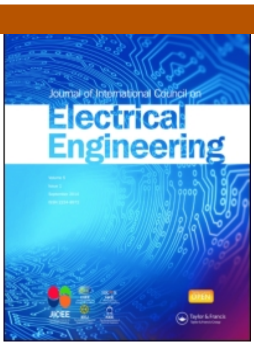

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A study on electric power management for power producer-suppliers utilizing output of megawatt-solar power plants

Hirotaka Takano[a], Yuya Nagaki[b], Junichi Murata[c], Tatsuya Iizaka[d], Naoto Ishibashi[d] and Tohru Katsuno[d]

[a]Faculty of Engineering, University of Fukui, 3-9-1, Bunkyo, Fukui 910-8507, Japan; [b]Graduate School of Information Science and Electrical Engineering, Kyushu University, 844, Motooka, Nishi-ku, Fukuoka 819-0395, Japan; [c]Faculty of Information Science and Electrical Engineering, Kyushu University, 844, Motooka, Nishi-ku, Fukuoka 819-0395, Japan; [d]Corporate R&D Headquarters, Fuji Electric Co., Ltd 1, Fuji-machi, Hino 191-8502, Japan

ABSTRACT

The growth in penetration of photovoltaic generation units (PVs) has brought new power management ideas, which achieve more profitable operation, to Power Producer-Suppliers (PPSs). The expected profit for the PPSs will improve if they appropriately operate their controllable generators and sell the generated electricity to contracted customers and Power Exchanges together with the output of Megawatt-Solar Power Plants (MSPPs). Moreover, we can expect that the profitable cooperation between the PPSs and the MSPPs decreases difficulties in the supply-demand balancing operation for the main power grids. However, it is necessary that the PPSs treat the uncertainty in output prediction of PVs carefully. This is because there is a risk for them to pay a heavy imbalance penalty. This paper presents a problem framework and its solution to make the optimal power management plan for the PPSs in consideration with the electricity procurement from the MSPPs. The validity of the authors' proposal is verified through numerical simulations and discussions of their results.

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Economic load dispatching control (ELD); electric power exchanges; electric power management; megawatt-solar power plants (MSPPs); power producer-suppliers (PPSs); unit commitment (UC)

1. Introduction

The government of Japan has set a fundamental target of installing photovoltaic generation units (PVs) to 28 GW by 2020 and 53 GW by 2030. In addition, owing to the introduction of Feed-in Tariff (FIT) system in July 2012,[1] both domestic and non-domestic PVs have been attracting significant attention, and the resulting PV penetration is revolutionizing the electrical power industry. If the PVs installation keeps growing steadily, it will become more difficult for the power grid operation to maintain the power supply and demand balance. This is because imprecise prediction of the PV outputs increases the uncertainty in demand prediction. Therefore, the Japanese power utilities are now under pressure to overhaul the power grid operation, especially in the supply-demand balancing operation.

On the other hand, from a viewpoint of Power Producer-Suppliers (PPSs),[2] who can produce and purchase electricity, and then sell them to contracted customers and Electric Power Exchanges (PEXs), the growth in PV penetration gives opportunities to promote their profitable power management.[3–5] If the PPSs appropriately operate their controllable generators (CGs) and sell the generated electricity together with the purchased electricity from owners of Megawatt-Solar Power Plant (MSPP), they will gain a profit supported by the FIT system.[6] However, the PPSs have a risk of purchasing very expensive electricity from the main power grids when they cannot procure sufficient electricity by using their CGs and the MSPPs only. Hence, in order to maximize the profit from electricity trading, the PPSs have to deal with the uncertain PV output prediction carefully, which, in turn, eases difficulties in supply-demand balancing operation of the main power grids.

In this paper, the authors present a problem framework and its solution to make a power management plan for the PPSs in consideration with the electricity procurement from the MSPPs. The aim of this research is to design a profitable and stable power management which provides not only the better selling profit to the PPSs and the MSPP owners, but also the reduction in operational difficulties for the main power grids. With a view to maximizing the

CONTACT Hirotaka Takano takano@u-fukui.ac.jp

expected profit of the PPSs, the proposed solution determines the optimal set of the CG outputs, the procuring electricity from the MSPP owners, and the selling electricity to the PEXs. In the solution procedure, the profit maximization is achieved by considering electricity price in the PEXs, operational costs of the CGs and uncertainty in the output prediction of PVs. The validity of the authors' proposal is verified through numerical simulations and discussions of their results.

2. Problem definition

2.1. Outline of target problem

This paper treats a profitable cooperation between PPSs and MSPP owners considering the imprecise output prediction of PVs. There can be two different models: (1) the PPSs produce electricity using their CGs and purchase electricity from the MSPP owners, and (2) the PPSs has both CGs and MSPPs. The difference in these models is whether there is the trade between the PPSs and the MSPP owners or not, and thus the PPS-model 1 is more difficult than the PPS-model 2. In this paper, the PPS-model 1 is mainly discussed.

In Figure 1, the PPS produces electricity by its CGs and procures electricity from the MSPP owners, and then sells them to the contracted customers and the PEX. Since there is necessity to notify the amount of selling electricity to the PEX in advance, the PPS has to predict electricity that can be purchased from the MSPP owners. However, PV is one of the most unstable generation units affected by the weather condition, and thus, by the time of notification, only inaccurately predicted PV outputs are available. In addition, if the PPS cannot procure the notified amount of electricity, the shortage must be compensated by purchasing electricity from the main power grids with a heavy imbalance penalty. Under the circumstances, it is important for the PPS to make an appropriate power management plan (the optimal set of the CG outputs, the procuring electricity from the MSPPs and the selling electricity to the PEX) considering the uncertainty in output prediction of PVs.

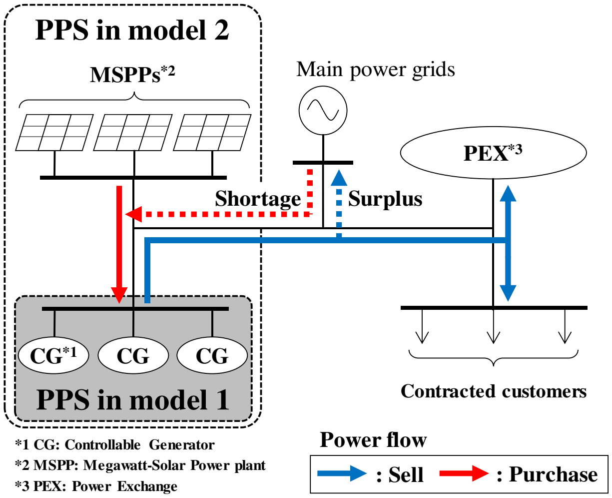

Figure 1. PPS models.

2.2. Problem formulation

The power generation planning is to determine on/off states of the CGs and their outputs in order to maximize the total expected profit for the PPS under several constraints. Moreover, it is necessary to calculate the optimal amounts of the procuring electricity from the MSPP owners and the selling electricity to the PEX. That is to say, the target problem has the four optimization variables. For the purpose of simplifying the target problem, the authors set the following three assumptions:

Assumption 1:

the electrical power demand of contracted customers is exactly given,

Assumption 2:

the predicted PV outputs and their historical data are given,

Assumption 3:

the electricity price is notified to the PEX in advance.

Under these assumptions, the objective function can be expressed as

$$F\left(\boldsymbol{p},\ \boldsymbol{x}, \boldsymbol{u},\ \boldsymbol{g}\right)$$

$$= \sum_{t=1}^{T} \int_{0}^{p_t^{MAX}} \left\{Receipt_t\left(x_t\right) - Payment_t\left(p_t\right) - Cost_t\left(\boldsymbol{u}_t,\ \boldsymbol{g}_t\right)\right.$$

$$\left. -Penalty_t\left(p_t,\ x_t\right)\right\} \cdot f\left(p_t^*\right)\, dp_t^*, \qquad (1)$$

$$\begin{cases} If\ \ p_t^* \le p_t' \ \ then\ \ p_t = p_t^* \\ If\ \ p_t' < p_t^* \ \ then\ \ p_t = p_t' \end{cases}, \qquad (2)$$

where T is the end time of target period; NG is the highest CG number; p_t^{MAX} is the total capacity of MSPPs; p_t is the total procurable electricity from the MSPPs assumed by the PPS; p_t' is the total requesting electricity from the PPS to the MSPPs; p_t^* is the total output of MSPPs, which is unknown at the time of making the generation plan; $f\left(p_t^*\right)$ is the probability density function of PV output; x_t is the notified selling electricity from the PPS to the PEX; $u_{i,t}$ is the state of CG i, which is an element of vector $\boldsymbol{u}_t$ and also an element of vector $\boldsymbol{u}$; $g_{i,t}$ is the output of CGs, which is an element of vector $\boldsymbol{g}_t$ and also an element of vector $\boldsymbol{g}$.

In Equation (1), each of the right-handed terms is defined as

$$Receipt_t(x_t) = DP_t \cdot D_t + XP_t \cdot x_t, \tag{3}$$

$$Payment_t(p_t) = (MSP_t - GS) \cdot p_t, \tag{4}$$

$$Cost_t(\boldsymbol{u}_t, \boldsymbol{g}_t) = \sum_{i=1}^{NG} \{Fuel(u_{i,t}, g_{i,t}) + SC_i \cdot u_{i,t} \cdot (1 - u_{i,t-\Delta t})\}, \tag{5}$$

$$\text{If } D_t + x_t - p_t < \sum_{i=1}^{NG} G_i^{MIN} \cdot u_{i,t} \text{ then}$$

$$\begin{cases} Fuel_t(\boldsymbol{u}_t, \boldsymbol{g}_t) = \sum_{i=1}^{NG} \left(A_i + B_i \cdot G_i^{MIN} + C_i \cdot G_i^{MIN^2}\right) \cdot u_{i,t}, \\ Penalty_t(p_t, x_t) = \sum_{i=1}^{NG} G_i^{MIN} \cdot u_{i,t} + p_t - (D_t + x_t) \end{cases}, \tag{6}$$

$$\text{If } \sum_{i=1}^{NG} G_i^{MIN} \cdot u_{i,t} \leq D_t + x_t - p_t \leq \sum_{i=1}^{NG} G_i^{MAX} \cdot u_{i,t} \text{ then}$$

$$\begin{cases} Fuel_t(\boldsymbol{u}_t, \boldsymbol{g}_t) = \sum_{i=1}^{NG} (A_i + B_i \cdot g_{i,t} + C_i \cdot g_{i,t}^2) \cdot u_{i,t}, \\ Penalty_t(p_t, x_t) = 0 \end{cases}, \tag{7}$$

$$\text{If } \sum_{i=1}^{NG} G_i^{MAX} \cdot u_{i,t} < D_t + x_t - p_t \text{ then}$$

$$\begin{cases} Fuel_t(\boldsymbol{u}_t, \boldsymbol{g}_t) = \sum_{i=1}^{NG} \left(A_i + B_i \cdot G_i^{MAX} + C_i \cdot G_i^{MAX^2}\right) \cdot u_{i,t} \\ Penalty_t(p_t, x_t) = VIO_t \cdot \left\{D_t + x_t - \left(\sum_{i=1}^{NG} G_i^{MAX} \cdot u_{i,t} + p_t\right)\right\} \end{cases}. \tag{8}$$

where DP_t is the selling price to the contracted customers; D_t is the sum of the contracted demand; XP_t is the selling price to the PEX; MSP_t is the purchasing price from the MSPP owners; SC_i is the startup cost of CGs; VIO_t is the imbalance penalty; GS is the subsidy from the government (subtracting avoidable cost from FIT); G_i^{MAX} and G_i^{MIN} are the maximum and the minimum CGs output; A_i, B_i and C_i are the fuel cost coefficients.

In addition, the operational constraints can be formulated as shown below:

Output constraint for CGs:

$$G_i^{MIN} \cdot u_{i,t} \leq g_{i,t} \cdot u_{i,t} \leq G_i^{MAX} \cdot u_{i,t}$$

$$(i = 1,\ 2,\ \cdots, NG,\ \ t = 1,\ 2,\ \cdots, T), \tag{9}$$

State duration constraints for CGs:

$$\begin{cases} If\ \ 0 < u_{i,t}^{ON} < MUT_i\ \ then\ \ u_{i,t} = 1 \\ If\ \ 0 < u_{i,t}^{OFF} < MDT_i\ \ then\ \ u_{i,t} = 0 \end{cases}$$

$$(i = 1,\ 2,\ \cdots, NG,\ \ t = 1,\ 2,\ \cdots, T), \tag{10}$$

Ramp rate constraint for CGs:

$$\Delta G_i^{DOWN} \leq g_{i,t} - g_{i,t-1} \leq \Delta \cdot G_i^{UP}$$

$$(i = 1,\ 2,\ \cdots, NG,\ \ t = 1,\ 2,\ \cdots, T), \tag{11}$$

where $u_{i,t}^{ON}$ and $u_{i,t}^{OFF}$ are the consecutive operating and suspending duration of CGs; MUT_i and MDT_i are the minimum operating and suspending duration of CGs; $\Delta\ G_i^{UP}$ and $\Delta\ G_i^{DOWN}$ are the ramp-up and the ramp-down of CGs.

The above optimization problem is essentially similar to the traditional unit commitment (UC) and economic load dispatching (ELD) problem.[7–10] In the traditional UC and ELD problem, the optimization variables are ***u*** and ***g*** only. On the other hand, the authors define new variables ***p*** and ***x***, and then reformulate the optimization problem. Furthermore, the operational constraints for the supply-demand balancing and the spinning reserve are integrated into the objective function. In Equation (1), these operational constraints are represented as the penalty term, $Penalty_t(p_t, x_t)$, as defined in Equations (6–8).

3. Problem solution

3.1. Outline of UC and ELD problems solution

The optimization problems formulated in Section 2.2 can be classified into two problem types according to the characteristics of CGs and the settings of time interval.[11] When all the following conditions are satisfied, we can regard the target optimization problem as a static hierarchical optimization problem:

$$\begin{gathered} \Delta\ G_i^{UP} \geq G_i^{MAX} - G_i^{MIN} \\ -\ \Delta\ G_i^{DOWN} \geq G_i^{MAX} - G_i^{MIN} \end{gathered}$$

$$(i = 1, 2, \cdots, NG), \tag{12}$$

$$\Delta\ t \geq MUT_i + MDT_i$$

$$(i = 1, 2, \cdots, NG). \tag{13}$$

This is because the optimization variables at time t ($\boldsymbol{u}_t$ and $\boldsymbol{g}_t$) are independent of their values at time

Table 1. Specification of CGs.

	Modified fuel coefficient								Ramp rate [/min]	
i	A_i[JPY]	B_i [JPY/MW]	C_i [JPY/MW^2]	SC_i[JPY]	G_i^{MAX}[MW]	G_i^{MIN}[MW]	MUT_i[min]	MDT_i[min]	Up	Down
1	14,000	7,600	120	3,000	20	4.0	10	20	0.5	1.2
2	14,000	7,600	140	3,000	20	4.0	10	20	0.5	1.2
3	2,400	5,000	250	500	12	2.4	5	10	0.8	1.0
4	2,400	5,000	280	500	12	2.4	5	10	0.8	1.0
5	2,400	5,000	260	500	12	2.4	5	10	0.8	1.0

*All values are one hundred times as those in Ref. (12);
All values are twice as those in Ref. (12).

$t-\triangle t$ ($\boldsymbol{u}_{t-\Delta t}$ and $\boldsymbol{g}_{t-\Delta t}$). However, if any one of the above conditions is not satisfied, the power management plan at time $t-\Delta t$ affects it at time t. In this case, we must handle the target problem as a dynamic optimization problem. Either way, after selecting the feasible UC candidates, the optimal outputs of CGs can be calculated by the equal incremental cost loading method.[12]

3.2. *Enumeration-based solution*

When all the conditions (12) and (13) are satisfied, the constraints (10) and (11) become inactive, and thus we can replace the target problem with a static hierarchical optimization problem as explained in Section 3.1. Under this condition, the optimal power management plan can be obtained according to the following steps. First, based on the enumeration method, all feasible on/off state combinations of CGs, $\boldsymbol{u}_t$, are picked up on each interval. Second, the variables p_t and x_t are discretized within $\left[0, p_t^{MAX}\right]$ and $\left[0, \sum_{i=1}^{NG} G_i^{MAX} + p_t - D_t\right]$ respectively, and then one (p_t, x_t) is selected. Third, the optimal outputs of CGs, $\boldsymbol{g}_t$, are calculated for all enumerated feasible UC candidates using the extended equal incremental cost loading method. For each time interval t, the optimal power generation plan, $(\boldsymbol{u}_t, \boldsymbol{g}_t)$, is determined by comparing the objective function values, each of which corresponds to each UC candidate. Fourth, steps 2 and 3 are repeated for each set of $p_t$and x_t, and then the optimal power management plan, $(p_t, x_t, \ \boldsymbol{u}_t, \boldsymbol{g}_t)$, is selected. Finally, the selected plans are combined sequentially until the end of time period. As a result, we can make the globally optimal power management plan, $(\boldsymbol{p}, \boldsymbol{x}, \boldsymbol{u}, \boldsymbol{g})$.

In contrast, if any one of the conditions is not satisfied, it is impossible to enumerate all the feasible UC candidates because the optimization variables at time t depends on them at time $t-\triangle t$. In this case, metaheuristics such as Genetic Algorithms and Particle Swarm Optimizations become one of the most efficient approaches to the dynamic optimization problem; however, the details of their applications are beyond the scope of this paper.

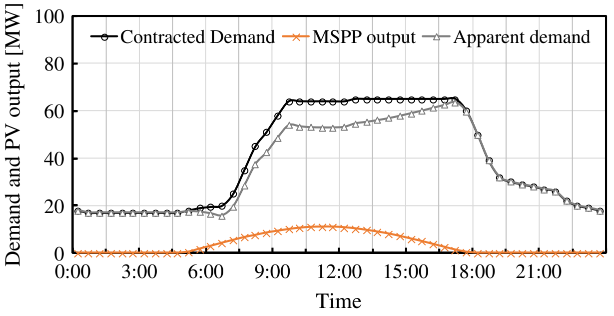

Figure 2. Example profiles of demand and MSPP output.

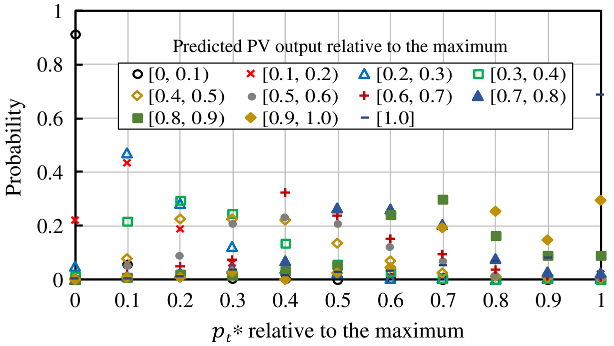

Figure 3. Probability distributions of PV output.

4. Numerical simulations

4.1. *Numerical simulation conditions*

Numerical simulations were carried out on the PPS-model 1 illustrated in Figure 1. The parameters in the PPS model were set to the following: the PPS has five CGs, the sum of their maximum output is 76.0 MW, the sum of peak demand of the contracted customers is 65.0 MW, and the maximum total output of MSPPs is 11.0 MW. The detailed specifications of each CG, which were made by referring to,[12] are summarized in Table 1. Figure 2 shows the daily profiles of the contracted demand and the sum of ideal MSPP outputs output, and Figure 3 shows conditional probability distributions of PV outputs given their predicted values. The predicted PV outputs reflect weather and time and are used here as substitutes for them. The probability distributions were made by the predicted and

Table 2. Price setting (JPY/kWh).

FIT price			32.0
Avoidable cost			10.0
Selling price to contracted customers			14.0
Imbalance penalty in surplus case			0
Imbalance penalty in shortage case	Acceptable variation (-3% or higher)		14.3
	Less than acceptable variation	Daytime in summer	48.2
		Daytime excluding summer	40.8
		Nighttime	25.2

*Daytime: From 8:00 to 22:00;
Summer: From July 1 to September 30.

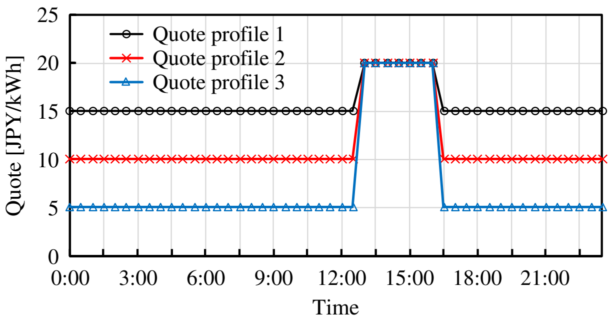

Figure 4. Quote profiles 1–3.

the actual PV outputs measured from 1 June 2011 to 31 May 2012. Table 2 summarizes the price setting.

According to the following three scenarios, the optimal power management plans were determined, and then their results were discussed.

Scenario 1:

The PPS sells only produced electricity (without MSPPs outputs).

Scenario 2:

The PPS makes power management plans with a trust in the predicted MSPP output.

Scenario 3:

The PPS makes power management plans in accordance with the authors' proposal.

In the numerical simulations, the time interval is set to 30 min (($\triangle t = 0.5$), and the target period is assumed 24 h ($t = 0, 0.5, 1.0, \cdots, 23.5$). By the setting, all the conditions (12) and (13) are satisfied. For this reason, the authors apply the enumeration-based solution to the problem, and determine the globally optimal solutions in each set of x_t and p_t.

4.2. *Example of daily planning result*

First, the authors determined the daily power management plans using three quote profiles. These quote profiles are shown in Figure 4, and their characteristics are explained below:

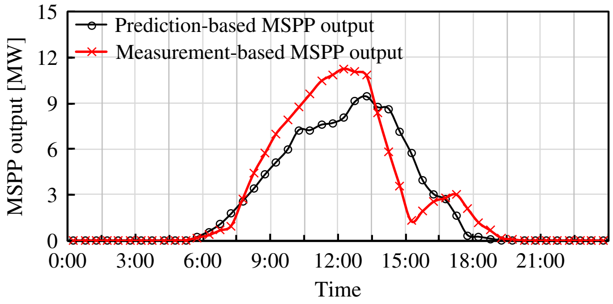

Figure 5. Daily MSPP outputs.

Quote profile 1:

The selling price is 20.0 JPY/kWh from 13:00 to 16:00 (peak period) and 15.0 JPY/kWh in the other period (off-peak period). These prices are higher than the operation cost of any CG during the period.

Quote profile 2:

The off-peak price is 10.0 JPY/kWh which is higher than the operation costs of CGs 1 and 2 (lower than those of CGs 3, 4 and 5).

Quote profile 3:

The off-peak price is 5.0 JPY/kWh which is lower than the operation cost of any CG.

The net cost that the PPS must pay when purchasing electricity from the MSPP owners, that is $(MSP_t - GS)$, is 10.0 JPY/kWh. In the authors' proposal (Scenario 3), since the PPS secures the margins to provide against the surplus or the shortage in actual operation, there is a possibility that the MSPP owners cannot sell the whole generated electricity to the PPS. Figure 5 shows the measurement-based and the prediction-based MSPP outputs on the optimization target day that is 1 June 2012. The difference between these MSPP outputs influences the power management plans on the scenarios 2 and 3.

Table 3 summarizes the calculated daily expected profits in all the quote profiles, and Figure 6 illustrates the determined power management plans in Quote profile 2. By the comparison in Table 3, we can confirm that the proposed daily plans show the best results. It is noteworthy that the daily expected profits in Scenario 3 are higher than those in Scenario 2 in spite of notifying less amount of the selling electricity. As for Figure 6, there are differences in both the produced electricity and the purchased one between the optimal plans in the scenarios 2 and 3, especially from 7:00 to 16:00. In particular, the PPS did not purchase electricity from MSPPs until 13:00 in Scenario 3. This is because the electricity price in the PEX is too low for the PPS to take risk of purchasing MSPP power. Moreover, since the imbalance penalty in the shortage is serious as shown in Table 2, the reserve margins were secured in Figure 6 (c) to cope with likely supply shortage from 13:00 to 16:00. In other words, the

Table 3. Results of daily calculation in each scenario.

		Daily expected profit [JPY]	Daily selling electricity to PEX [MWh]	Daily purchasing electricity from MSPP owner [MWh]
Scenario 1	Quote profile 1	8,892,357	879.0	0
	Quote profile 2	5,410,622	138.5	0
	Quote profile 3	5,317,500	33.0	0
Scenario 2	Quote profile 1	8,926,957	930.5	51.5
	Quote profile 2	5,425,671	174.5	51.5
	Quote profile 3	5,269,938	61.5	51.5
Scenario 3(proposed)	Quote profile 1	9,050,792	913.5	48.5
	Quote profile 2	5,501,904	151.5	20.0
	Quote profile 3	5,408,780	46.0	20.0

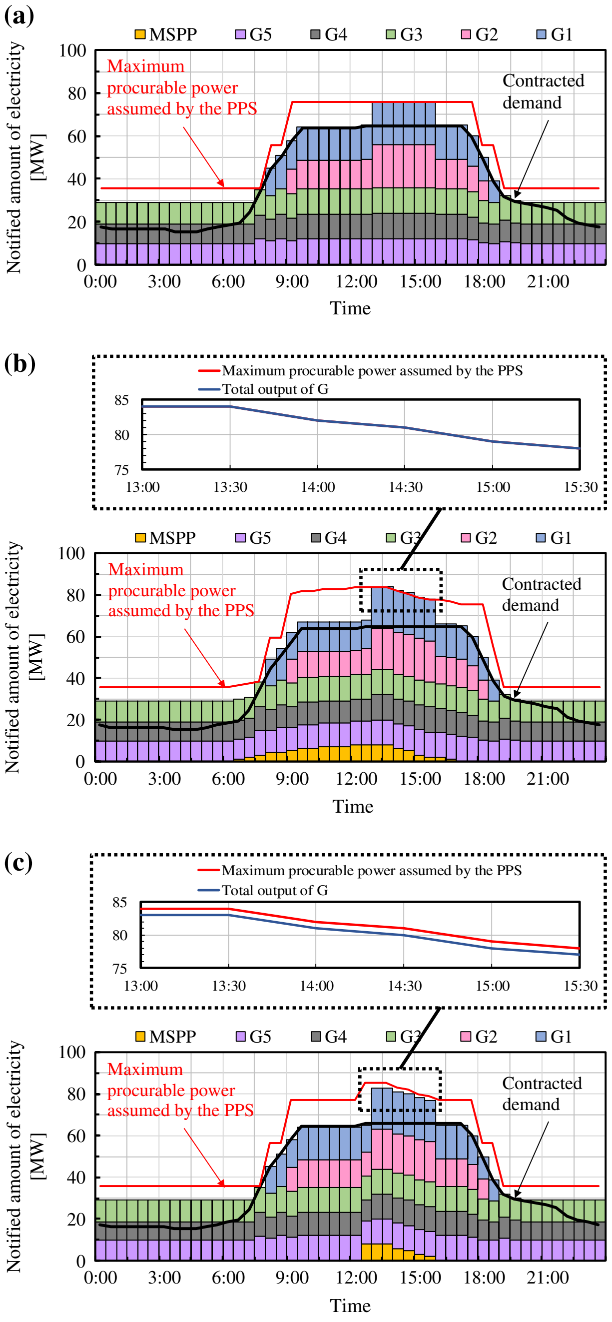

Figure 6. Determined optimal power management plans.

Notes: (a) Power management plan in Scenario 1, (b) Power management plan in Scenario 2, (c) Power generation in Scenario 3 (proposed).

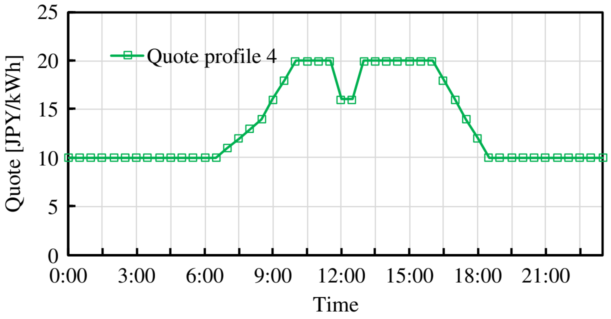

Figure 7. Quote profile 4.

PPS takes over a part of responsibility for keeping the supply-demand balance under the uncertain PV output prediction. As a result, the actual shortage in Scenario 3, which was calculated by using the measured PV outputs, decreased 6.3 MW in comparison with that of Scenario 2 (Scenario 2: 15.2 MW, Scnario3: 8.9 MW). Therefore, we can conclude that the authors' proposal was functioning appropriately.

4.3. *Result of eleven months planning*

Next, long-term expected profits were calculated using the PV data measured from 1 June 2012 to 30 April 2013 under the same scenarios and quote profiles. In the long-term numerical simulations, another daily quote profile is newly added as Quote profile 4, and the additional quote profile in the PEX is shown in Figure 7. The quote profiles and the contracted demand were used repeatedly during the target period. The authors assume that the PPS purchases electricity at 33.0 JPY/kWh, which is higher price than the FIT price shown in Table 2 (FIT price: 32.0 JPY/kWh), from the MSPP owners. Owing to this assumption, the MSPP owners also make an extra profit when the PPS purchases their electricity.

The calculated total amounts of expected profit and penalty are shown in Table 4. In addition, an example of determined power management plans in Quote profile 4 are summarized in Figure 8. In Table 4, the expected profits in the proposed plan (Scenario 3) is highest in all

Table 4. Comparison of total amount of expected profits in each scenario.

		Total amount of expected profit for PPS [JPY]	Total amount of expected payment to MSPP owners [JPY]	Total amount of expected penalty [JPY]
Scenario 1	Quote profile 1	2,961 million	0	0
	Quote profile 2	1,802 million	0	0
	Quote profile 3	1,771 million	0	0
	Quote profile 4	1,979 million	0	0
Scenario 2	Quote profile 1	2,966 million	133 million	110 million
	Quote profile 2	1,804 million	133 million	38 million
	Quote profile 3	1,754 million	133 million	41 million
	Quote profile 4	1,998 million	146 million	103 million
Scenario 3(proposed)	Quote profile 1	3,008 million	124 million	18 million
	Quote profile 2	1,828 million	66 million	9 million
	Quote profile 3	1,797 million	66 million	9 million
	Quote profile 4	2,035 million	130 million	20 million

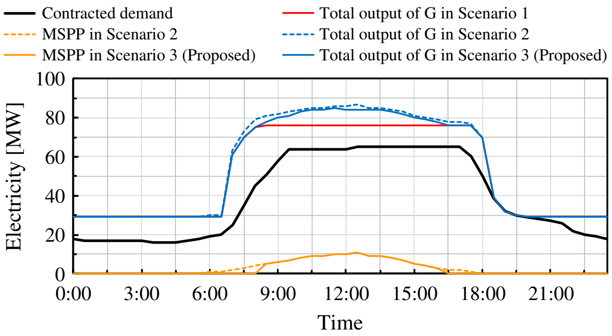

Figure 8. Optimal power management plans on 4 July 2012.

scenarios. Moreover, both expected profits in the scenarios 2 and 3 exceed that of Scenario 1. By the comparison, the authors conclude that the proposed framework is useful not only for the PPS but also the MSPP owners who sell electricity to the PPS. This is because there is a possibility that the PPS purchases electricity in higher price from the MSPP owners using the additional profit.

These verification results show that the authors' proposal is functioning well to achieve a profitable and stable power management which provides both the better selling profit to the PPS and the MSPP owners, and the reduction of difficulties in the supply-demand balancing operation for the main power grids.

5. Conclusions

In this paper, the authors proposed a problem framework and its solution to make a profitable and stable power management plan of PPSs in cooperation with MSPPs. As the results of the numerical simulations, the proposed problem framework and its solution were functioning very well. Moreover, the profitable cooperation between the PPSs and the MSPPs provided not only the better selling profit to the PPSs and the MSPP owners, but also the reduction in operational difficulties for the main power grids. For these reasons, we can conclude that the profitable cooperation will become one of the most efficient operations utilizing massive PVs with few adverse effects for the main grids' operation.

In future work, with a view to discovering the further profitable cooperation, the authors consider to optimize the electricity trade between PPSs and MSPP owners.

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Notes on contributors

Hirotaka Takano received his master's and the doctor of engineering degrees from University of Fukui, Japan, in 2003 and 2006, respectively. He then became an assistant at Department of Electrical and Computer Engineering, Gifu National College of Technology from 2006 to 2011, and an assistant professor at Faculty of Information Science and Electrical Engineering, Kyushu University from 2011 to 2015. He is now a senior assistant professor at Faculty of Engineering, University of Fukui. His research interests are in advanced operation and planning of electric power systems, and optimization applications.

Yuya Nagaki received his MS degree from Kyushu University, Japan, in 2015. He then joined Chubu Electric Power Co., Inc.

Junichi Murata received his master's and the doctor of engineering degrees from Kyushu University, Japan, in 1983 and 1986, respectively. He then became a research associate and now is a professor at the Faculty of Information Science and Electrical Engineering, Kyushu University. His current research interests are in learning systems, optimization techniques and their applications especially in energy management systems.

Tatsuya Iizaka received his MS degree from Saitama University, Japan, in 1994. He then joined Fuji Electric Co., Ltd. He holds the PhD degree. His research interests are intelligent systems application and power supply-demand control systems.

Naoto Ishibashi received his MS degree from Meiji University, Japan, in 2011. He then joined Fuji Electric Co., Ltd. His research interest is intelligent systems application.

Tohru Katsuno received his MS degree from Meiji University, Japan, in 1990. He then joined Fuji Electric Co., Ltd. His research interests are analysis and control in electric power systems.

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