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Advantage of a Home Energy Management System for PV Utilization Connected to Grid

Akira Yoshida [a,f]***, Shinya Yoshizawa*** [b,f]***, Yu Fujimoto*** [c,f]***, Noboru Murata*** [b,f]***, Shinji Wakao*** [b,f]***, Shin-ichi Tanabe*** [d,f]***, Yasuhiro Hayashi*** [b,f] ***and Yoshiharu Amano*** [e,f]

a Department of Applied Mechanics and Aerospace Engineering, Waseda University, 1-4-3 Okubo, Shinjuku, 169-8555, Tokyo, Japan. a.yoshida@aoni.waseda.jp
b Department of Electrical Engineering and Bioscience, Waseda University, Japan. shin-yosi@fuji.waseda.jp, noboru.murata@eb.waseda.ac.jp, wakao@waseda.jp, hayashi@waseda.jp
c Institute for Nanoscience and Nanotechnology, Waseda University, Japan. y.fujimoto@aoni.waseda.jp
d Department of Architecture, Waseda University, Japan. tanabe@waseda.jp
e Research Institute for Science and Engineering, Waseda University, 17 Kikui-cho, Shinjuku, 162-0044,Tokyo, Japan. yoshiha@waseda.jp
f CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi-shi, 332-0012, Saitama, Japan

Abstract:

Residential houses are in the process of introducing power generators such as photovoltaic (PV) power generators and fuel cell cogeneration systems. Under current laws in Japan, surplus electricity from a residential PV system can be sold by feeding it back into the electrical grid. However, when a lot of neighboring power generators make and feed back electricity at the same time, there is an issue of an upper voltage violation of the provisions of the laws and regulations relating to the Electricity Business Act in the distribution system of the electrical grid. The issue has been solved by stopping power generators when they reach an upper voltage limit, 107V. Another solution is to acknowledge demand response signal from electrical grid operator to store electricity in residential batteries using Home Energy Management System (HEMS). The research question is that how to collaborate HEMS and Grid Energy Management System (GEMS). This paper developed an evaluation framework for the cooperative behavior between HEMS and GEMS. Using this evaluation framework, this paper demonstrated the optimal operational strategy of HEMS including PV in the case that HEMS is informed voltage profile from GEMS, and also assessed amount of PV suppression quantitatively in residential sector in practical aspect.

Keywords:

HEMS, PV, Electrical Battery, Distribution System, Voltage Violation.

1. Introduction

Power generators such as photovoltaic (PV) power generators and fuel cell cogeneration systems (FC-CGS) have recently been available for residential application. Under current laws in Japan, PV power generators are able to sell surplus electricity by feeding it back into the electrical grid [1]. Smart meters which include communication functions have also been introduced to residential applications. Smart meters can be utilized for making a demand-response scheme which is able to change electric power rates half-hourly as demand-side management. A smart meter receives a demand response (DR) signal from the grid operator for power supply-demand rationalization [2]. It is expected that residential energy systems can save electricity using this communication of the smart meter. However, nowadays, householders are required to respond manually by turning off home electronics to DR signal when they are informed of DR signal from smart meter. Furthermore, residential energy systems, such as FC-CGS, PV power generators, and batteries (BT), are operated independently. Therefore, one issue concerning energy rational use in the residential sector is that there is variation in the responsiveness to a DR signal. A Home Energy Management System (HEMS), which manages all the residential energy equipment in order to achieve whole optimized operation of the equipment as a whole, has been proposed as one solution to the DR-signal-responsiveness issue [3]. A planning algorithm is needed which achieves fully optimized operation of all the equipment in a house while considering the uncertainty of future demand, in order to fulfill an EMS role. In other words, one of the technical issues is to develop the HEMS operating technique based on predicted information concerning future events. The current state of the HEMS is only able to confirm energy usage in one house. There is room to develop the HEMS functions that are required to enable the overall optimized operation of residential energy systems. Smart house's scheduling problem for HEMS is solved using particle swarm optimization by Pedrasa et. al [4]. Tascikaraoglu reported an experimental smart home with various renewable energy sources and storage systems [5]. In its paper, power forecasting of wind turbine and PV is predicted by artificial neural network-based approach. Amjad investigated HEMS including electric vehicle (EV) and micro-combined heat and power generation unit for improving that efficiency using mixed integer nonlinear programming (MINLP) [6]. Many researchers investigated unit sizing and operational planning problem of energy system using MINLP technique, for example, Yokoyama et. al. addressed cooperation between distributed power source and power grid through time-of-use (TOU) pricing[7]. Moreover Gamou et. al. also formulated unit sizing problem of cogeneration system in consideration of uncertain energy demand using MINLP [8]. In Japanese context, Kawashima investigated Building Energy Management System (BEMS) which coordinates some HEMS including EV at the viewpoint of mixed logical dynamic system [9]. BEMS is also reported by Kim [10] and Missaoui [11].

The issue of upper voltage violation of the grid under the provisions of laws and regulations relating to the Electricity Business Act occurs grid when a lot of neighboring power generators produce and feed electricity back to the grid [12]. Here, in this study, *distribution system* represents electrical distributed power grid, which is composed of electric power substation, pole transformer, low- and high-voltage power distribution line and pole air switch. The issue is expected to be solved by controlling the distribution system with a Grid Energy Management System (GEMS) [13]. As a matter of fact, the issue has been solved by suppressing the output of PV power generators with residential power conditioning systems (PCS) when reaching an upper voltage of 107 V. In a research field of microgrid, stochastic programming (SP) framework have been developed in order to compensate output fluctuation of renewable energy source. Niknam developed improved teaching-learning-based optimization method for stochastic multi-objective optimal micro-grid operation by considering uncertainties including wind turbine and PV units power output, load demand, and market price over the 24 h study horizon [14]. Liang described survey for a stochastic modeling and optimization in a microgrid [15].

The residential energy systems and the distribution system have been evaluated individually, and each has its suitable evaluation method. However, the operational results of HEMS and GEMS influence each other, especially in the case of including distributed power sources in the distribution system of the electrical grid, because these systems are connected electrically to each other. Therefore, establishment of an evaluation method for the system, which is connected to both the residential energy and distribution systems, is expected to contribute to the design of the next generation energy system including distributed power sources such. Of course, the evaluation of the electric grid has given consideration to the load characteristics of each customer; on the other hand, the evaluation of residential energy system has not given consideration to grid characteristics. Here, we have aimed at establishing a method of evaluating a residential energy system having a power generator with the goal of designing the next generation system. Our main research question is how to foster collaboration between HEMS and GEMS. As a first step towards answering this question, we do a basic examination of the evaluation method of a HEMS scheme which is connected to the distribution system. One of the objective is to assess amount of PV suppression quantitatively in residential sector in practical aspect. Another objective is to reveal how change in HEMS behavior in the case of confirming voltage profile. In addition, the proposed HEMS evaluation scheme is expanded from the HEMS method described in another paper we have submitted to this conference, titled “Economic evaluations of residential energy systems based on prediction-operational planning-control method under time-of-use prices” submitted to this conference.

2. HEMS scheme with grid information

This section describes the HEMS method including forecast, power flow calculation, and the scheme connecting both methods. Figure 1 shows the research framework of this study. In Fig. 1, there are two arrowed lines. The bottom one shows the proposed HEMS evaluation scheme, which plans an operational strategy based on grid information derived from a power flow calculation. The top arrow is the reference HEMS method, which plans an operational strategy without grid information. Each method is composed of like a function block in MATLAB/Simulink, and, this approach makes it easy for us to solve the operational planning problem under uncertainty without solving a stochastic differential equation.

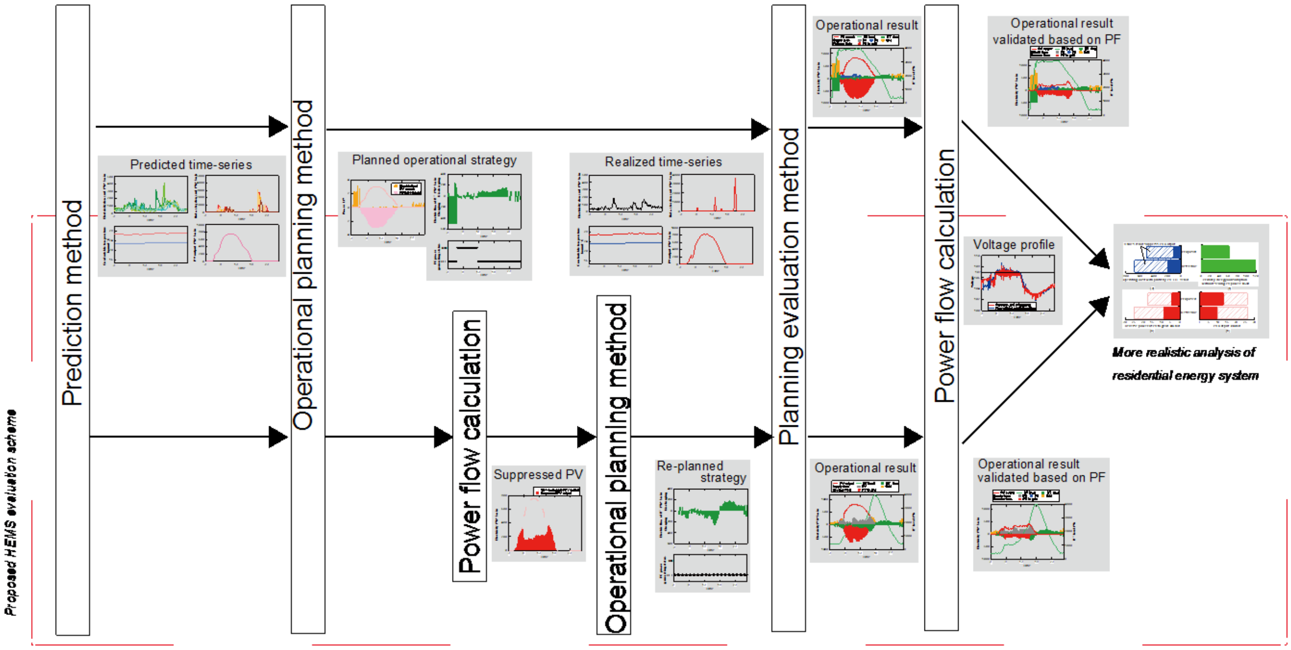


Fig. 1. Framework of this study and proposed HEMS evaluation scheme.

2.1. Prediction - Operational planning - Planning evaluation on HEMS

The proposed HEMS scheme evaluates the plan, which is derived from an optimal operational planning problem under uncertainties of future events, namely the energy demand and PV output for the next day. It is difficult to predict residential energy demand with high accuracy because the demand has large fluctuations with both long- and short-term trends. In order to predict energy-demand time series for the next day, the next day's demand time series is assumed to be similar to the time series that have occurred in the past. The distance structures of energy demand and PV output are measured by regression based Metric Learning in this context [16]. Firstly, at the prediction step, the next day's energy demands and PV output are obtained from the database-defined distance structures mentioned above using a Just-In-Time (JIT) modeling technique which is known to be a practical prediction method [17]. Next, at the operational step, the predicted energy demands and PV output are input as exogenous variables into an optimal operational planning problem, and then, the operational strategy is decided in terms of minimizing the householder's expense. Finally, at the planning evaluation step, the daily operational performance is evaluated based on the system operation with the planned operational strategy and the actual energy demand and PV output. In other words, the proposed HEMS method makes *ex-ante* decisions representing the operational strategy of the energy system, and then, does an *ex-post* evaluation of the system's actual performance when the energy system operates in accordance with the operational strategy.

2.1.1. Just-in-timing modeling for predicting residential energy and PV data

We first made a database composed of electricity and domestic hot water (DHW) demand and climate conditions in each household, and then developed forecast system, which utilizes JIT modeling. This system extracts some similar cases, which are represented the forecast of the next day, from input of electricity and DHW demand and climate conditions on previous day. What is forecast problem is to forecast future energy demand and PV output from input of history of energy demand, PV output and climate conditions. Traditional forecast model uses linear regression against this problem. Operational planning based on forecast energy demand derived from the traditional forecast model might be fragile, because traditional forecast model has an issue that the model is not able to consider energy demand's diversity caused by human activity. Forecast system which is able to output some forecasted scenarios is effective, in order to operate robustly against forecast error. At the forecasting energy demand for PEFC-CGS, we adapted JIT model utilizing k-nearest neighbor method which is able to extract some candidates of realistic forecasting time series, to make a forecast system. The JIT model outputs some candidates of time series forecasting by using similarity measure between data in database and input data obtained at that time.

2.1.2. Stochastic optimal operational planning problem

Figure 2 shows a schematic diagram of the energy system which consists of a PEFC-CGS, a PV power generation system, a BT, a PCS, a room air conditioner (AC), automatic window (AW), thermal insulation automatic blind (TB), and sunlight shielding automatic blind (SB).

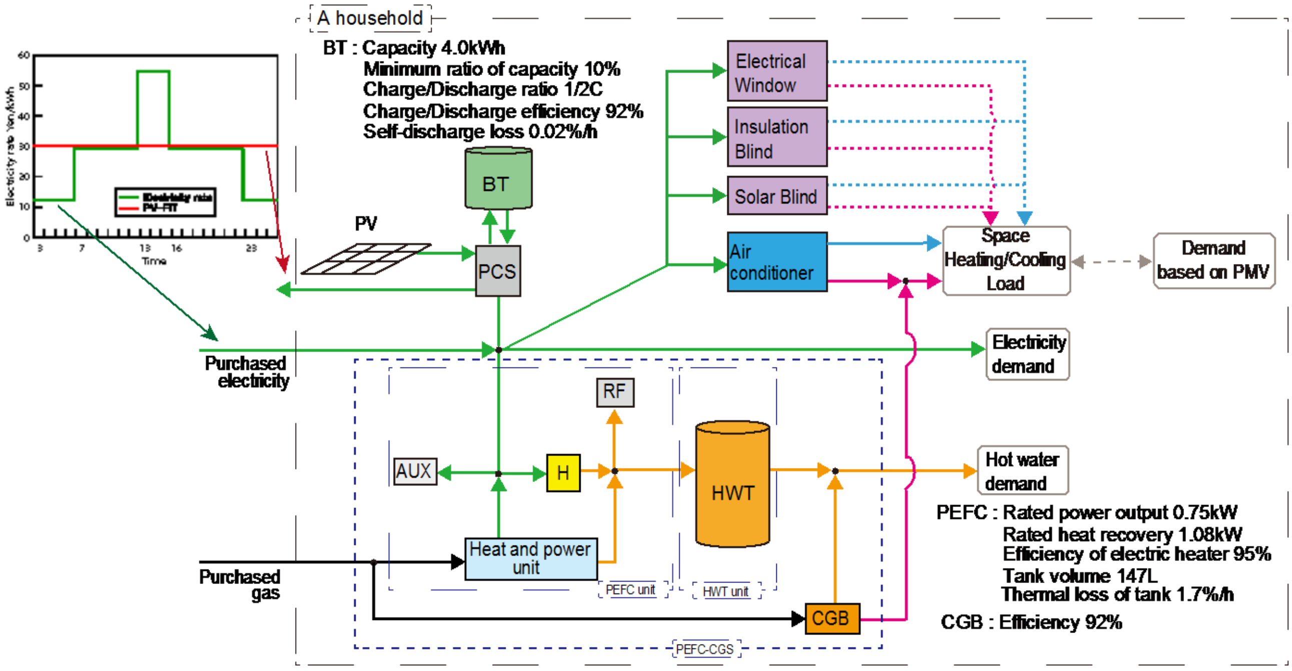


Fig. 2. Schematic diagram of residential energy system.

Operational planning problem of residential energy system is formulated by SP technique. Stochastic operational planning problem cannot be calculated in an unchanged form because future energy demand is represented by stochastic variables. In SP framework, there are two main types of deterministic equivalent problems, which are directly calculable. One approach is known as "wait-and-see", where a decision is made based on perfect information about the future prospect. Altogether, the wait-and-see problem is given one energy demand scenarios, and shows the best performance of the system. The other approach is "here-and-now", which makes a decision before the stochastic variables are realized. The here-and-now problem is known as a scenario-based SP problem. A scenario-based SP problem which is formulated by Mixed Integer Linear Programming

(MILP), is given some scenarios as parameters; some scenarios discretize the forecasted probability space. The reality is that we cannot get perfect information on future energy demand. Hence, a decision based on one scenario of future energy demand and PV output might be not robust. The one of aims of proposed method using SP framework is to make robust and rational decisions based on some forecasted scenarios. Here-and-now problem is generally formulated as follow:

$$\min \bar{J} = E[\boldsymbol{c}^{\top}(\omega)\boldsymbol{x}] \tag{1}$$

$$\mathrm{s.t.}\, \mathbf{A}(\omega)\boldsymbol{x} \geq \boldsymbol{b}(\omega) \tag{2}$$

where $\omega = 1, \ldots, \Omega$ indexes a set of scenarios. This approach regards parameters as stochastic variables.

In the operational planning problem, the evaluation period is 24 hours long, starting from 3:00 am, and is divided into intervals of T. The sampling period represents $\delta t = 24/T$. The constraint equations in the optimization problem are the energy and mass balances represented by continuous variables, and the device states represented by binary variables. As shown in the equation below, the stochastic optimal operational planning problem, with exogenous input variables, minimizes the expected operational costs as an objective function. The exogenous variables are PV output and energy-demand patterns having probability P. Additionally, when deciding the operation of the system for the next day, we add constraints for the BT I/O flow rate and the FC status for each scenario in each sampling period [18].

$$\bar{J} = \frac{\left(\sum_{\omega=1}^{\Omega} P_{\omega} \sum_{t=1}^{T}\left(C_t^{\mathrm{e}} e_{t,\omega}^{\mathrm{buy}} + C^{\mathrm{g}} g_{t,\omega}^{\mathrm{buy}} - C^{\mathrm{PV}} e_{t,\omega}^{\mathrm{r}}\right)\right)}{\Omega} \tag{3}$$

where J, C, e, g, and Ω are the objective function, the cost conversion factor, electricity, gas consumption, and the number of predicted scenarios, respectively. In (3), the indexes t and ω repserent time and scenario respectively, and the superscripts e, buy, g, PV, and r refer to electricity, purchased from the grid, gas consumption, PV, and electricity sold to the grid, respectively.

2.1.3. Planning evaluation against realized value

This step evaluates the planning derived by operational planning problem using the predicted energy and PV patterns as constrained conditions. As shown in the equation below, the operational performance is evaluated with real values of energy demand and PV output while minimizing operational cost for each sampling period from 3:00 a.m. on one day to 3:00 a.m. the following day.

$$\sum_{t=1}^{T}\left[\min\left(C_t^{\mathrm{e}} e_t^{\mathrm{buy}} + C^{\mathrm{g}} g_t^{\mathrm{buy}} - C^{\mathrm{PV}} e_t^{\mathrm{r}}\right)\right] \tag{4}$$

Because the operational step has already decided the operational strategies, namely, the PEFC power generating status and the upper limit of electric flow at the BT in each sampling period, the planning evaluation step controls the electric flow of the PEFC and the BT, and also controls the energy supply for room heating/cooling using the AC etc., in each sampling period.

2.2. Power flow calculation for radial distribution system

Figure 3 shows a flowchart of the power flow calculation. This calculation requires three types of input data. The first is the grid configuration, which represents the connections between power generators, electric transformers and the electric feeder line. The second is the equipment parameters such as the impedance of the electric feeder line. The last is the operational conditions, which are the electric load on each node and the generating power of the distributed power source, as constraint conditions. The electric load and reverse power of the operational conditions are calculated by the stochastic optimal operational planning problem described above.

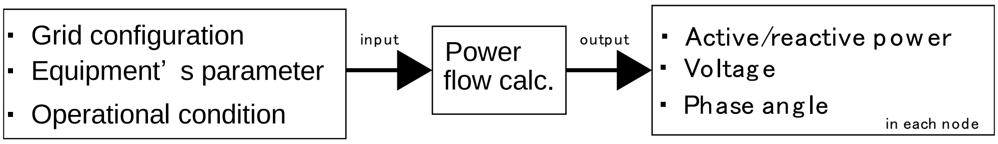


Fig. 3. Flowchart of power flow calculation.

As shown by the equations below, the power flow of the distribution system is calculated by solving the power equation using convergent calculations:

$$P_{PV_i} - P_{L_i} - V_i \sum_{k=1}^{n} V_k [G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k)] = 0 \quad (5)$$

$$Q_{PV_i} - Q_{L_i} - V_i \sum_{k=1}^{n} V_k [G_{ik} \sin(\theta_i - \theta_k) - B_{ik} \cos(\theta_i - \theta_k)] = 0 \quad (6)$$

where P and Q are the active and reactive power respectively, and G and B are the conductance and susceptance respectively. In (5) and (6), i and k are the indexes of nodes, the subscripts PV and L represent the PV and electric loads, respectively, and n, V and θ are the number of nodes, the voltage, and the phase angle, respectively [19].

The Japanese distribution system is a radial one. In order to easily solve the above non-linear multidimensional equation, a method using the characteristics of a radial distribution system is proposed [20][21]. This study uses a backward-forward sweep method to get the optimal solution with fast convergence. The backward-forward sweep method does convergent calculations composed of forward and backward sweeps. With a given initial value, the forward sweep calculates physical amounts, e.g., the current, voltage, phase angle, and active and reactive power, from the distribution substation toward the terminal nodes. On the other hand, the backward sweep calculates the physical amounts from the terminal nodes toward the distribution substation. The sampling interval of the power flow calculation is set at ten seconds. As described above in this study, three-phase power-flow calculation does easily power flow calculation algebraically by making use of characteristics of radial distribution system, without solving non-linear multidimensional equation for bulk power system.

2.3. Operational planning based on grid information

As shown in Fig. 1, the power flow calculation evaluates the operational strategy, which is derived at the operational planning step by the HEMS, with a view to grid constraints such as voltage. The two of input parameters of the power flow calculation are the PV output and the electric load time series of the house, which are derived by the HEMS. The power flow calculation derives the analog values of the nodes, which represent the receiving ends of residential houses. The values are pointed voltage, angle phase, and active and reactive power. In the power flow calculation, the PCS of the house suppresses the PV output when the receiving end voltage of the house is over 107 V.

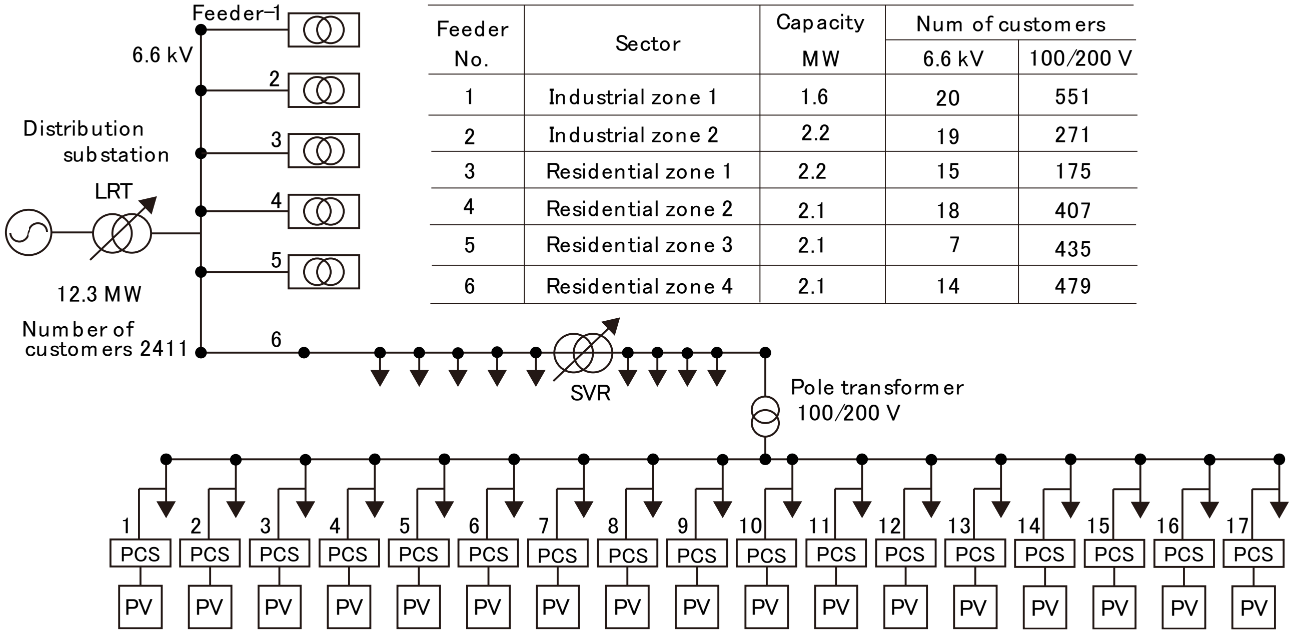
3. Conditions of numerical analysis

This section describes conditions preceding the numerical analysis in the next section.

3.1. Specifications of distribution system

The detailed model of the electrical distribution system is based on the actual electrical grid and consists of the distribution substation, and industrial and residential zones. Figure 4 shows the model of the above distribution system; the numerical analysis in the next section focuses on the 6th feeder.

The Load-Ratio control Transformer (LRT) and Step Voltage Regulator (SVR) have the voltage-booster functions, which controls the tap ratio, in order to maintain proper voltage. If the LRT and SVR are changing tap ratios to suit the electric load, voltage regulation is always able to maintain the proper voltage. However, in actual operation, the tap ratio is changed only a few times per day because the mechanical switches wear with every use. Therefore, voltage violation may occur depending on the grid configuration, including the electrical load and reverse power of the PV system. In this study, the operational parameters of the LRT and SVR, which are integer values determining tap ratios, are set at points during light load periods in the actual distribution system. Operational set points of the pole transformer in the distribution system are fixed and are not changed. Assumed 2030's Japanese situation, all buildings already have installed PV and PCS systems, and the PV data is taken from measured values in the Kanto region of Japan. The assumption, where all buildings have their own PVs, represents a future scenario, as PV systems are installed on almost all newly built houses over the coming decade. As a matter of course, deciding suitable operational parameters for the LRT and SVR based on predicted electrical load including reverse power from the PV leads to a decrease in the suppression of PV output. However, that is beyond the scope of this paper.



Feeder No.	Sector	Capacity MW	Num of customers	
			6.6 kV	100/200 V
1	Industrial zone 1	1.6	20	551
2	Industrial zone 2	2.2	19	271
3	Residential zone 1	2.2	15	175
4	Residential zone 2	2.1	18	407
5	Residential zone 3	2.1	7	435
6	Residential zone 4	2.1	14	479

Fig. 4. Radial distribution system with 1 bank and 6 feeders.

PCS introducing along with PV has the suppression function of PV output. The suppression function assumes to suppress active power with a constant speed in the case that PCS detects voltage violation in each house.

3.2. Specifications of HEMS

This section describes the parameters of the residential energy system and of the economic factors. The main system parameters are shown in Fig. 2 [22]. A residential house with the HEMS is set at No.15 in Fig. 4. As shown in Fig. 2, a TOU rate is chosen as the electric power price of this problem, and the feed-in-tariff (FIT) of the PV and the other power generator is 30 yen/kWh [1]. Figures 5 and 6 show four kinds of the predicted and realized time series. The numerical analysis targets one day in May as a period of light load on the electrical grid. As expected, predicted energy demands are not exactly the same as realized value. However, peak time and level of the energy demands are almost accurately-predicted.

4. Numerical analysis

This section analyses the effect of collaboration between the HEMS and the distribution system. The targeted day in May has the most voltage violation of the year, because the period of light load overlaps the period when the PV generates a lot of electricity. The operational planning problem of the residential energy system is implemented by AMPL, and is solved by Gurobi version 6.0. The others of proposed mathematical models are implemented and are solved by MATLAB.

4.1. Optimal operational strategy with/without grid information

Figures 7 and 8 are the FC status generating power and electric flow of the BT, respectively. Figures 7 (a) and 8 (a) show the situations of stopping the FC power generation, and of charging to the BT from the PV because the HEMS is informed that the PCS must suppress PV output. Figure 9 shows the operational results with actual values. Figures 10 (a) and (b) show the operational results considering grid constraints. The comparison between Figures 9 and 10 confirms that the HEMS needs the power flow calculation results. The comparison between Figure 10 (a) and (b) shows that using the grid information at the operational planning step enhances the usefulness of the proposed HEMS scheme. It is suggested that the operational strategy, which uses BT for storing PV power, is effective ways for mitigation of PV suppression in light load period. Figure 11 shows voltage profile at the receiving end of targeted household. Reaching upper voltage, 107 V, is confirmed by this figure in spite of self-consumption of PV output. In other words, operational strategy's change of PCS at one household has limited effectiveness against mitigation of voltage violation for electrical grid because neighboring PV units are feeding back lots of electricity into electrical grid still. Therefore, it is suggested that coordinative behavior of neighboring HEMSs might be effective for voltage violation for electrical grid caused by residential PV output.

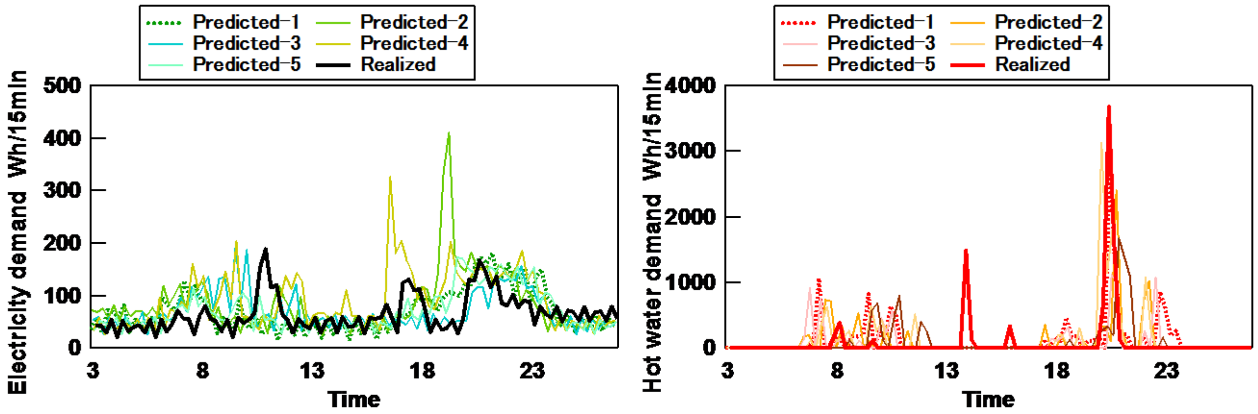


Fig. 5. Predicted and realized time series, (left) electricity demand, (right) DHW demand.

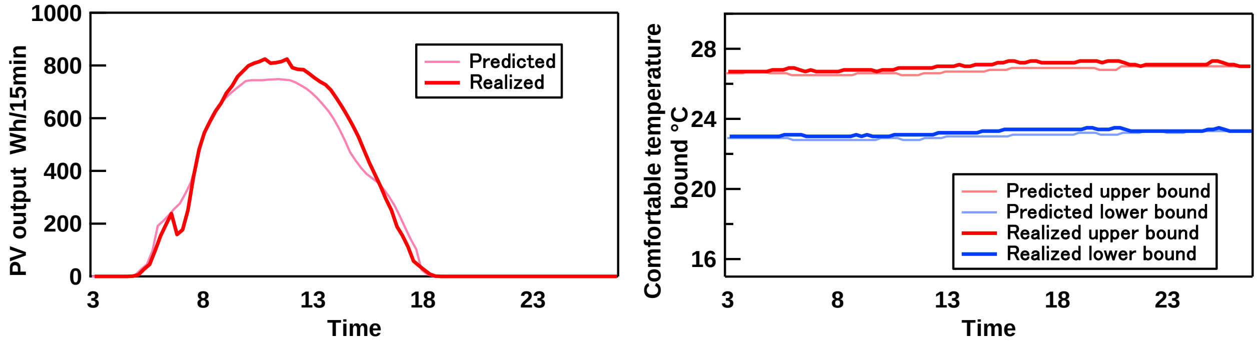


Fig. 6. Predicted and realized time series, (left) PV output, (right) comfortable temperature bound.

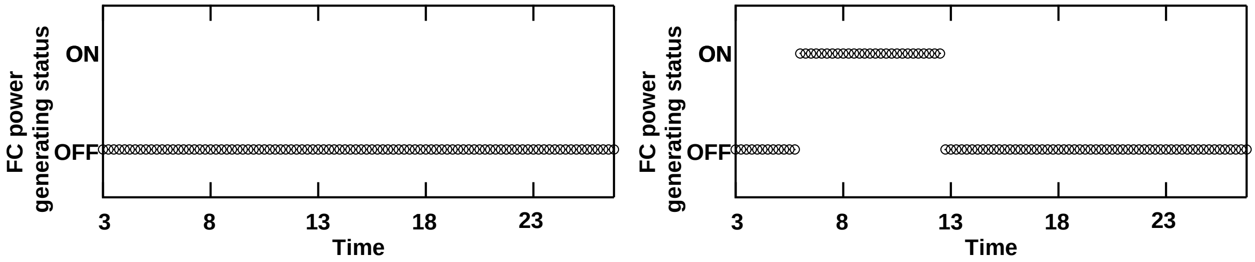


Fig. 7. Operational strategies of FC statuses, (left) with grid information, (right) without grid information.

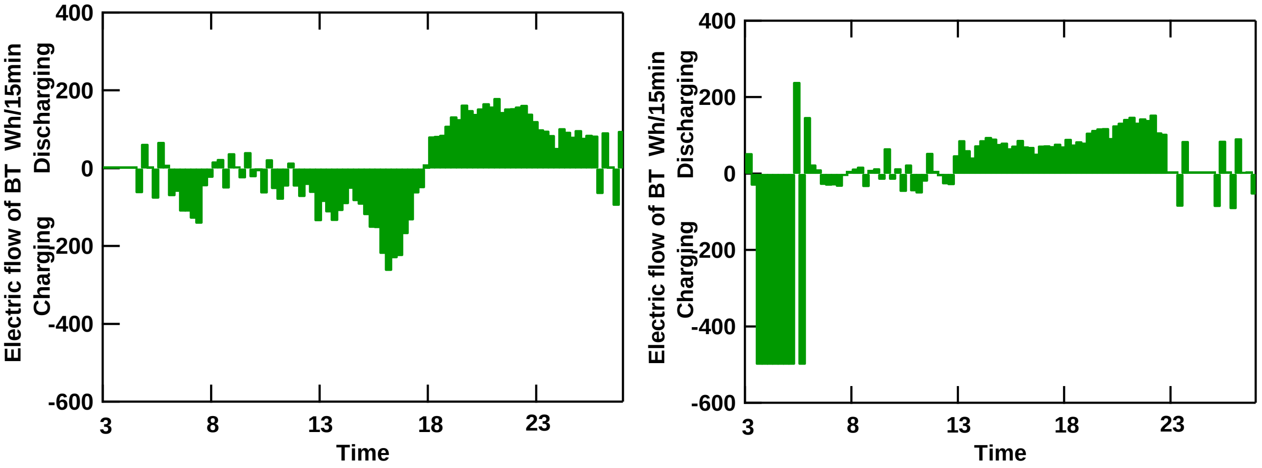


Fig. 8. Operational strategies of BT flows, (left) with grid information, (right) without grid information.

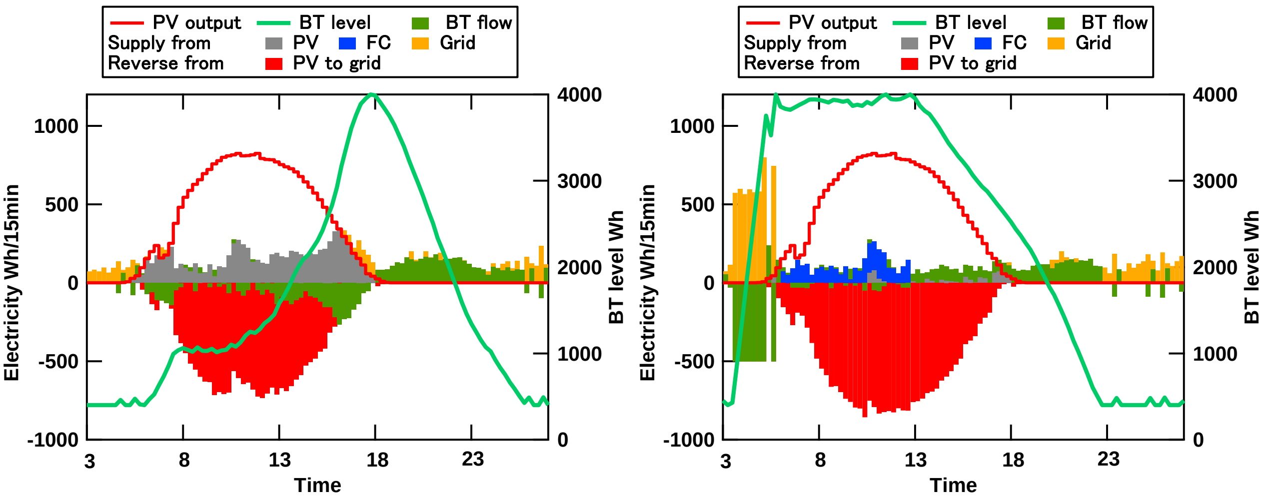


Fig. 9. Operational results, (left) with grid information, (right) without grid information.

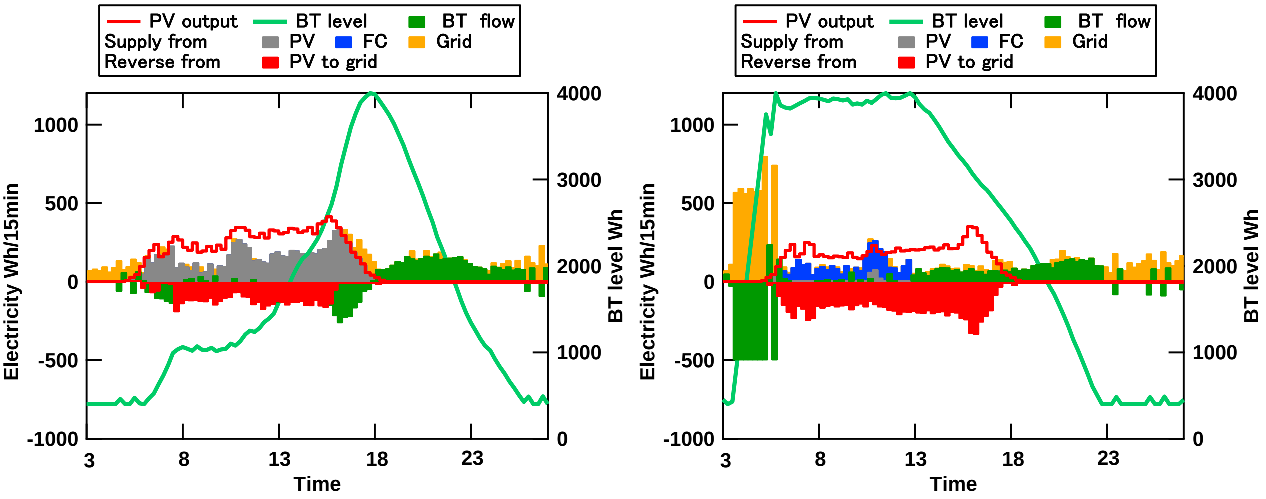


Fig. 10. Operational results validated based on power flow calculation at viewpoint of voltage profile, (left) with grid information, (right) without grid information.

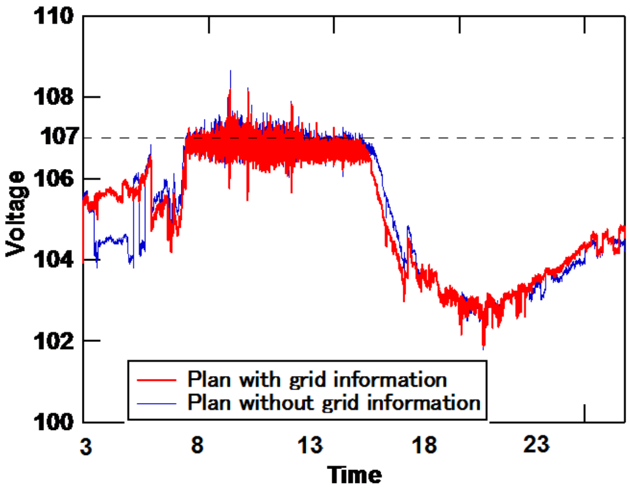


Fig. 11. Voltage profile of one day at receiving end of targeted household.

4.2. Energy and economic performances validate based on power flow calculation

Figure 12 shows the daily values of the two schemes, with and without gird information, at the planning stage, and the details are shown in Table 1.

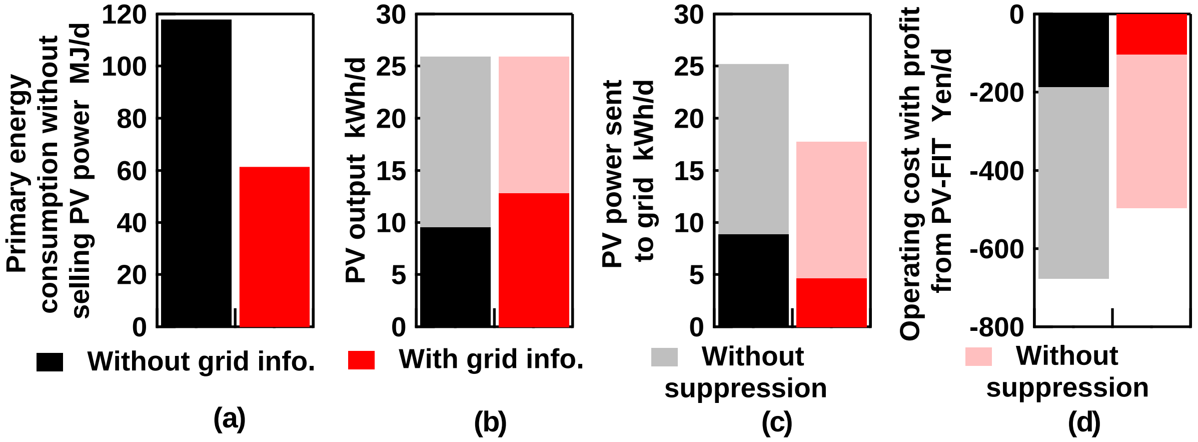


Fig. 12. Daily operational performances validated based on power flow calculation at viewpoint of voltage profile, (a) primary energy consumption, (b) PV output, (c) reverse power, (d) operating cost.

Table 1. Operational performance of HEMS with/without grid information

Connection	Suppression	Primary energy consumption MJ/d	PV output kWh/d	Reverse power kWh/d	Operating cost Yen/d	PV suppression kWh/d	Gas consumption Nm^3/d	Purchased electricity kWh/d
With grid	Before After	61.41	25.95 12.85	17.77 4.67	-495.47 -102.47	13.10	0.84	2.48
Without grid	Before After	118.03	25.95 9.59	25.24 8.88	-676.76 -185.96	16.36	1.10	7.20

As shown in Fig. 12, reversing the PV output at a maximum without communication with the grid may result in a loss of PV output. The PV output at the planning step is suppressed 13 kWh/d with grid information and 16 kWh/d without grid information, and these are 13/26≈50 %, and 16/26≈62%, respectively. This result shows that the proposed HEMS scheme can reduce the opportunity loss of PV output when using PV power at the house. In other words, the HEMS can decrease suppression of PV output 16.4-13.1=3.3 kWh/d, and the collaboration of HEMS and GEMS is expected to decrease suppression. Moreover, it is difficult to profit at light loads with a strategy of maximizing the PV output power returned to the grid, because of the grid constraints. These results suggest that the operational strategy which considers the both profit and utilization of PV output, is the effective way of HEMS in light load period in the case of that each house in residential sector has PV and PCS.

5. Conclusion

In order to introduce a lot of PVs in residential sector, clearly, the way to control voltage profile is needed as illustrated in this paper. This paper developed an evaluation framework for the cooperative behavior between HEMS and GEMS. Using this evaluation framework, this paper also demonstrated optimal operational strategy of HEMS for PV utilization in the case that HEMS is informed voltage profile from GEMS. The obtained results are shown below:

(1) A residential energy system having a power generator requires an evaluation including grid constraints in the light load periods because a half of the PV output suppressed in practical aspect.

(2) The HEMS is able to plan a suitable operational strategy stopping a distributed power generator except a PV power generator under special situations, namely on the light load day, when receiving grid information predicted by the grid operator.

(3) The operational strategy, which uses the BT for storing the PV power, is effective ways for mitigation of PV suppression in light load day.

(4) Operational strategy's change of PCS at one household has limited effectiveness against mitigation of voltage violation for electrical grid because neighboring PV units are feeding back lots of electricity into electrical grid still. Therefore, it is suggested that coordinative behavior of neighboring HEMSs might be effective for voltage violation for electrical grid caused by residential PV output.

Responding to the above results, in order to design HEMS capable of collaborating with the distribution system, our future work will reveal the suitable operational algorithms of the HEMS and GEMS.

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Nomenclature

$\boldsymbol{A}$	technology matrix
$\boldsymbol{b}$	right-hand side vector
B	susceptance
$\boldsymbol{c}$	objective vector
C	objective function conversion factor
e	electricity
g	gas flow
G	conductance
J	objective function
k	node index
n	number of nodes
V	voltage
$\boldsymbol{x}$	decision vector

Greek symbols

θ	phase angle
ω	scenario index
Ω	number of scenarios

Subscripts and superscripts

e	electricity
buy	purchased from grid
g	gas
PV	PV

P	active power, probability	r	reversed electricity
Q	reactive power	L	load
t	time index	i	node index
T	number of sampling time		

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