Coordinated Operation Scheduling Method for BESS and Thermal Generators based on Photovoltaic Generation Forecasts Released Every Several Hours

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Abstract—**The application of photovoltaic (PV) generation forecasting to supply–demand operation is essential for power systems with large integrations of PV generation. Forecasting errors may cause supply–demand imbalances such as power shortfall and surplus, which lead to outage and PV curtailment, respectively. Thus, it is important to improve forecasting accuracy. However, even if forecasting is completely accurate, PV curtailment is occasionally necessary in power systems with extremely large installed PV capacity. In this case, energy storage devices, such as a battery energy storage system (BESS), are necessary for more efficient use of PV energy. In this study, we propose a coordinated control method for a BESS and thermal generators considering their unit commitment. The method is based on forecasted PV power outputs that are released and updated every several hours. Numerical simulations are conducted to evaluate the effectiveness of the proposed method for decreasing supply–demand imbalances.**

Keywords—Battery energy storage system; photovoltaic (PV) generation forecast; power system; unit commitment (UC)

I. INTRODUCTION

In recent years, the installed capacity of photovoltaic (PV) generation in Japan has grown at an increasing rate owing to the review of the nuclear policy and feed-in tariff policy. Accumulated installed capacity reached 34.4 GW in 2015, and the installation target for 2030 is set as 100 GW [1]. The capacity of electricity generation is approximately 200 GW. If the installation of PV systems continues at its current rate, power surplus and shortfall may increase. In future supply‐demand operation, it is necessary to decrease power surplus and shortfall. This has led to the study of output curtailment methods for PV generation to reduce power surplus and application methods for the PV generation forecasts in Japan [2],- [3].

We have developed a supply‐demand operation method using PV generation forecasts [4]. In a previous study [4], we concluded that energy shortfall could be effectively reduced by applying accurate PV generation forecasts to supply‐demand operation; however, this method cannot significantly reduce power surplus. Utilization of energy storages devices, such as a battery energy storage system (BESS), is indispensable to effectively use power surplus. Therefore, in this study, we propose and evaluate a coordinated method for determining and modifying the charge/discharge schedule of a BESS and the unit commitment (UC) of thermal power generators. This method is based on PV generation forecasts that are released every several hours in a power system with high installed PV generation.

II. MODIFICATION OF SCHEDULES BASED ON FORECASTS RELEASED EVERY SEVERAL HOURS

In this study, we use forecasts that are released every several hours to determine and modify the BESS charge/discharge schedule and the UC of thermal power generators for the reduction of power surplus and shortfall.

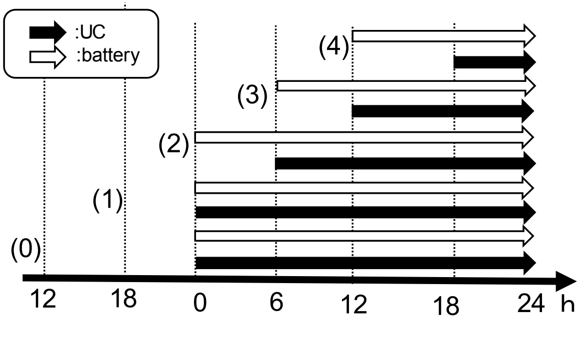

Fig. 1. Modification of BESS and UC scheduling.

In Fig.1, the BESS charge/discharge schedules and the UC of thermal generators are represented by white and black arrows, respectively. As shown by (0) in Fig.1, the BESS charge/discharge schedule from 0 to 24 LT (local time) is determined based on the forecasted PV power output released at 12 LT of the previous day. Then, the UC of thermal power generators from 0 to 24 LT is determined. As shown by (1)‐(4), the BESS charge/discharge schedules from 0 to 24 LT are modified at (1) and (2), those from 6 to 24 LT are modified at (3), and those from 12 to 24 LT are modified at (4), based on the forecasted PV power outputs released at 18 LT of the previous day

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and at 0, 6, and 12 LT of the current day. After modifying the BESS charge/discharge schedules, the UC of thermal power generators from 0 to 24 LT, 6 to 24LT, 12 to 24 LT, and 18 to 24 LT is modified at (1), (2), (3), (4), respectively. Note that in (0)-(4), the charge/discharge are determined and modified so that the initial and end states of charge of the BESS will be identical, which will be presented in detail in Section III-B.

III. CHARGE/DISCHARGE SCHEDULING OF BESS

In this study, we assume that the BESS is operated for effectively using the energy surplus resulting from a large amount of PV generation. We propose a charge/discharge scheduling method, in which the BESS charges when a power surplus is expected to occur and discharges at other times, using PV generation forecasts that are released every several hours.

A. Condition on the Number of Operating Generators at Each Time Period

Before determining or modifying the BESS charge/discharge schedule and the UC of thermal power generators, the minimum and maximum numbers of operating thermal power generators are obtained at each time period based on the latest forecasted PV power outputs at that time. If the minimum number is determined, the amount of power surplus can be calculated. Assuming that electric power facilities consist of nuclear power, thermal power, and hydropower plants, the number of operating thermal power generators (*N)* must satisfy the constraint conditions represented by (1) - (3) to ensure adequate reserve and regulating capacity for preventing power surplus and shortfall and suppressing frequency fluctuations. (Here, the thermal power generators start up in the following order: i = 1, 2….N). Eq. (1) is the condition on the load frequency control (LFC) regulating capacity for short-term load and PV power output fluctuations in the entire power system. Eqs. (2) and (3) are the conditions on supply–demand balance.

$$\sum_{i=1}^{N} u'_{i,j} \cdot C_{LFC,i} + C_H \geq R_D \cdot P'_{D,j} + R_{PV} \cdot P'_{PV,j} \tag{1}$$

$$P'_{D,j} - P'_{PV,j} - P_{NU} - P_H \geq \sum_{i=1}^{N} u'_{i,j} \cdot \left(P_{MIN,i} + C_{LFC,i}\right) \tag{2}$$

$$P'_{D,j} - P'_{PV,j} - P_{NU} - P_H \leq \sum_{i=1}^{N} u'_{i,j} \cdot \left(P_{MAX,i} - C_{LFC,i}\right) \tag{3}$$

where, $u'_{i,j}$ denotes the states of generator i at time j (1: operation, 0: stopping), $C_{LFC,i}$ is the LFC regulating capacity of generator i at time j, C_H is the total LFC regulating capacity of the hydro power plants, R_D and R_{PV} are the required percentages of LFC regulating capacity for short-term load and PV power output fluctuations, respectively, $P_{MAX,i}$ and $P_{MIN,i}$ are the maximum (rated) and minimum outputs of generator i, respectively, $P'_{PV,j}$ and P'_{Dj} are the forecasted PV power output, which excludes output curtailment if required, and load demand at time j, respectively, and P_{NU} and P_H are the totals output of nuclear power and hydro power plants, respectively.

When (1) or (2) is not satisfied, the BESS charges or PV power output is curtailed to prevent power surplus. In this study, we assume that a power system operator can forecast the PV power outputs of the entire power system and set the maximum PV power output that does not cause power surplus as a threshold value at each time period. When PV power output is larger than the threshold value, it is charged by the BESS or curtailed. The maximum PV power outputs at time j calculated using (1) and (2) ($P_{PV\_MAX1,j}$, $P_{PV\_MAX2,j}$) are given by (4) and (5), respectively.

$$P_{PV\_MAX1,j} = \frac{\sum_{i=1}^{N} u'_{i,j} \cdot C_{LFC,i} + C_H - R_D \cdot P'_{D,j}}{R_{PV}}, \tag{4}$$

$$P_{PV\_MAX2,j} = P'_{D,j} - \left\{ \sum_{i=1}^{N} u'_{i,j} \cdot \left(P_{MIN,i} + C_{LFC,i}\right) + P_{NU} + P_H \right\}. \tag{5}$$

The smaller value among $P_{PV\_MAX1,j}$ to $P_{PV\_MAX2,j}$ is selected as a threshold value for the total PV power output.at time j. When the available PV power output at time j is larger than the threshold value in current day operation, power surplus is prevented through BESS charging and PV curtailment. The forecasted amount of the curtailed PV power at time j ($P'_{suppress,j}$) is given by

$$P'_{suppress,j} = P'_{PV0,j} - \min\left(P_{PV\_MAX1,j}, P_{PV\_MAX2,j}\right), \tag{6}$$

where P'_{PV0j} is the forecasted PV power output without charging or curtailment at time j.

B. Charge/Discharge Schedule

The PV power output exceeding the threshold value in (6) is charged by the BESS. However, the amount exceeding the inverter capacity of the BESS is not charged. The charging power at time j is given by

$$P'_{charge,j} = MIN\left\{C_{INV}, MAX\left(0, P_{suppress,j}\right)\right\}, \tag{7}$$

where C_{INV} is the inverter capacity of the BESS.

The constraint condition on the battery capacity of the BESS is given by

$$\eta \cdot \sum_{j=1}^{T} C_j \cdot P'_{charge,j} \cdot \Delta T \leq C_{BAT}, \tag{8}$$

where η is the charging efficiency of the BESS, C_j is the state of the BESS at time j (1: charging, 0: idling or discharging), C_{BAT} is the battery capacity of the BESS, T is the scheduling period, and ΔT is unit time (ΔT = 1 [h]). The left-hand side of (8) is the total charged energy in the BESS for one day.

Discharge powers are determined through quadratic programing. The objective function is set to minimize

$$\mathrm{f_d} = \sum_{j=t_b}^{T} \left(P'_{D,j} - P'_{PV,j} - P'_{discharge,j}\right)^2 \cdot \Delta T, \tag{9}$$

where $P'_{discharge,j}$ is the discharge power of the BESS at time j and t_b is the start time of the schedule, which is represented the starting points of the white arrows in Fig.1.

f_d is the squared sum of the energy supplied by the power plants other than PV generation; its minimization implies the leveling of net load. It is intended to reduce the fuel and startup costs of the thermal power generators as much as possible. The BESS can discharge only when it is charging or PV curtailment is not required. ($P'_{discharge,j}$ is zero at other time periods.) The constraint conditions include inverter capacity, the balance between charge and discharge energies, initial and end conditions, and the battery capacity of the BESS.

The constraint condition on the inverter capacity of the BESS is given by

$$0 \le P'_{\mathrm{discharge,\,j}} \le C_{INV}. \tag{10}$$

The constraint condition on the balance between the charge and discharge energies of the BESS is given by

$$\eta \cdot \sum_{j=1}^{T} C_j \cdot P'_{charge,j} \cdot \Delta T = \sum_{j=1}^{T} \left(1 - C_j\right) \cdot P'_{discharge,j} \cdot \Delta T. \tag{11}$$

The constraint condition on the initial and end conditions is given by

$$\mathrm{E'_{BESS,T}} = E'_{BESS,0} = 0.5 \cdot C_{BAT}. \tag{12}$$

The initial state of charge of the BESS is 50% of the battery capacity. It charges throughout the day; however, it must return to 50% at the end of the day. $E'_{BESS,j}$, which is the stored energy of the BESS at time j, is given by

$$\mathrm{E'_{BESS,T}} = E'_{BESS,0} + \eta \cdot \sum_{k=1}^{j} P'_{charge,k} \cdot \Delta T - \sum_{k=1}^{j} P'_{discharge,k} \cdot \Delta T. \tag{13}$$

The constraint condition on the battery capacity of the BESS is given by

$$0 \le E'_{BESS,j} \le C_{BAT}. \tag{14}$$

IV. UC OF THERMAL POWER GENERATORS [4]

The UC of the thermal power generators is determined and modified through dynamic programing. The objective function is set to minimize

$$f = \sum_{i=1}^{N} \sum_{j=t}^{T} \left\{ u_{i,j} \cdot FC_i\left(P'_{i,j}\right) \cdot \Delta T + u_{i,j} \cdot \left(1 - u_{i,j-1}\right) \cdot SC_i \right\}, \tag{15}$$

where FC_i and SC_i are the fuel cost function and the start-up cost of generator i, respectively, $P'_{i,j}$ is the scheduled output of generator i at time j, and t is the start time of the schedule. Thus, the scheduling period of the UC is from t to T. [5]. The constraint conditions include the upper and lower limits of generators, supply–demand balance, LFC regulating capacity for short-term load fluctuations, and the priority dispatch for PV generation. In addition, the charge and discharge powers determined in the latest BESS schedule are considered.

V. CURRENT DAY OPERATION

A. Charging/Discharging of BESS

As shown in Fig. 1, the charge/discharge schedule of the BESS is determined and modified every 6 hours. The charge and discharge powers follow the latest BESS schedule in current day operation.

B. Optimal Load Dispatch for Thermal Power Generators

The operating and stopping states of the generators follow the latest modified UC in current day operation. The outputs of the generators are regulated for optimal load dispatch at each time period through quadratic programing [4]. The objective function is set to minimize

$$f' = \sum_{i=1}^{N} u_{i,j} \cdot FC_i\left(P_{i,j}\right), \tag{16}$$

where $P_{i,j}$ is the actual output of generator i at time j [5].

The constraint conditions are the same as those used for determining the UC.

C. Power Shortfall and PV Curtailment

Power shortfall occurs if the requested outputs are larger than the total maximum outputs of the operating generators. This is caused by forecasting errors. The power shortfall at time j ($P_{shortfall,j}$) is given by

$$P_{shortfall,j} = P_{D,j} - P_{PV,j} - \left\{ \sum_{i}^{N} u_{i,j} \cdot \left(P_{MAX,i} - C_{LFC,i}\right) + P_{NU} + P_H \right\}. \tag{17}$$

PV power output is curtailed if the available PV power output is larger than the sum of the scheduled charged power of the BESS and the maximum PV power output determined in (4) and (5). The curtailed PV power at time j ($P_{suppress,j}$) is given by

$$P_{suppress,j} = P_{PV0,j} - \min\left(P_{PV\_MAX1,j}, P_{PV\_MAX2,j}\right) - P'_{charge,j}. \tag{18}$$

VI. SIMULATION CONDITION

We perform a supply‑demand operation simulation using a power system model for the Kanto region of Japan. Table I shows the specifications of the thermal power generators [4]. The available capacities of the nuclear power and hydropower plants are 6000 MW and 1200 MW, respectively. The total output of the nuclear power and hydropower plants is assumed to be constant at 100% and 95%, respectively. The remaining 5% in the case of the hydropower plants is available for the LFC regulation. The installed inverter and battery capacities of the BESS are 10

GW and 70 GWh, respectively, and the charge/discharge efficiency is 80%.

We use the actual hourly data on the load demand for Tokyo Electric Power Company in April and May 2010 [6]. We assume that the load demand can be exactly forecast at 12 LT of the previous day. We use the actual hourly data on solar irradiation for 2010, which is averaged across six sites in the Kanto region [7]. PV power output is calculated by multiplying normalized solar irradiation by installed PV capacity and the system output coefficient (0.8 in this study). The installed capacity of PV generation is 30 GW. We employ the solar irradiation forecast data calculated by AIST using the source code of a mesoscale model developed by the Japan Meteorological Agency [8], [9].The data for April and May 2010 are used for the simulation. The forecast data are released at 12 (from 0 to 24 LT) and 18 LT (from 0 to 24 LT) of the previous day and at 0 (from 0 to 24 LT), 6 (from 6 to 24 LT), 12 LT (from 12 to 24 LT) of the current day. The errors decrease as the release time of PV generation forecasts increases [4].

Three simulation cases are considered. In Case 1, the BESS charge/discharge schedule and the UC of thermal power generators are determined based on the forecasted PV power outputs released at 12 LT of the previous day, and they are not modified. In Case 2, they are determined based on the forecasted PV power outputs released at 12 LT of the previous day. Then, they are modified based on updated forecasts that are released every 6 h, as described in Sections II and III. In Case 3, they are determined based on the perfectly forecasted PV power outputs released at 12 LT. Case 3 is the reference case, where forecasts are completely accurate.

VII. SIMULATION RESULTS

Fig. 2 shows the total energy shortfall for each case in April and May. The total energy shortfall in Case 2 is lower than that in Case 1 because energy shortfall occurs owing to forecasting errors and the UC is modified based on more accurate forecasts in Case 2. No energy shortfall is observed in Case 3 because forecasts are completely accurate. The results show that the total energy shortfall is reduced by modifying the UC based on more accurate forecasts.

TABLE I. SPECIFICATIONS OF THERMAL POWER GENERATORS [4]

	Rated output [MW]	Lower limit [MW]	Merit order	Number of generators	Total capacity [MW]
Coal	1,000	300	1-12	12	12,000
	700	105	13-16	4	2,800
CC	250	63	38-111	74	18,500
	100	30	17-37	21	2,100
LNG	700	140	112-130	19	13,300
	200	80	131-143	13	2,600
Oil	700	175	150-153	4	2,800
	500	100	144-149	6	3,000
	250	50	154-168	15	3,750
			Total	168	60,850

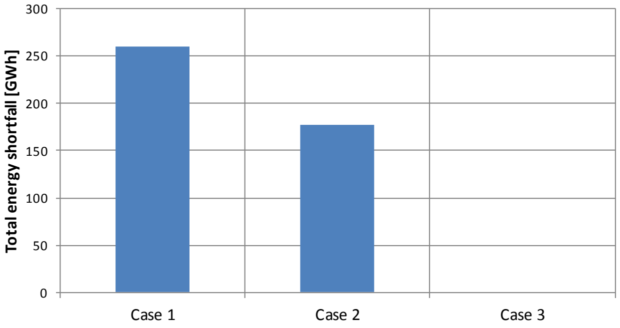

Fig. 2. Total energy shortfall in April and May.

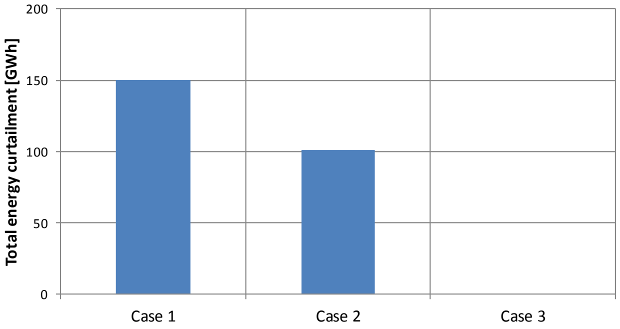

Fig. 3. Total PV energy curtailment in April and May.

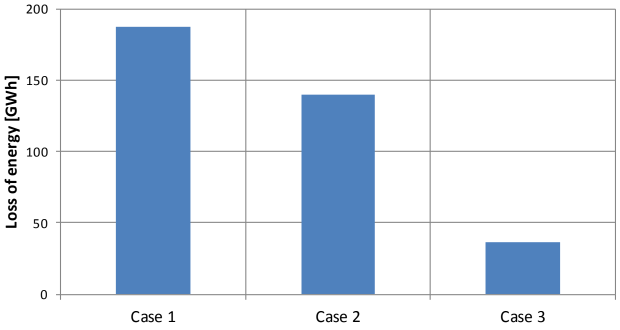

Fig. 4. Total energy loss in April and May.

Fig. 3 shows the total PV energy curtailment for each case in April and May. The total PV energy curtailment in Case 2 is lower than that in Case 1 because the BESS schedule is modified every 6 h in Case 2. No PV energy curtailment is observed in Case 3 because forecasts are completely accurate. Fig. 4 shows the total energy loss for each case in April and May. This energy loss (*PV_loss*) is the loss of the energy generated through PV generation; it is calculated as the sum of the total PV energy curtailment and battery loss due to charging efficiency. *PV_loss* is given by

$$PV\_loss = \sum_{i=1}^{D} \sum_{j=1}^{T} \left\{ P_{suppress,j} + \left(P_{charge,j} - P_{discharge,j} \right) \right\}. \quad (19)$$

Even though the total PV energy curtailment in Case 3 is zero, energy loss occurs in this case owing to charging efficiency, as seen in Fig. 4. This is the minimum energy loss that can be achieved by improving forecast accuracy.

The total energy loss in Case 2 is smaller than that in Case 1. These result show that energy loss can be reduced by modifying the BESS charge/discharge schedule and the UC based on accurate PV generation forecasts released every several hours. The energy loss in Case 2 is larger than that in Case 3, and it could be reduced through more accurate forecasts or the operation methods of the BESS. In future, it is important to further reduce the PV energy loss in Case 2 and bring it closer to the energy loss in Case 3.

The daily load curve for April 7 for each case is shown in Figs. 5-7. These are examples of a day when energy shortfall is high. The BESS is not scheduled to charge or discharge because forecasted PV power outputs are small. The energy shortfall in Case 2 is lower than that in Case 1. Energy shortfall does not occur in Case 3 because of completely accurate forecasts. These results show that modifying the UC is effective for reducing energy shortfall.

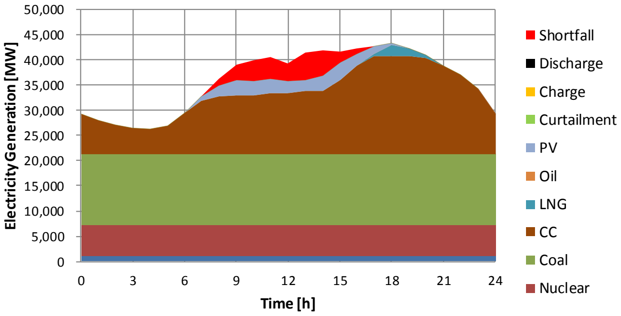

Fig. 5. Daily load curve in Case 1 (April 7).

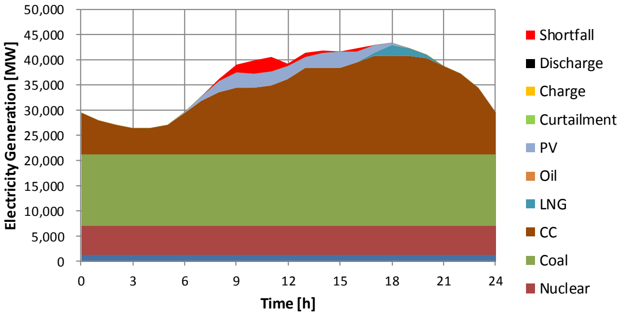

Fig. 6. Daily load curve in Case 2 (April 7).

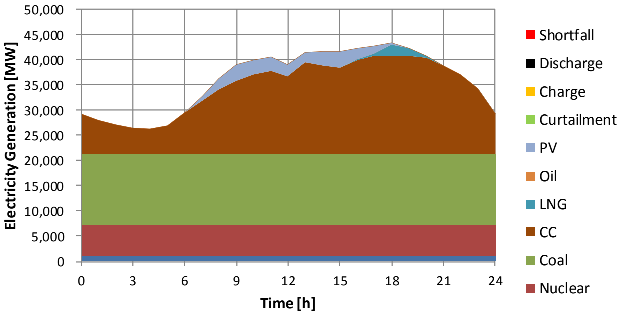

Fig. 7. Daily load curve in Case 3 (April 7).

The daily load curve for May 9 for each case is shown in Figs. 8-10. These figures are examples of a day when PV energy curtailment is high. As PV power output was forecasted to be small at 12 LT of the previous day, a considerable amount of PV energy can be observed without charging in Case 1. The PV energy curtailment in Case 2 is lower than that in Case 1 because of the modification of the BESS charge/discharge schedule every 6 h. In addition, it can be seen that load demand is leveled in Case 2 and Case 3 because the BESS discharging during load demand is high.

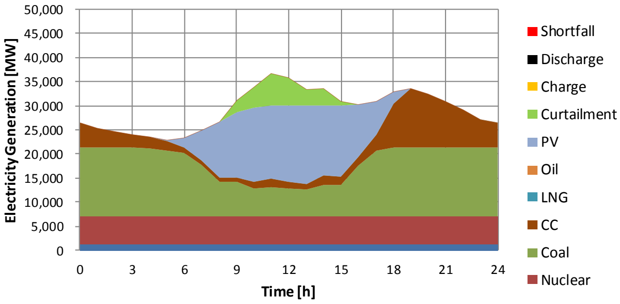

Fig. 8. Daily load curve in Case 1 (May 9).

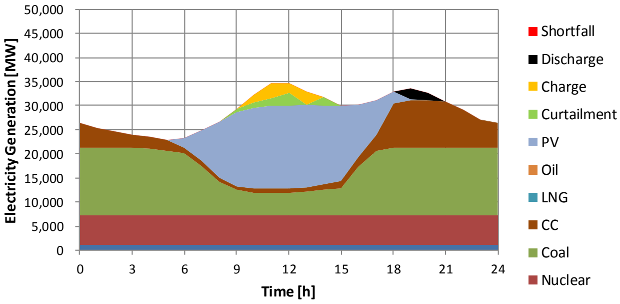

Fig. 9. Daily load curve in Case 2 (May 9).

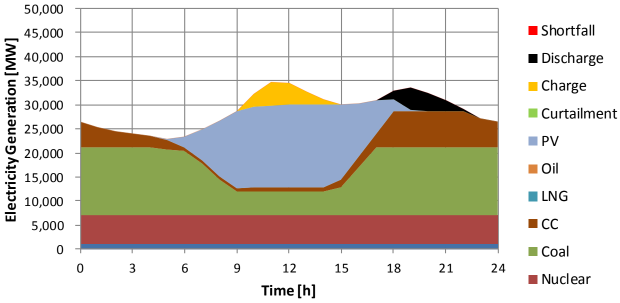

Fig. 10. Daily load curve in Case 3 (May 9).

VIII. CONCLUSION

In this study, we proposed a coordinated method for determining and modifying the charge/discharge schedule of a BESS and the UC of thermal power generators using forecasted PV power outputs that were released every several hours. The simulation results showed that the modification of the UC is effective to reduce the energy shortfall, and that of the BESS schedule is effective to reduce the PV energy curtailment, respectively. In future work, we will evaluate the proposed method for longer a period such as one year. Moreover, we will analyze the impact of the larger installed PV capacity considering several scenarios.

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