the capacity planning when battery energy storage is used as a companion for grid-connected solar PV systems. We consider the concrete context of the National Electricity Market of Singapore (NEMS). For electricity markets like NEMS that adopt real-time bidding and clearance, we propose solutions that can enable a battery-companioned solar PV system to behave in the same way as traditional dispatchable generators. We observe that the battery capacity requirement can be reduced by shortening the cycle length for real-time bidding and clearance or by allowing occasional disconnection of solar PV units. To further reduce the battery capacity, we discuss the design of more flexible forms of contracts between the grid and the solar PV systems.**

I. INTRODUCTION

The cost for solar photovoltaic (PV) modules has decreased significantly over the past years and the trend is likely to continue [1]. This enables a steady increase of its adoption in many parts of the world. Solar PV systems are classified according to their end-use application. In Singapore, there are mainly two types, namely, *grid-tied* and *off-grid* solar PV systems [2]. The former, which is the focus of this paper, is more commonly adopted on Singapore's main island, which is well covered by the national power grid. It is used to reduce one's dependence on utility power, increase renewable energy production, and help conserve the environment. Whereas, the latter is used in the areas out of power grid coverage like offshore island or in the applications where it is not technically and/or commercially feasible to tap electricity from the power grid like traffic signage. Because of solar power's non-dispatchable nature, when it makes up a significant portion of the generation mix in a power grid, it becomes a key challenge for power system operators to manage their intermittency effects. For example, an unpredictable event such as cloud cover or an afternoon thunderstorm can change drastically the solar generation output from its maximum to nearly zero. Without corresponding reserves being prepared as backup, the stability of the grid could be undermined.

Motivated by this, there has been increasing interest in the approaches to using battery storage to enable the wide adoption of grid-connected solar PV systems [3]. One approach is to provide battery energy resources as independent reserve resources for central dispatching, without specifically coupling them to any specific solar PV sources. Another approach, which is the focus of this paper, is to associate battery banks with specific solar generators. A battery bank will be designed to adapt to the corresponding solar sources. A solar PV source and its companion battery will then be managed together as an integrated facility. This grants the local facility manager with greater controls. For instance, the manager potentially has the freedom to select among different ways to participate in the electricity market — as nondispatchable generators, as dispatchable generators, or under some enhanced demand response schemes. Such a higher level of controls can potentially maximize the payoff for the installation of such a system and minimize the associated risks to the grid.

In this paper, we specifically focus on the planning of the battery capacity for such a battery-companioned solar PV system, so that they can be presented to the grid as dispatchable generators, i.e., each of them can mimic the behaviour of a traditional dispatchable generator. A key advantage for mimicking a dispatchable generator is that battery-companioned solar PV systems can be easily integrated to a mature market that was established for dispatchable generators. Specifically, participating in such a well-understood market allows the owner of a battery-companioned solar PV system to avoid many uncertainties in the emerging markets of nondispatchable generators. As an example of such uncertainties, in Singapore, nondispatchable generation may be charged for extra cost for their externalities (including additional reserves), or may even be denied the grid connection if the total amount of reserve in the system becomes insufficient [4]. While studying this specific coupled operational mode (i.e., use nondispatchable generators and batteries to mimic dispatchable generators) may be of practical interests on

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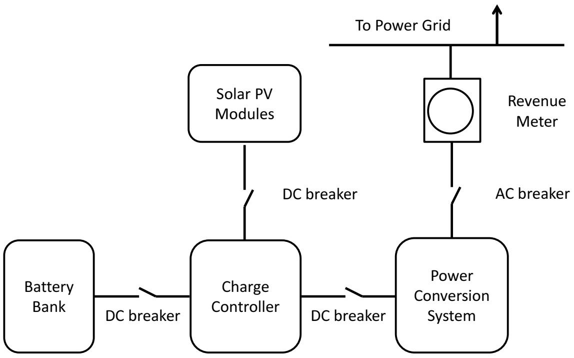

Fig. 1. A simplified single-line diagram for a grid-connected battery-companioned solar PV system.

their own, they can also serve as a baseline to help guide the market design for the emerging nondispatchable generators.

The main contributions of this paper are:

- For representative markets like the National Electricity Market of Singapore (NEMS), which adopts real-time bidding and clearance, we propose solutions that enable a battery-companioned solar energy resource to behave as a dispatchable power generator.
- We show that the battery capacity can be reduced by shortening the cycle length of the real-time bidding and clearance on the wholesale electricity market.
- To help further reduce the battery capacity, we discuss the design of more flexible forms of contracts between the grid and the solar PV systems. We present a concrete example as a candidate for such flexible contracts, and discuss a few others.

The rest of the paper is organized as follows. Section II discusses related work on battery energy storage systems for solar PV sources and electricity markets. Section III derives the solutions that enable a battery-companioned solar PV system to mimic the behaviour of a dispatchable generator. Based on the solutions, we show how cycle length in market operations can help reduce the battery capacity requirement. Section IV provides discussions about the design of more flexible forms of contracts between the grid and the solar PV systems. We conclude in Section V.

II. BACKGROUND

A. Battery Energy Storages for Solar PV Sources

For many power grids around the world, solar PV sources could potentially make up a significant portion of the total generation mix. This poses the challenge of developing effective system-level solution to deal with the intermittency of the solar resources. With the improvement of battery energy storage technologies, installing batteries together with the solar sources are being considered as a candidate solution to address this challenge. Figure 1 shows a simplified setup where a solar PV unit is companioned by a battery energy storage system, which are together connected to the grid. Here the charge controller can manage the charging / discharging behaviour of the battery according to the need. For instance, batteries can be used to absorb excessive power generated by the solar sources, and also deliver power back to compensate any unexpected decrease of solar power generation. For modern battery systems, the switching between different operating modes can be carried out almost instantaneously.

While there have been a number of research efforts investigating the use of battery energy storages for solar power integration, e.g. [5], [6], they mainly take the power grid's operational perspective, and discuss various applications, e.g., ramp rate control, frequency control, voltage control, reactive power support, and etc. In this paper, we study the battery capacity planning problem from a facility owner's perspective and explicitly consider its operation in a real-time (spot) electricity market. Our focus is to investigate how to enable a battery-companioned solar PV system to mimic a dispatchable generator while minimizing the requirement on the battery capacity. We note that the minimization of battery capacity requirement is of great interest to the facility owner, since the battery bank contributes a major portion of the infrastructure cost of a battery-companioned solar PV system. For instance, Table I summarizes the typical system cost of a few energy storage technologies [7].

B. Electricity Markets

We take the National Electricity Market of Singapore (NEMS) as an example to explain the basic operations of a real-time electricity market. In the real-time market of NEMS [8], every half an hour is a dispatching period. For each period, dispatchable generators in a system submit their price-quantity offers, while the market operator provides the load forecast. Based on this, a market clearing engine automatically computes the least-cost dispatch schedule, which decides the dispatch quantity for each bidding generator. Each generator is paid according to the market clearing price for the energy. This price may vary according to the location of the generators (so called nodal prices). Singapore's Energy Market Authority (EMA) expects all price-quantity offers to be finalized about one hour before the actual dispatching period, which is called the *gate closures on offers*.

In Singapore, the matching of the solar PV generation and the necessary reserves is currently done in a centralized manner. Specifically, EMA proposes to adopt a *dynamic pathway* approach to support the uptake for solar PV technologies [4]. This approach aims to ensure that sufficient reserves are available in the system to manage the intermittency effects. There are two key thresholds in the dynamic pathway approach: The first threshold, the *intermittent generation threshold* (IGT), reflects the

TABLE I
PLANT COST OF CURRENT BATTERY TECHNOLOGIES [7].

		Vanadium Redox Flow	Advanced Lead Acid	Lithium-ion
Plant cost	\$/KW	3335-3756	4360-5166	2183-5265
	\$/kWh at rated Depth of Discharge (DOD)	747-834	1090-1291	1092-1755
	\$/kWh at 100%DOD	747-834	654-775	928-1404

amount of intermittent generation sources (in Singapore context, they are mostly the solar PV units) that the grid can already support based on its current procurement of reserves. Traditionally, the amount of spinning reserves is designed to at least be able to handle the tripping of the largest on-line generating unit. In Singapore, IGT is currently set to 600 MW by EMA. Once the installed capacity of solar power exceeds IGT, the market needs to procure additional reserve resources solely for accommodating the solar PV units. The second threshold, the *intermittent generation limit* (IGL), reflects the maximum amount of solar PV capacity that a power system can support. It is computed based on the total amount of reserves capacity that is available in the system. Based on the "causer-pays" principle, EMA's proposed rule is to distribute the cost for procuring these additional reserves (i.e., the amount between IGT and IGL) solely among the solar PV units. Finally, once the total solar PV capacity reaches IGL, the system cannot further accommodate any additional solar PV units.

Since the cost for procuring reserves is also determined dynamically every half an hour based on the market condition, this can create uncertainties and additional risks for solar PV owners. By mimicking a dispatchable generators, a battery-companioned solar PV system would be able to avoid the uncertainties due to reserve costs and the potential barrier posted by insufficient total reserves.

III. MIMICKING A DISPATCHABLE GENERATOR

Consider a solar PV source with a maximum power output of x (in the unit of KW). Hence, for every half-hourly dispatch interval, its theoretical maximum energy output is xh where $h = 0.5$ hours. Its minimum output can be as low as 0 KWh. Now consider its companion battery storage system with a capacity rating of Y (in the unit of KWh). By mimicking a dispatchable generator, the battery-companioned solar PV system should supply the amount of energy as dispatched by the market clearing engine. The system should neither oversupply, nor undersupply. Recall that the system submits a price-quantity offer for each half-hourly dispatching period. Suppose at the beginning of a dispatching period, its stored energy is Z (in the unit of KWh), where $Z \in [0, Y]$. We now analyse the design for this battery-companioned solar PV system, specifically, the requirement on the battery capacity Y, in order to mimic a traditional generator.

A. Work-Conserving Design

We first consider a *work-conserving design* that ensures no solar power is wasted. Specifically, we want to avoid the situation when the solar PV units need to be disconnected and hence the power generation will be paused. Such a situation can occur when the companion battery is fully charged while the system is not allowed to supply power into the grid.

Let us first ignore the effect of gate closures on offers and assume that the offers can be submitted right before the beginning of a dispatch interval, so that the facility manager knows the value of Z, i.e., the stored energy in the battery.

The system should not bid for more than

$$B_{max} = Z.$$

The reason is clear: if the system bids more than Z and it turns out that the solar PV system generates zero energy in the dispatch interval, the system would fail to deliver what it promises.

To ensure solar PV units can work continuously, it is also easy to see that the system needs to bid at least

$$B_{min} = Z + xh - Y.$$

The bid should be submitted with a low offering price so that this bid will be taken by the market clearance engine almost surely. To understand why this is the minimum bid that the system needs to submit, consider the case when the solar PV units generate its maximum energy, i.e, xh. Bidding less than B_{min} would result in battery overflow and force the solar PV units to be disconnected.

Hence, because of these two extreme cases, a valid bidding should fall into the range of $[B_{min}, B_{max}]$. This range is non-empty, if and only if $B_{max} \geq B_{min}$, which translates to

$$Y \geq xh.$$

Recall that x is the maximum power output of the solar PV source and h is the length of a dispatch interval.

Suppose that the facility owner aims to minimize the installation cost and hence sets Y to its minimum value, i.e., $Y = xh$. Under this setting,

$$B_{max} = B_{min} = Z.$$

The system has a simple bidding strategy, i.e., to bid at Z, its current amount of stored energy in the battery, at a sufficiently low offering price, to ensure its bid will be almost surely taken by the market clearance engine. This strategy will result in an interesting behavior: all the energy stored in the battery prior to the dispatch interval (i.e., Z) will be supplied to the grid in the coming dispatch interval, while all the energy generated in the dispatch interval will be put into the battery and reserved for the future bidding.

With a slightly larger Y, the system can now submit two or more bids to the market, the first one is $Z+xh-Y$KWh at the offering price, which is expected to be taken by the market clearance engine. The second one can be up to Z and at a higher price. The intent is to ensure that the first bid will be (almost surely) taken, while the other bid(s) can opportunistically help increase the revenue of the system.

Now we consider the realistic situation with the gate closures on offers. Recall that in Singapore the market engine requires that offers to be finalized around one hour prior to the beginning of the dispatch period under normal circumstances. If the battery capacity Y roughly corresponds to the maximum energy generated by the solar PV source in half an hour. The one hour waiting period from submitting an offer to the real dispatching could introduce a lot of uncertainty, since the stored energy may change because of the solar PV inputs and/or the ongoing dispatching schedules. We observe that one strategy to avoid such uncertainty is to simply increase the battery capacity by 3 times. Now we view the enlarged battery as three independent component batteries, each is of the original size (as analysed previously when we ignore the gate closures). These three component batteries will be used in different intervals in a round-robin way. For example, if the first component battery is used for submitting the current bidding (to be dispatched one hour later), it will be freezed for the next one hour, while all charging / discharging will be conducted on the other two batteries. This increases the total capacity required by the battery to

$$Y \geq 3xh.$$

While the above strategies are easy to implement, it may result in a relatively large amount of battery storage. This can increase the deployment cost for solar PV technologies. Our analysis above suggests that one can reduce this cost by reducing the waiting period between the gate closures point and the starting of the actual dispatch interval. Technically this is feasible, since in NEMS the hard gate closure is only 5 minutes before the actual dispatching. This short 5 minutes time is likely reserved for running the market clearance engine and carrying out the dispatch decisions. The current 1 hour waiting period is mainly a soft safeguard to help ensure the market stability. Considering this, it is feasible that this soft safeguard can be removed for the special battery-companioned solar PV generators.

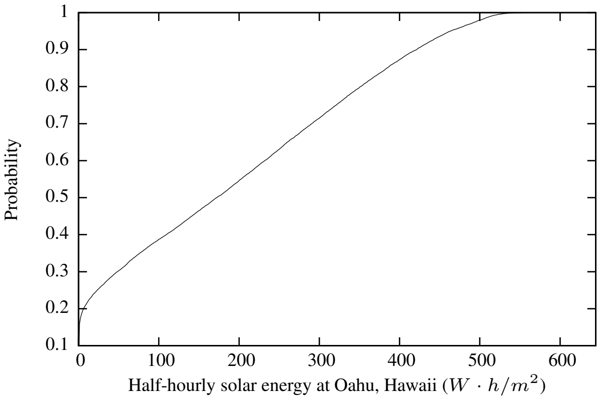

Fig. 2. Cumulative distribution function of half-hourly solar energy.

B. Non-Work-Conserving Design

This section discusses the capacity design when the requirement that the battery needs to work continuously is not strictly imposed. If the facility owner does not impose the continuously working requirement, the lower bounds for the bidding in Section III-A can be removed. In this case, if the battery is full and if the power generated by the solar panel is more than what is allowed by the dispatching contract (this can happen because we remove the bidding lower bound requirement), the controller will need to disconnect the solar PV units (or some of them) so that the contract does not get violated.

If one allows such disconnection to happen with a small probability, our analysis below based on real data traces shows that the minimum capacity requirement derived in Section III-A can be reduced considerably.

In Section III-A, we consider xh as the maximum energy output over any dispatching interval. However, reaching the maximum energy output may be rare in reality, making the capacity analysis in Section III-A conservative. We now use the real data traces of solar energy collected during 20 months from March 2010 to October 2011 at Oahu, Hawaii [9] to investigate the possibility that the maximum is achieved. The data traces were logged by a LICOR LI-200 Pyranometer mounted on a 7-foot tripod mounted on ground, which measures the solar radiation flux density from a field of view of 180 degrees. Although the power output of a PV panel is affected by various factors such as facing angle and conversion efficiency, the solar radiation flux density is a major factor for power output. Figure 2 plots the cumulative distribution function (CDF) of half-hourly solar energy based on the measured flux density. We can see that the CDF curve has a flat tail when approaching 1. Specifically, the CDF curve gets very close to 1 at around $500\,\mathrm{Wh/m^2}$, yet the maximum value in the data trace is at $647\,\mathrm{Wh/m^2}$, which is considerably higher than $500\,\mathrm{Wh/m^2}$. Hence, if we set xh to a value around $500\,\mathrm{Wh/m^2}$, the probability that the battery is fully charged during a dispatching interval

TABLE II
BATTERY CAPACITY REDUCTION VERSUS ALLOWED PV DISCONNECTION PROBABILITY.

PV disconnection probability	5%	1%	0.1%
Battery capacity reduction	28%	20%	16%

and hence the PV needs to be disconnected is rather low. Corresponding to Figure 2, Table II lists the percentages of battery capacity reduction given different allowed PV disconnection probabilities. As shown in the table, if a PV disconnection probability of 1% is allowed, the battery capacity requirement can be reduced by 20%.

IV. MORE FLEXIBLE FORMS OF CONTRACTS

This section discusses alternative approaches for reducing the batteries capacity requirement, besides the change of gate closure duration and the work-conserving requirement as discussed in previous section. Since the above requirement is based on the deterministic knowledge that the energy generated by the solar PV source in a dispatch interval is bounded in the range of [0, xh], we investigate whether the battery capacity requirement can be reduced by leveraging stochastic knowledge of the solar PV outputs. For this, we need to consider more flexible forms of contracts between the battery-companioned solar PV system and the grid.

In practice, one can use external information (e.g., season, time-of-day, weather forecast, historical data, etc) to determine a likely range of solar PV generation for a dispatch interval. Suppose the forecast value falls in a range of [Z_1, Z_2] with a probability of $1 - \epsilon$. Given this stochastic knowledge, if the contract allows the battery-companioned solar PV system to deviate from its offer with a small probability ϵ, the battery-companioned solar PV system can then bid according to [Z_1, Z_2] instead of the original larger range of [0, xh]. Specifically, the maximum bid it can submit can be increased to $B_{max} = Z + Z_1$, and for work-conserving design, the minimum bid can be reduced to $B_{min} = Z + Z_2 - Y$. To satisfy $B_{max} \geq B_{min}$, we have $Z + Z_1 \geq Z + Z_2 - Y$, or:

$$Y \geq Z_2 - Z_1.$$

This shows that a lower battery capacity requirement can potentially be achieved through accurate forecast (e.g., by leveraging advanced information processing techniques).

The unique characteristic of this problem is: 1) Since the battery capacity planning is a long-term static decision, the selection of the value of Y should satisfy all dispatching intervals in the trace with high probability. 2) For a given interval, the method can adjust both Z_2 and Z_1 in order to minimize their distance while maximizing the probability that the actual energy generated falls into [Z_1, Z_2].

We envision that there can be other forms of flexible contracts between the grid and battery-companioned solar PV systems. For instance, the grid can allow a battery-companioned solar PV system to operate within a range of energy generation values, instead of committing to a single value. Ideally, the design of such contracts should allow reduced capacity requirement of a battery-companioned solar PV system, while at the same time allowing stable and simple grid operations.

V. CONCLUSION

This paper discusses the capacity planning issues when using battery energy storage as a companion for grid-connected solar photovoltaic systems. Specifically, we show that for an electricity market that adopts real-time bidding and clearance, simple solutions can enable a battery-companioned solar PV system to behave in the same way as traditional dispatchable power generators. Through simple analysis, we show that battery capacity requirement can be substantially reduced by changing the gate closure time constants in market operations or by allowing the solar panel to be shut down occasionally. To further reduce the amount of battery storage needed, we discuss the design of more flexible forms of contracts between the grid and the solar PV systems. A flexible contract has great potential to further reduce the battery capacity requirement. To achieve this, however, advanced information processing techniques for accurate solar power generation forecasting will be needed.

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