Study on Market Price Based Dynamic Renewable + Battery Control to Maximize Market Revenue

Sichao Kan *

Under the FIP mechanism renewable developers are expected to sell their electricity through the electric power exchange market in the future. To hedge market price fluctuations and to counter the so-called "Cannibalism" issue, batteries could be utilized. This study discusses how to dynamically control battery operation based on market price signals to maintain high market revenue for the renewable + battery system. Battery operation control is disaggregated into 2 steps: control of charging/discharging, and decision of electricity discharging amount. A method of using the previous day's market price signal to conduct the control process is examined and the simulation results suggest that this method could help increase market revenue when battery installation happens to an extend that affects market prices. The study also attempted reinforcement learning for battery control and found that though the reinforcement learning could help bring higher market revenue, the results highly rely on the pre-set learning conditions and more study on this method will be needed in the future.

Keywords: Electricity Exchange Market, Renewable Energy, Battery Operation

1. Background

The subsidy mechanism for large scale solar PV and wind will be changed from feed-in tariff (FIT) to feed-in premium (FIP) in Japan. Under the FIP system, renewable energy electricity will be sold in the Japan Electric Power Exchange, with a premium on top of the market price.

Under the FIP system, renewable developers' revenue becomes vulnerable to market price fluctuations. Batteries are one of the options for developers to maximize their market revenue. As too much electricity from solar PV and wind, the marginal costs of which is low, flows into the market, the market prices in certain hours could plunge and result in the decrease of the renewable developers' revenue from the market. The so-called cannibalism phenomenon (References [1] and [2]) is one of the issues with the FIP system. A previous study (Reference [3]) analyzed batteries' role in mitigating the cannibalism phenomenon.

This study considers a method to control battery operation in response to electricity market price fluctuations to maximize revenue from electricity sales in the market. As is the case with the previous study (Reference [3]), the analysis is carried out with a case study of the Kyushu region which is one of the largest solar PV market in Japan.

2. Defining the Problem

According to the previous study (Reference [3]), the installation of batteries allows electricity from solar PV to be sold in the evening when electricity market prices are high, which can mitigate the impact of the cannibalism phenomenon. However, in the simulation of the previous study, the hours for electricity sales from solar PV-battery systems were fixed between 17:00 and 21:00 (**Figure 1**). Under this case, if solar PV-battery systems continue to increase, a large amount of low-cost electricity from solar PV-battery system could in turn cause market prices during the evening hours to drop (**Figure 2**).

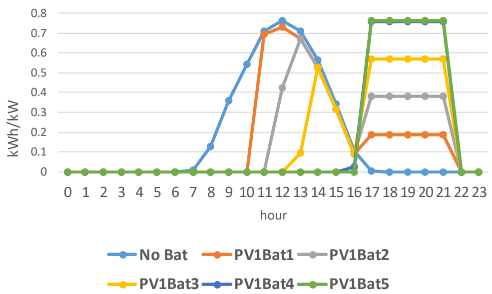

Figure 1 Assumption on the output of solar PV-battery system in the previous study

*Senior Researcher, the Institute of Energy Economics, Japan

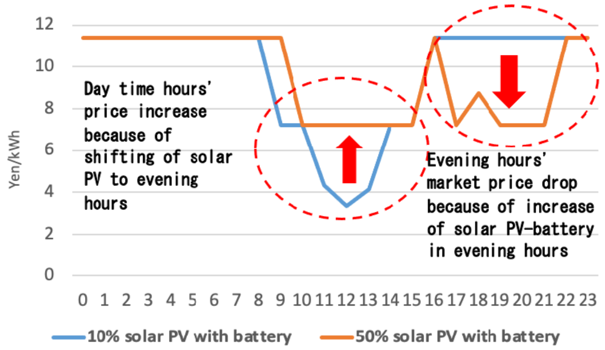

Figure 2 Market price drop caused by the increase of solar PV-battery system

(source) Simulation results from the previous study (Reference[3)])

To resolve this problem to improve market sales revenue, battery operation is required to be dynamically controlled in response to market price fluctuations.

3. Methodology and key assumptions

This study uses the same multi-agent-based electricity market simulation model as in the previous study (Reference [3)]). Simulation case is Kyushu Electric Power Company's service area. All power generators in the area are assumed to participate in the market. The simulation assumes one buyer agent and multiple seller agents for each power generation technology. As in the previous study (Reference [3)]), because of data availability interval for market settling is assumed to be 1-hour.

The previous study (Reference [3)]) assumed two cases for solar PV generation capacity – 7,850 MW (actually installed capacity) and 16,673 MW (approved capacity at the end of FY2017). However, this study only covers the 16,673 MW case.

As is the case with the previous study (Reference [3)]), the bidding block of the buy agent is calculated based on hourly electricity demand (2017) disclosed by Kyushu Electric Power Company. Seller agents' bidding block, the volume is considered equal to installed capacity for non-variable renewable power generation technologies. For each variable renewable energy technology, the quantity of electricity to offer to be bid is calculated by the installed capacity and the output curve estimated from the historical output data. Output from solar PV-battery systems depends on battery operation control (the operation control method is detailed in 3.1). **Table 1** shows assumed battery configurations. Assumptions for each power generation technology are the same as in the previous study (Reference [3)]) (**Table 2**).

Table 1 Assumptions on battery configuration

Item	Assumption
Battery Capacity	3 kWh battery per 1 kW solar PV
Rated Output	Battery capacity（kWh）/hour
Charging Efficiency	95%
Discharging Efficiency	95%
Selfdischarging	0.2%/hour

Table 2 Assumptions on the power generation cost and capacity of various technologies

	Hydro	Nuclear	Coal	Gas	Oil	Biomass	Geothermal	Solar PV	Wind	Solar PV＋battery
Generation cost（Yen/kWh）	2.3	5.4	7.2	11.4	26.7	25.2	12.5	3.34	4.15	3.34
Capacity（MW）	1,901	1,780	3,983	4,981	3,560	52	192	7,850	500	scenario

(source) Same with the previous study (Reference [3)])

3.1 Battery operation control

Given that revenue from electricity sales in the market depends on the price and volume of electricity sold, to increase revenue, it is desirable for solar PV-battery systems to charge during hours with low market prices and to discharge when the market price is high. Therefore, this study assumes that battery operation is controlled in two stages: (1) determining the timing for charging and discharging (a charging or discharging command signal for each hour) and (2) deciding the amount of electricity for charging or discharging. Although there are various logics to link market price with the decision making of the charging/discharging timing as well as the charging/discharging amount, this study assumed a method using indicators calculated by market prices of the previous day.

(1) Timing for charging and discharging

It is assumed that charging and discharging do not happen at the same time, no discharging is assumed during the hours between 10:00 and 18:00 when there is solar PV output. So, the decision making for charging/discharging timing is only required for the remaining hours. Although the market price may change from day to day, there are some common trends for high- and low-price hours. This study uses market price of the previous day to decide on the charging and discharging timing of the current day. First the previous day's average market price is calculated. For the same hours, when the previous day's market price is higher than the average price, command signal for battery discharging is issues. For the other hours, the command signal is charging.

(2) Amount of electricity to be charged or discharged

In response to a charging command signal, the battery will be charged up to its full capacity. If there is still solar PV electricity generation when the battery is charged full, the electricity will be sold to the market.

In response to a discharging command signal, the desirable amount of electricity to be discharged is first calculated based on market prices to maximize electricity sales during high-price hours. The actual discharging amount will be limited by the electricity stored in the battery and battery's rated output power. This study calculated the economically desirable discharging amount by multiplying the battery's rated output power by the ratio calculated from the previous day's market prices. To calculate the ratio of a given discharging hour, first, the sum of the price gaps between discharging hours' market prices (previous day) and the previous day's average market price is calculated. For a certain discharging hour, the hour's discharging ratio is the ratio of the hour's price gap divided by the price gaps sum (Figure 3). The actual discharging volume is smaller between the economically desirable discharging amount electricity stored in the battery.

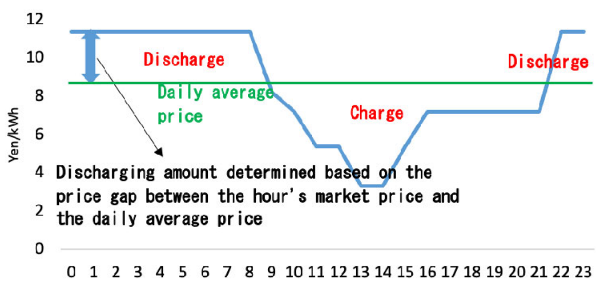

Figure 3 Control of battery's charging/discharging

4. Results

4.1 Market sale revenue

The previous study (Reference [3]) showed that if massive solar PV electricity is flowed into the market (solar PV capacity increases from 7,850 MW to 16,673 MW), the solar PV developer's annual revenue from electricity market will decline from 11,845 yen/kW to 6,714 yen/kW because of the cannibalism phenomenon. If batteries are installed to shift solar PV electricity sales to evening hours, annual market revenue could be increased by 4,232 yen/kW (**Figure 4**). As noted above, however, revenue for solar PV-battery systems would decline if there are too many such systems, which will result in lower market price in evening hours. If the share of solar PV-battery systems expands from 10% to 50% in terms of total solar PV capacity, revenue for solar PV-battery systems will decrease by 2,400 yen/kW (**Figure 4**).

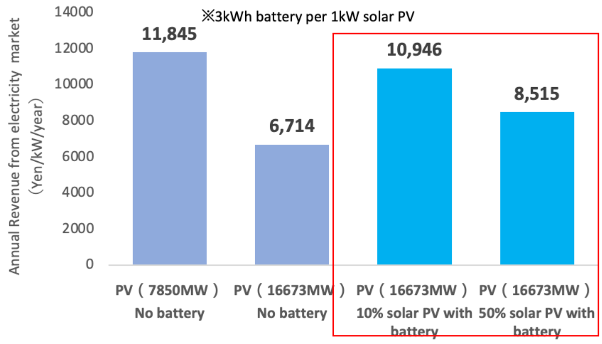

Figure 4 Change of market revenue with installation of battery

(source) results from the previous study (Reference[3])

The effectiveness of the battery operation control method discussed in this study can be shown from the results of the two cases: batteries are installed for 10% of solar PV capacity (**Figure 5**) and for 50% of solar PV capacity (**Figure 6**).

The simulation results suggest that the battery operation control discussed in this study is effective in improving the solar PV-battery system's market revenue when the penetration of battery high (capacity of solar PV with battery accounts for 50% of total solar PV capacity) (**Figure 6**). However, when the installation of battery is relatively small (solar PV-battery accounts for 10% of solar PV capacity) the system's market sales revenue benefits little from dynamic control of battery (**Figure 5**).

Electricity market price is usually high in evening hours, which means that to increase revenue selling electricity in these hours is desirable. As stated before, when the installation of batteries increases because of the concentration of electricity selling from solar PV-battery systems in evening hours, market price in these hours will decline, resulting in the decrease of market revenue. In this case, dynamic battery operation control to shift the output of battery from evening hours to other high-market-price hours will improve market sales revenue.

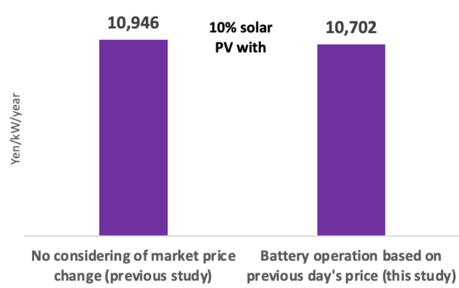

Figure 5 Change of market revenue by dynamic battery operation (solar PV with battery accounts for 10% of total capacity)

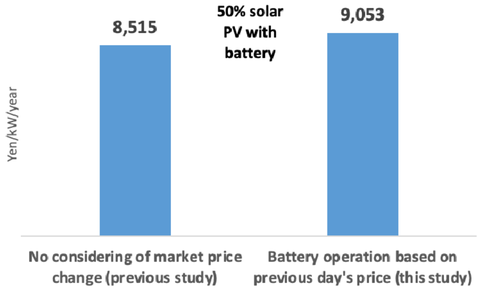

Figure 6 Change of market revenue by dynamic battery operation (solar PV with battery accounts for 50% of total capacity)

4.2 Considering reinforcement learning for battery control

This study also tested using reinforcement learning for battery control. Reinforcement learning allows an agent (batteries in this study) to select profit-maximizing option from multiple options through learning. This study applied reinforcement learning in the process of decision making of the amount of electricity to be discharged. Multiple options of discharging amount are assumed in advance and through a learning strategy, the solar PV-battery agent will select the one that is expected to maximize market sales revenue.

Simulation results suggested that how to set the discharging amount options has great impacts on the results of learning. **Figure 7** shows annual market sales revenue results for two cases. Case 1, the maximum dischargeable amount is 26% of rated battery output, and Case 2, the maximum dischargeable amount is 100% of rated battery output. Even with the same learning strategy, the difference in annual market revenue between the 2 cases is as much as 2,010 yen/kW. Revenue under Case 2 is lower than that under Case 1 because under the assumptions of Case 2, hourly discharging amount is larger and in the learning process, there is still the possibility that options of larger discharging amount are selected even the market price is not the highest. On the other hand, revenue under the assumptions of Case 1 is higher than that using the method discussed in 4.1.

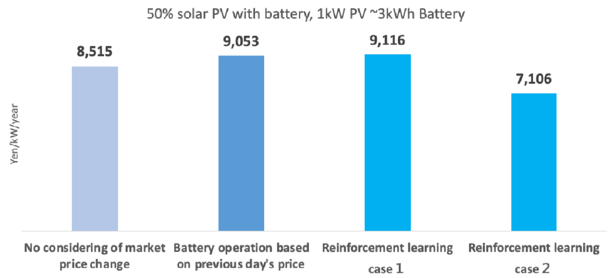

Figure 7 Market revenue results using reinforcement learning

5. Conclusion and implications

This study used a multi-agent market simulation model to analyze the effectiveness of dynamic battery operation in response to the change of electric market price. Simulation results suggested that as solar PV-battery systems expand, dynamic battery operation control based on market price can contribute to the improvement of the system's market sales revenue. This study discussed two battery operation control methods: one based on previous-day market price only and the other based on previous-day market price as well as reinforcement learning. Although reinforcement learning could help to further improve market sales revenue, the result is highly dependent on the pre-set learning conditions.

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Contact: report@tky.ieej.or.jp