MULTI-OBJECTIVE OPTIMIZATION OF A BATTERY ENERGY MANAGEMENT FOR AN OFF-GRID SMART HOUSE

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ABSTRACT

Recently in japan, an off-grid smart house is attracted for effective energy utilization and measure of a blackout at the time of an accident. In the off-grid smart house, it is effective that a photovoltaic (PV) generator, a solar collector (SC), which use as a renewable energy, a heat pump (HP) which is energy saving hot water supply equipment, and a fixed battery for saving electricity are introduced. Also, if an electric vehicle (EV) is introduced into this smart house, domestic power consumption can be supported by using a battery of the EV. However, there is necessary to determine optimal capacity of the fixed battery and optimal number of PV panels, when the off-grid smart house is designed.

So, this paper proposes an off-grid smart house, utilized by the PV generator, SC, HP, fixed battery, and EV, which is independent from an electric power system. The HP, the fixed battery, and EV are used as controllable loads. This paper plans to disclose the capacity of fixed battery and number of PV panels which are set, for getting optimal operational method of controllable loads, and showing operation of the off-grid smart house without shortage of electricity.

INTRODUCTION

In recent years, the demand reduction from fossil fuels is recommended to produce energy. Increase use of fossil fuels causes depletion of fossil fuels as well as environmental problems like global warming. Therefore, in japan, it is considered about life which does not use supplied electricity from an electricity company. So, a smart house consists of a photovoltaic (PV) generator and a solar collector (SC), which are use renewable energy, a Heat pump which is energy saving hot water supply equipment, and a fixed battery which saves electricity. Also, if an electric vehicle (EV) is introduced into this smart house, domestic power consumption can be supported by using a battery of the EV. Furthermore, development of EV charging infrastructure in Japan is progressing through quick charging systems that charge to the battery of the EV by quickly. So that, electricity into the smart house can be supplied by discharging from the battery of the EV which is charged outdoor adequately, and introduction costs are reduced, because of the capacity of a fixed battery and number of PV panels which are introduced into the smart house are reduced. Therefore, a self - sufficient life of electricity without electricity supply from the electricity company, by living the smart house which have the PV system, SC, HP, fixed battery, and EV. So that, it is expected that energy utilization became effective and measure of a blackout at a time of the accident.

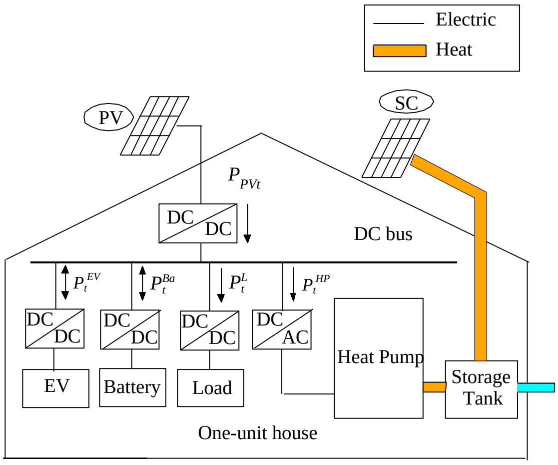


Figure 1 Off-grid Smart house model

So, this paper proposes an off-grid smart house consists of a PV generator, a SC, a HP, a fixed battery, and EV, which is independent from an electric power system. The HP, fixed battery, and EV are used as controllable loads. The capacity of the fixed battery and number of PV panels which are set, this paper plans optimal operational method of controllable loads by using multi-objective optimization method. This paper plans to display the capacity of fixed battery and number of PV panels which are set, for getting optimal operation of controllable loads by using a multi-objective optimization method. Moreover, by simulating the operational conditions which can fullfill the electricity demand by self-sufficient supply of the electricity too, this paper consider about proposed off-grid smart house.

ELECTRIC POWER SYSTEM

Off-grid smart house model

The off-grid smart house model assumed in this paper is shown in Fig. 1. The PV generator, SC, HP, fixed battery, and EV systems are introduced into this smart house. The HP, fixed battery, and EV are used as controllable loads. In this paper, use of the hot-water

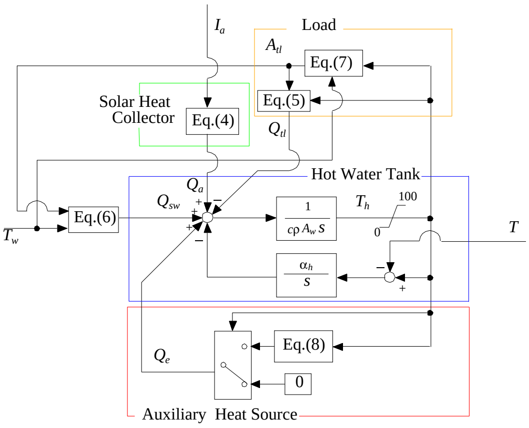


Figure 2 Model of solar collector

supply is assumed for the smart house at both morning and evening. The hot water temperature of the storage tank is set for a target temperature of 55 °C at 7 p.m. When the water temperature is less than the target temperature, the HP starts functioning to boil supply water and raises the storage water to the target temperature. The HP water heater assumes a storage tank capacity of 370L, a rated heating capability of 1kW/4kW, and a COP of 4.0. Furthermore, the EV is assumed for outside use as a passenger vehicle from 8 a.m. to 6 p.m. The capacity of EV is set to 6.0kW/24kWh. Here, the capacity of the fixed battery is determined by simulation.

Photovoltaic system

In this paper, the parameters of the PV are as follows: The conversion efficiency η_{PV} is 14.4%, n_{PV} [panels] is the number of panel, and panel area S_{PV} is 1.3 m^2. Moreover, PV output P_{PV} obtained from amount of insolation I_a [kW/m^2] is calculated from the following equation.

$$P_{PV} = \eta_{PV} n_{PV} S_{PV} I_a (1 - 0.005(T_{CR} - 25)) \quad (1)$$

Here, T_{CR} is cell temperature [°C].

Solar collector system

In this paper, the parameters of the SC are as follows: The conversion efficiency η_{SC} is 60%, the number of panels n_{SC} is 3 sheets, and panel area S_{SC} is 1.6 m^2. The solar collector system can be modeled by equations (2) - (8). Fig.2 shows the solar collector system mathematical model. The temperature change characteristics and time change characteristics of the storage water can be obtained by the following equations.

$$c\rho A_w \frac{dT_h}{dt} = Q_h \quad (2)$$

$$\frac{dQ_h}{dt} = -\alpha_h (T_h - T_a) \quad (3)$$

Here, T_h is the temperature of the water in the storage tank [°C], A_w is the capacity of storage tank [L], Q_h is the heat capacity of the water in the tank [cal], c is the specific heat of the water [cal/(g)] (=1.0 cal/(g)), ρ is the density of the water [g/L] (=1000 g/L), and α_h is the coefficient of heat transfer, T_a is the ambient air temperature [°C].

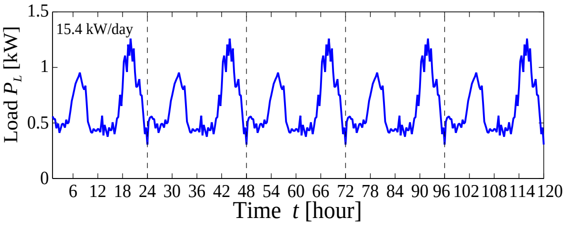


Figure 3 Power consumption

The quantity of heat collected in heat collection panel Q_a [J] is expressed by the following equation:

$$Q_a = \eta_h I_a n A_c \quad (4)$$

Here, η_h is the efficiency of conversion to heat, I_a is the solar radiation [J], n is the number of panels, and A_c is the heat collection area per panel [m^2].
Heat lost to the hot-water supply Q_{tl} [cal], heat added by the water supply Q_{sw} [cal], hot water used from the tank at supply time A_{tl} [L], quantity of water supplied to the tank A_{sw}, and heat added from an auxiliary heat source Q_e [cal] are found using following equations:

$$Q_{tl} = c\rho A_{tl} T_h \quad (5)$$

$$Q_{sw} = c\rho A_{sw} T_w \quad (6)$$

$$A_{tl} = A_{sw} = \frac{T_l - T_w}{T_h - T_w} A_l \quad (7)$$

$$Q_e = c\rho A_w (T_e - T_h) \quad (8)$$

Here, T_l is the temperature of the hot-water supply [°C], T_w is city water temperature [°C], A_l is the quantity of hot water at the time of use of the hot-water supply [L], and T_e is goal heat temperature [°C].

OPTIMIZATION METHOD

Objective function

P_t^L, P_t^{PV}, P_t^{Ba}, P_t^{EV}, and P_t^{HP} in Fig.1 are respectively power consumption excluding controllable loads, PV output, discharge and charge power of the fixed battery, discharge and charge power of the EV, and power of the HP in the smart house at a given time. Equation (9) expresses the load dispatching balance of the off-grid smart house in Fig. 1.

$$P_t^L = P_t^{PV} + P_t^{Ba} + P_t^{EV} - P_t^{HP} \quad (9)$$

Objective functions in this paper, minimize the number of PV panels n_{PV} [panels] and supplied electric power to the off-grid smart house by the battery of the EV which is charged outdoor P_t^{DEV}[kWh], and are expressed in equations (10) and (11), redpectively.

$$\begin{aligned} F_1 &= \min\ n_{PV} \\ F_2 &= \min \sum_{t=1}^{T} P_t^{DEV} \end{aligned}$$

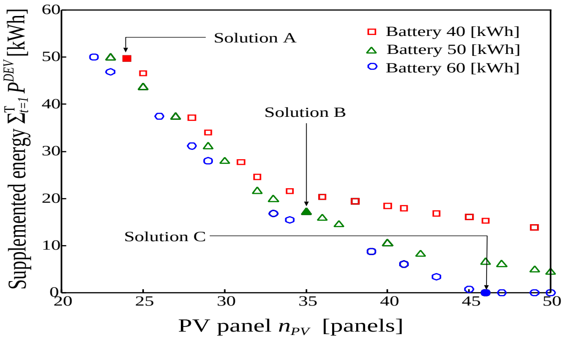


Figure 4 Preto optimal solutions

Table 1 Evaluation result of the solutions

Solution	$\sum_{t=1}^{T} P_t^{DEV}$	n_{PV}	Battery
A	49.8 [kWh]	24 [modules]	40 [kWh]
B	17.2 [kWh]	35 [modules]	50 [kWh]
C	0 [kWh]	46 [modules]	60 [kWh]

In this paper, two optimization methods are used. By using the tabu-search which is a kind of single-objective optimization method and the objective which minimze the shortage of electricity for the power consumption, optimal operational method of controllable loads is planed. Next, by using the non-dominated genetic algorithm 2 (NSGA2) which is a kind of multi-objective optimization method, a set of optimal pareto solutions of the two objective function, which are trade-off relation each other, is searched. By the set of optimal pareto solutions, the optimal number of the PV panels and supplied electric power of the EV for operating the off-grid smart house.

Constraints

Operation constraints of equipment in the smart house are shown in equations (12) ∼ (17).

$$|P_t^{Ba}| < P_{max}^{Ba} \tag{10}$$

$$|P_t^{EV}| < P_{max}^{EV} \tag{11}$$

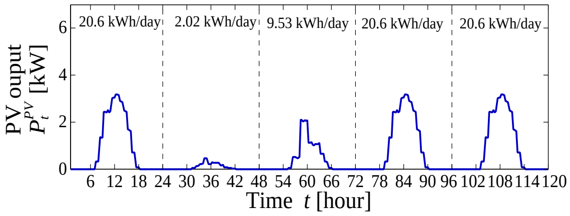
$$0.2\, C_{max}^{Ba} < C_t^{Ba} < 0.8\, C_{max}^{Ba} \tag{12}$$

$$0.2\, C_{max}^{EV} < C_t^{EV} < C_{max}^{EV} \tag{13}$$

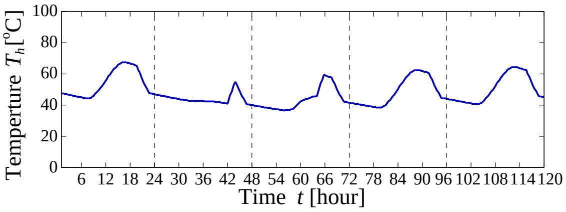
$$0.55\, C_{max}^{EV} < \sum_{s=1}^{5} C_{(t=7+24(s-1))}^{EV} < C_{max}^{EV} \tag{14}$$

$$\sum_{t=1}^{T} P_t^{S} - P_t^{DEV} = 0 \tag{15}$$

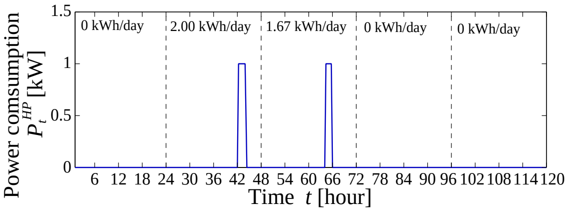
$$P_t^S = P_t^L - P_t^{PV} - P_t^{Ba} - P_t^{EV} + P_t^{HP} \tag{16}$$



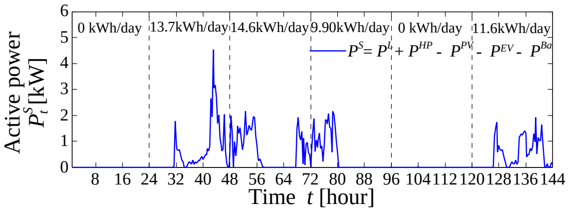
(a) PV output power



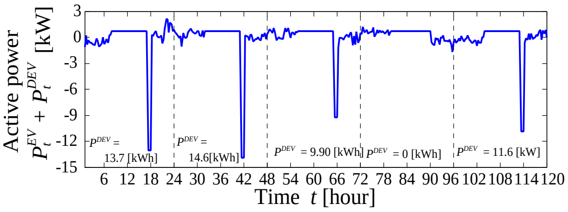
(b) Water temperature of storage tank



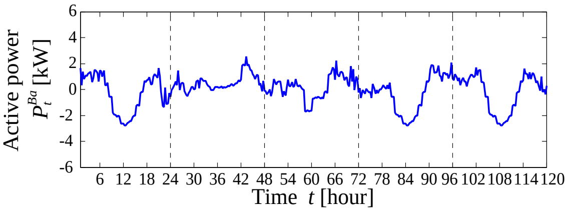
(c) Power consumption of HP



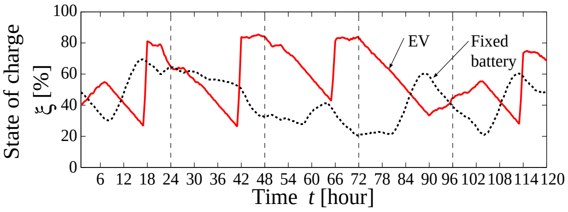
(d) Shortage of electricity



(e) Active power of EV



(f) Active power of fixed battery



(g) State of charge for fixed battery and EV

Figure 5 Simulation result of solution A

Where, P_t^{Ba} is the active power of the fixed battery [kW], P_t^{EV} is the active power of the EV [kW], P_{max}^{Ba} is the maximum allowable value of discharge and charge power for the fixed battery [kW], P_{max}^{EV} is the maximum allowable value of discharge and charge power for the EV (6kW), C_t^{Ba} is the state of charge of the fixed battery [kWh], C_t^{EV} is the state of charge for the EV [kWh], C_{max}^{Ba} is the maximum allowable state of charge for the fixed battery, and C_{max}^{EV} is the maximum allowable state of charge for the EV(24kWh), s is the simulation day [day].

Equations (12) and (13) show the inverter constraints of the fixed battery and EV, respectively. Equations (13) and (14) show the state of charge constraints of the fixed battery and EV, respectively. Equation (16) shows the state of charge constraints for the EV at 7 a.m. every day. Equation (17) is constraint not to occur shortage of supplied electricity for satisfying the power consumption in the off-grid smart house.

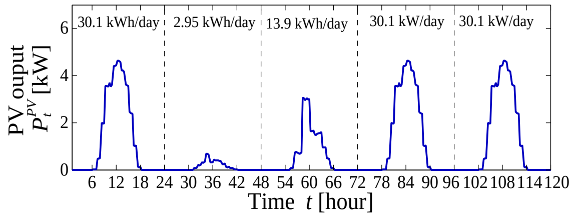
SIMULATION RESULT

Simulation conditions

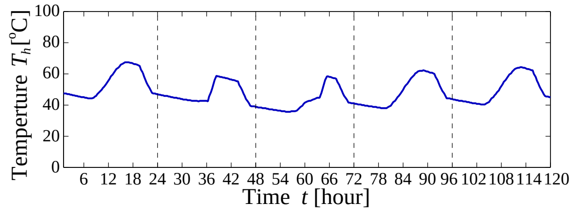
In this simulation, operation term is 5 days which weather conditions are sunny, rainy, cloudy, sunny and sunny in order. Fig. 3 shows power consumption excluding controllable loads. For volumes of hot water supply used in the smart house, 150L was used as a shower during the 3 hours, from 7 p.m. to 10 p.m. If water temperatures of storage tank dropped lower than 55°C at 7 p.m., the water was heated by the HP. The battery of the EV is assumed used outdoor as passenger car at 700Wh from 8 a.m. to 6 p.m. If shortage of supplied electricity occur, the battery of the EV is charged by quickly from 8 a.m. to 6 p.m. of previous day.

Simulation results

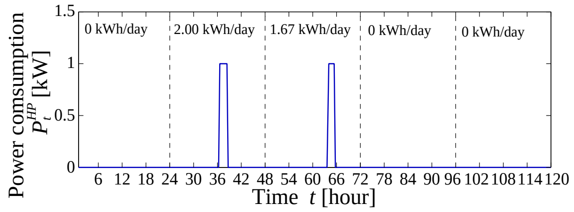
Simulation result of NSGA2 is shown in Fig. 4. This figure shows that if introduction capacity of PV panels and the fixed battery is small, supplied electricity from the battery of the EV is large. Operational methods of controllable loads in three cases which are shown in Fig. 4 are shown in Fig. 5, 6, and 7. Also, results of solutions A, B and C obtained from Fig. 4 are summarized in Table. 1. Figs. (a) of these figures show PV output. Figs. (b) and (c) of these figures show water temperatures in the storage tank and power of HP, respectively. On the day of cloudy and rainy, it can be observed that the temperatures of storage tank fulfill temperature goals by HP and SC heating due to water temperatures in the storage tank dropping lower than the goal temperature at 7 p.m. Figs. (d) of these figures show the shortage of electricity when supplied electricity from the EV is nothing. Figs. (e) of these figures show charged and discharged power of the EV. These Figs. (e) show that if shortage of electricity of the next day is predicted, the EV is charged outdoor from 5 p.m. to 6 p.m. In Figs. (f) of these figures,



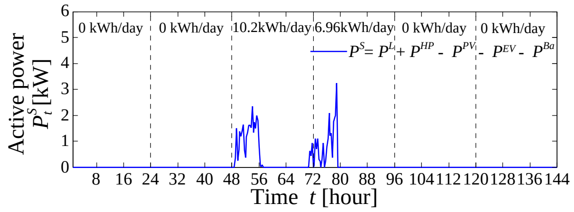
(a) PV output power



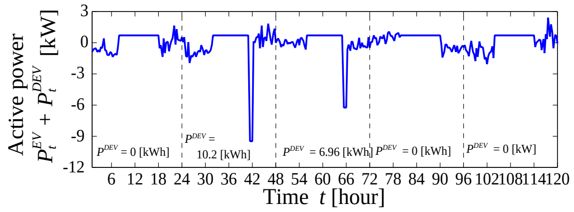
(b) Water temperature of storage tank



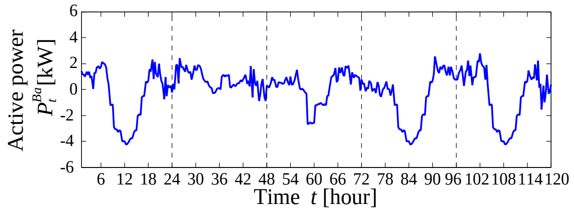
(c) Power consumption of HP



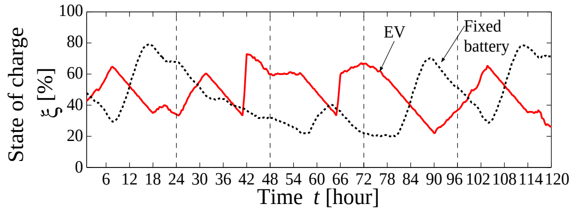
(d) Shortage of electricity



(e) Active power of EV

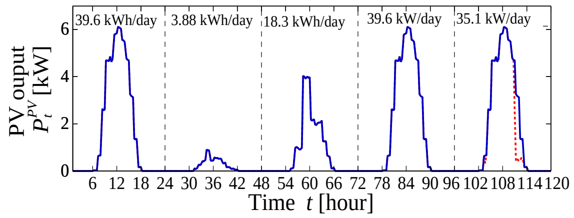


(f) Active power of fixed battery

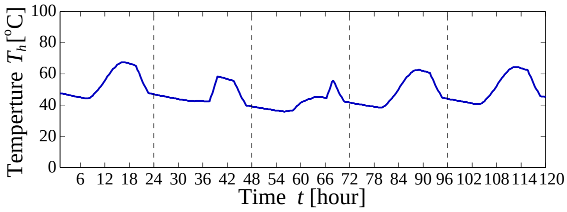


(g) State of charge for fixed battery and EV

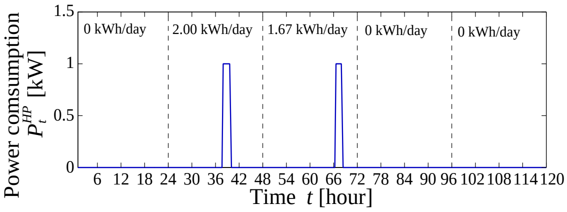
Figure 6 Simulation result of solution B



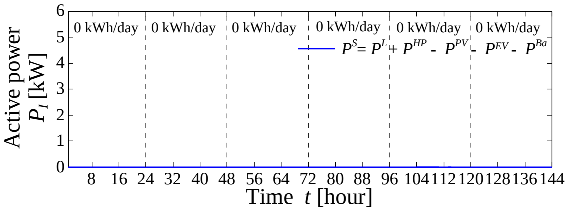
(a) PV output power



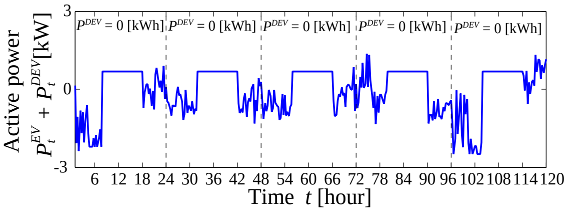
(b) Water temperature of storage tank



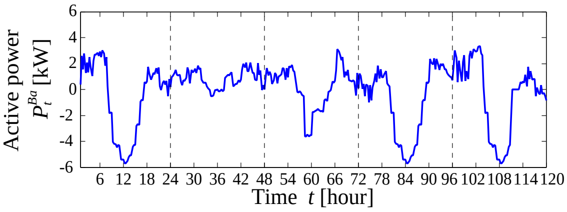
(c) Power consumption of HP



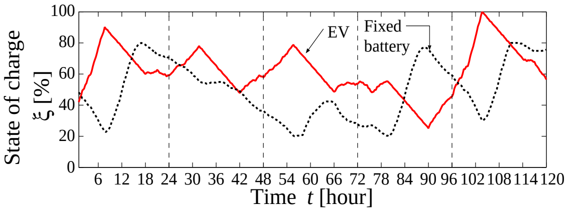
(d) Shortage of electricity



(e) Active power of EV



(f) Active power of fixed battery



(g) State of charge for fixed battery and EV

Figure 7 Simulation result of solution C

charged and discharged power of the fixed battery are shown and it is understood that the inverter constraints are satisfied.

Figs. 5, 6, and 7 show that a consumer which can introduce the equipment with large capacity does not have to charge the EV outdoor for operating the off-grid smart house. However, a consumer which cannot introduce the equipment with large capacity have to charge the EV outdoor for operating the off-grid smart house. By simulation results, the off-grid smart house on the day which amount of PV output is low can be operated by suplied electric power of the EV.

CONCLUSION

In this paper, an off-grid smart house includes a PV generator, a SC, a HP, a fixed battery, and EV, which is independent from an electric power system is proposed. The capacity of the fixed battery and number of PV panels, optimal equipment capacity of the off-grid smart house is considered too. The simulation results show the off-grid smart house can operate withot shotage of electricity.

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