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MULTI-OBJECTIVE OPTIMIZATION FOR CAPACITY OF FIXED BATTERY IN A SMART HOUSE

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ABSTRACT

A smart house generally uses a photovoltaic (PV) generator system, a solar collector (SC), a heat pump (HP), and a fixed battery. Since the fixed battery can effectively utilize cheap electricity during the night time, the electricity bill of the consumer in a smart house can be reduced. A fixed battery with a large storage capacity further reduces the electricity bill. However, a larger capacity fixed battery is very costly. Therefore, in order to more effectively reduce the electricity bill, an electric consumer in a smart house needs to determine the storage capacity of the fixed battery considering feasible regulation.

With this in mind, this paper proposes and a multi-objective optimization problem for electric demand control and feasible regulation in the smart house. In this optimal problem, the pareto optimal solutions are obtained from each simulation case using a fixed battery introduced into the smart house. The simulation results offer an effective operational method of controllable loads and an acceptable capacity for the fixed battery for the consumer in the smart house.

INTRODUCTION

For the purpose of reducing electricity generation cost and CO_2 emissions, which contribute to global warming, it is necessary to reduce the peak electricity demand. The demand response (DR) system, which motivates a peak cut and a peak shift of the electric power demand of electric consumers, has been proposed. There is also the real-time pricing (RTP) system, which is a kind of DR system. The RTP price is an electricity tariff price which reflects the energy cost in an electricity market. Therefore, the RTP price is a dynamic electricity price and becomes higher when the electricity demand is larger.

Actually, in Illinois State in USA, there is a retail electricity company which uses a RTP price as an electricity tariff price for its electric consumers. The RTP price is high during the peak demand such as during the day. Therefore, an electric consumer, responds to the RTP price and saves during peak power consumption.

Use of an all-electric house utilizing a photovoltaic (PV) generator is increasing due to a growing interest in renewable energy. Also, by introducing a fixed battery and a home energy management system (HEMS), which manages energy in the house, PV outputs are more effectively used and the electricity bill can be lowered.

In traditional papers regarding the smart house, optimal control methods of controllable loads are generally proposed. The traditional paper showed that a smart house utilizing a fixed battery with large storage capacity can reduce an electricity bill without changing usage plans of electric appliances by the consumer.

However, if an electric consumer uses a fixed battery with a small storage capacity, regulation efforts, which change the usage plan of shiftable loads (a clothing washer, a dish washer, a cleaner, an iron) are necessary to reduce the electricity bill. On the other hand, an electric consumer, who can use a fixed battery with a large storage capacity, can reduce an electricity bill with a small effort. Therefore, it is considered that an optimal control method of controllable loads in a smart house considering the storage capacity of a fixed battery and regulation efforts of a electric consumer is effective. However, the relation between regulation efforts and an electricity bill is a multi-objective trade off. So, for solving this multi-objective optimization problem, a multi-objective evolutionary algorithm (MOEA) which searches a set of pareto optimal solutions is effective.

Therefore, in this paper, a smart house utilizing a PV generator, a solar collector (SC), a heat pump (HP), and a fixed battery is proposed. The HP and the fixed battery are used as controllable loads in the smart house. Here, an RTP price is used as the electricity bill price. An electric consumer in the smart house regulates their power consumption of shiftable loads of electric appliances. Moreover, this multi-objective optimization problem minimizes the electricity bill and regulation efforts. Also, the problem is solved using the non-dominated sorting genetic algorithm 2 (NSGA2), which is a type of MOEA. This simulation searches and compares sets of preto optimal solutions by simulated cases with different storage capacities for the fixed battery. The simulation results show the reg-

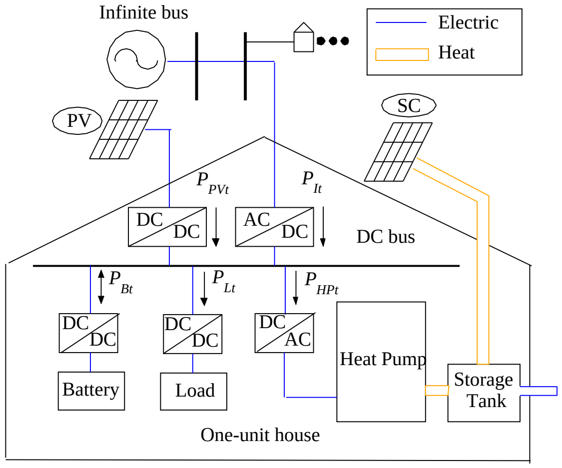


Figure 1 Smart house model

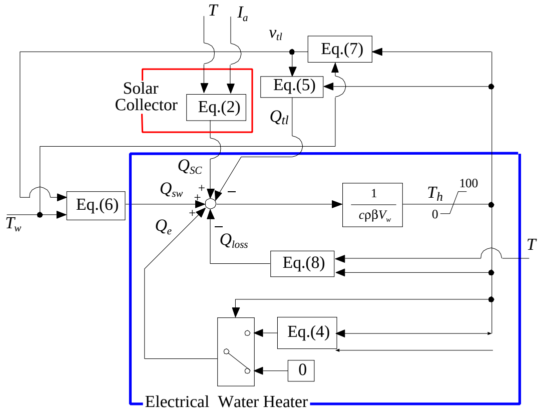


Figure 2 Model of solar collector

ulation effects can reduce the capacity of the fixed battery introduced to the smart hosue.

ELECTRIC POWER SYSTEM

Smart house model

The smart house model assumed in this paper is shown in Fig. 1. the PV generator, SC, HP, and fixed battery systems are introduced into this smart house. In this paper, use of the hot-water supply is assumed for the smart house at morning and evening. The hot-water temperature of the storage tank is set up for a target temperature of 50 °C and 60 °C, at 7 a.m. and 8 p.m., respectively. When the supply water is less than the target temperature, the HP heats up and circulates water, raising the supply water to the target temperature. The HP water heater assumes a storage tank capacity of 370 L, a rated heating capability of 1.0 kW/4.0 kW, and a COP of 4.0. Here, the capacity of the fixed battery is set by simulation cases.

Photovoltaic system

In this paper, the parameters of the PV are as follows: The conversion efficiency η_{PV} is 14.4 %, the number of panels n_{PV} is 18 [panels], and panel area S_{PV} is 1.3 m^2. Moreover, PV output P_{PV} [kW] obtained from the 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

The mathematical model for the solar collector system assumed in this paper is shown in Fig. 2. The solar thermal energy obtained from the solar collector Q_{SC} [kW] is calculated as shown in Equation (2)

$$Q_{SC} = \{F_R(\tau\alpha)_e I_a - F_R U_L (T_h - T_a)\} S_{SC} \quad (2)$$

where, F_R is heat removal efficiency, $(\tau\alpha)_e$ is the effective transmission absorption factor, U_L [kW/(m^2·°C)] is the integrated solar thermal loss coefficient, T_h [°C] is the water temperature in the storage tank, T_a[°C] is the ambient air temperature, S_{SC} [m^2] is the solar collector area per collector (S_{SC} = 4.8 m^2). $F_R(\tau\alpha)_e$ and $F_R U_L$ are 0.77 and 5.0×10^{-3}kW/(m^2·°C) respectively.

The temperature alteration and dynamic characteristics of the water temperature can be expressed as:

$$Q_{SC} + Q_{HP} - Q_{tl} + Q_{sw} - Q_{loss} = \beta A_w \frac{dT_h}{dt} \quad (3)$$

$$\begin{aligned} Q_{HP} &= \beta A_w (T_d - T_h) && (4)\\ Q_{tl} &= \beta v_{tl} T_h && (5)\\ Q_{sw} &= \beta v_{sw} T_w && (6)\\ v_{tl} &= v_{sw} = \frac{T_l - T_w}{T_h - T_w} v_l && (7) \end{aligned}$$

$$Q_{loss} = U_{st}(T_h - T_a) \quad (8)$$

where, Q_{HP}[kW] is the input thermal energy from the HP, Q_{tl}[kW] is the thermal energy for hot-water supply, Q_{sw}[kW] is the thermal energy for water supply, Q_{loss}[kW] is the convective heat loss of the storage tank from the storage tank to the SC, β[kW/(L·°C)] is the volumetric specific heat of water, A_w[L] is the storage tank capacity, t[h] is time, T_d[°C] is the target temperature, v_{tl}[L/h] is the amount of hot-water used from the storage tank, v_{sw}[L/h] is quantity of water supplied to the tank, T_l[°C] is the temperature of the hot-water supplied to the house, v_l[L/h] is the amount of hot-water supplied to the house, and U_{st}[kW/°C] is the heat loss coefficient of the storage tank between the storage tank and the outdoor air temperature.

OPTIMIZATION METHOD

Objective function

P_{It}, P_{Lt}, P_{PVt}, P_{Bt}, P_{EVt}, and P_{HPt} in Fig.1 are the interconnection point power flow in the smart house, 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 time t, respectively.

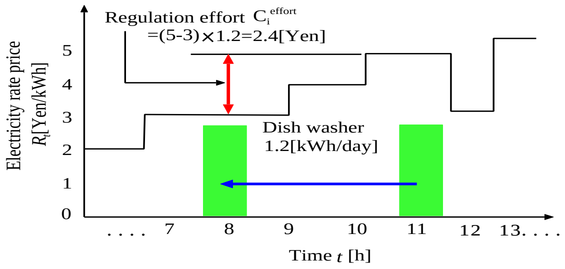


Figure 3 Example of regulation effort

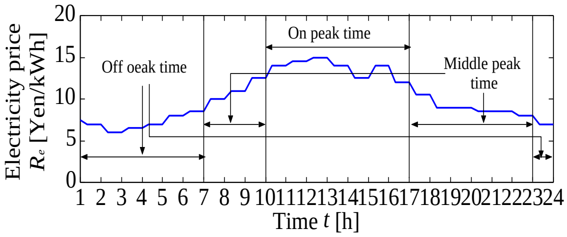
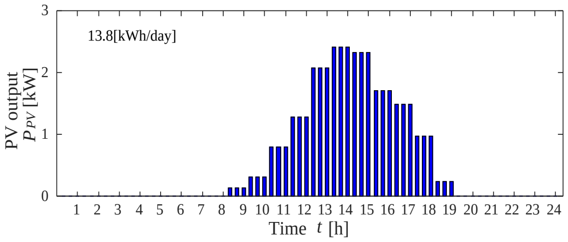
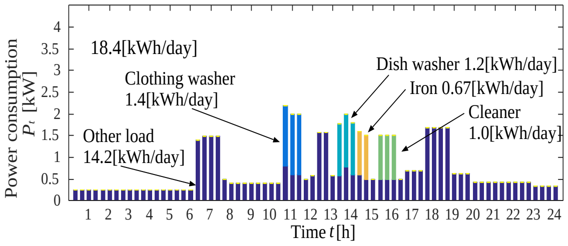


Figure 4 RTP rate price



(a) PV output power.



(b) Initial power consumption.

Figure 5 PV output and initial power consumption

Equation (9) expresses the demand and supply balance of the smart house in Fig. 1.

$$P_I = P_{Lt} + P_{HP} - P_{PV} - P_{Bt} - P_{EVt} \quad (9)$$

The power consumption excluding controllable loads P_{Lt} is obtained from equation (10), which is obtained from power consumption of all appliances used by the consumer.

$$P_{Lt} = \sum_{i \in I} P_{Lt}^{i} \quad (10)$$

Here, I is the set of the electric appliance i. In this paper, electricity tariff during one day R_t is the RTP price which is assumed in this paper. Also, the surplus power can be sold by the retail electricity price through a net metering program. The objective function which minimizes the electrici0y bill C_{day} [Yen] and the regulation effort E_r [Yen] during one day is shown in equation (11).

$$Minimize\ F\{C_{day}, E_r\} \quad (11)$$

The objective functions of equation (10) are formulated as

$$C_{day} = \sum_{t \in T} R_t (P_p - P_s) \quad (12)$$

$$E_r = \sum_{i \in I} C_i^{\text{effort}} \quad (13)$$

Where, T is the set of times t, R_t is the RTP price [Yen/kWh], P_p is the amount of purchased power [kWh], P_s is the amount of sold power [kWh], and C_i^{effort} is the reduced electricity bill after regulation of use plan of the electric appliance i.

Constraints

Operation constraints of equipment in the smart house are shown in equations (14) (16).

$$|P_I - P_{I(t-1)}| \leq P_{FB} \quad (14)$$

$$P_I \leq P_{It}^{\text{contact}} \quad (15)$$

$$P_{HPt} = \{0, P_{HPt}^{\max}\} \quad (16)$$

$$|P_{Bt}| \leq P_B^{\max} \quad (17)$$

$$0.2\, C_B^{\max} \leq C_{Bt} \leq 0.9\, C_B^{\max} \quad (18)$$

$$T_t^{i,\text{shift}} \leq \{0, T_t^{i,\max,\text{shift}}\} \quad (19)$$

Where, P_{FB} is the bandwidth of the interconnection point power flow variation in the smart house (2.0 kW), $P_{It}^{contact}$ is the contact power (4.0 kW), $P_{HPt}^{\max}$ is the rated power of HP (1.0 kW), P_{Bt} is the active power of the fixed battery, $P_B^{\max}$ is the maximum allowable value of discharge and charge power for the fixed battery (1.0 kW), C_{Bt} is the state of charge of the fixed battery [kWh], C_{Bmax} is the maximum allowable state of charge for the fixed battery, $T_t^{i,\text{shift}}$ is the shifted time of the electric appliance i, and $T_t^{i,\max,\text{shift}}$ is the maximum shiftable time of the electric appliance i,

Considering the constraints of power flow defined by equation (14), rapid current variation due to PV output can be suppressed. Equation (16) operates the HP system by rated power. Equations (17) and (18) show the inverter constraints and the state of charge of the fixed battery, respectively. Here, the storage capacity of the fixed battery is set by the simulation case studies. Equations (19) shows that shiftable loads of alppliances can be regulated between the maximum shiftable time and non-controllable loads of appliances can be not regulated.

Regulation effort

An example of a regulation effort of power consumption E_r by the consumer is shown in Fig. 3. A consumer can reduce an electricity bill by shifting power consumption of shiftable loads to a cheap electricity price time. The regulation effort of the consumer is evaluated by calculating power consumption blocks of

Table 1 Electric appliances data

Appliance	Power[kW]	Regulation
Refrigerator	0.25∼0.3	Non-controllable loads
Lighting	0.1∼0.5	
Cooking heater	0.2∼0.7	
TV	0.085	
Air conditioner	0.2∼0.4	
Clothing Washer	1.4	Shiftable loads
Dish Washer	1.2	
Iron	1.2	
Cleaner	1.0	

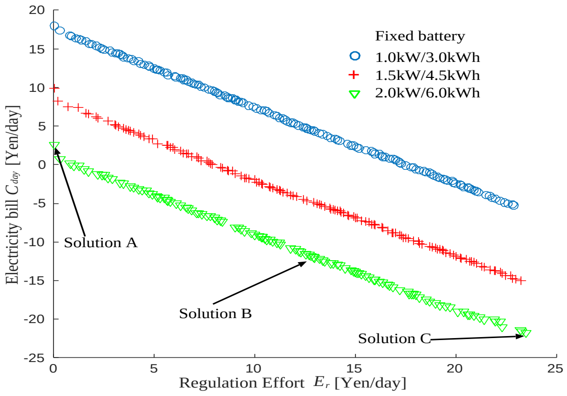
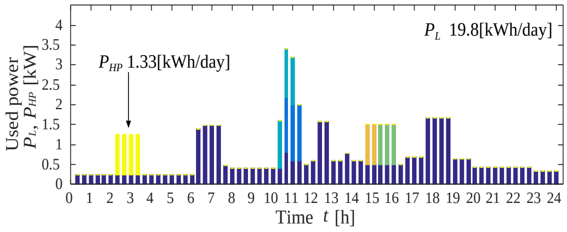
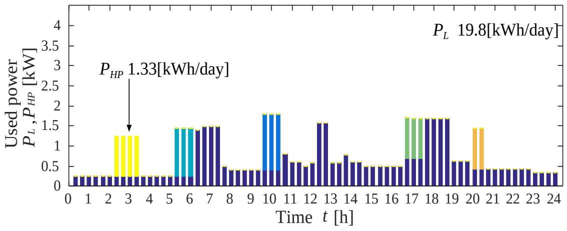


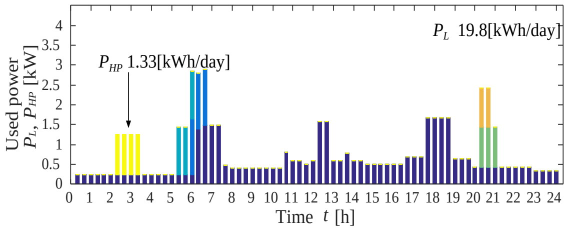
Figure 6 Pareto optimal front



(a) Power consumpton of solution A

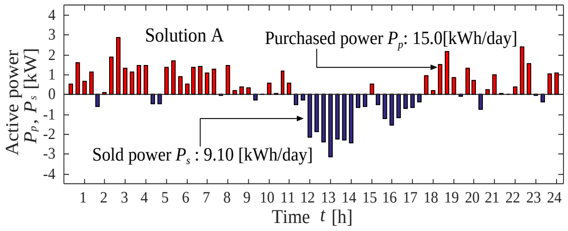


(b) Power consumption of solution B.

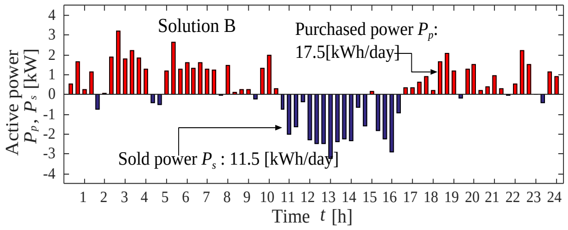


(c) Power consumption of solution C.

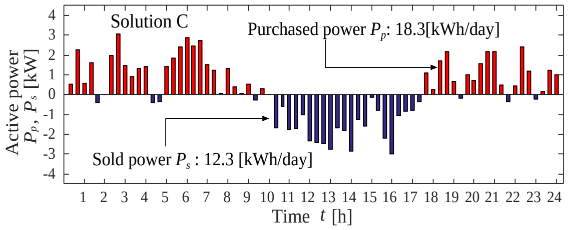
Figure 7 Power consumption of solutions



(a) Purchased and sold power of solution A



(b) Purchased and sold power of solution B.



(c) Purchased and sold power of solution C.

Figure 8 Purchased and sold power of solutions

Table 2 Evaluation result of the solutions

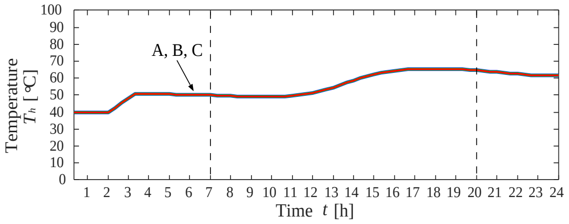
Solution	C_{day}	E_r
A	3.10 [Yen]	0.10 [Yen]
B	-12.1 [Yen]	11.0 [Yen]
C	-24.2 [Yen]	23.4 [Yen]

shiftable loads which are shifted to a cheaper electricity price time as shown in Fig. 3. By this evaluation method, the electricity bill, which is reduced by the consumer becomes larger so that it is considered a better regulation effort.

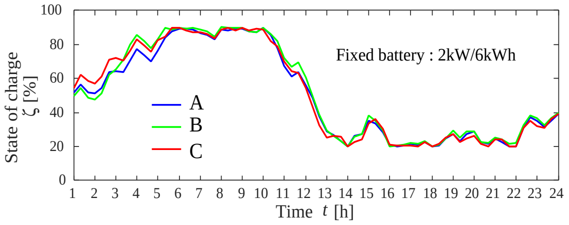
SIMULATION RESULTS

Simulation conditions

The RTP price, the PV output, and initial power consumption on the days which are assumed in this paper, are shown in Fig. 4 and Fig. 5, respectively. Construction of electric appliance loads in this paper are shown in Table. 1. The starting time of use of the shiftable loads is regulated. Also, the capacity of the fixed battery is set to 1.0 kW/3.0 kWh, 1.5 kW/4.5 kWh, and 2.0 kW/6.0 kWh in this simulation, and pareto optimal solutions obtained as results of these simulation cases are compared. For volumes of hot water supply used in the smart house, 30 L was used during the hour from 7 a.m. to 8 a.m. and 150L was used during the 3 hours from 7 p.m. to 10 p.m. Also, if water temperatures of storage tank dropped lower than 50 °C and 60 °C at the times 7 a.m. and 8 p.m. respectively, the water was then heated by the HP.



(a) Water temperature of storage tank



(b) State of charge for fixed battery.

Figure 9 Simulation results of controllable loads

Simulation results

Pareto optimal fronts obtained by the simulation are shown in Fig. 6. Also, results of solutions A, B and C obtained from Fig. 6 are summarized in Table. 2. Fig. 6 and Table 2 show the capacity of fixed battery is larger so that the electricity bill is lower with a small regulation effort. The consumed power (i.e., the combined power consumption of electric appliances and the HP) of solutions A, B and C is shown in Fig. 7. Fig. 7 shows the times of use of the shiftable loads from solution A are hardly shifted from the peak demand time. On the other hand, solution B, has a larger regulation effort to reduce the power consumption during the peak demand time. Also, the power consumption of shiftable loads is shifted to the off peak demand time, which means a cheaper electricity tariff price for solution B, as well as a large regulation effort. The purchased and the sold power of solutions A, B and C is shown in Fig. 8. Fig. 8 shows the regulation effort is larger so that the amount of sold power and the benefit of selling the surplus power increase during the peak time because of the high selling price. Fig. 9 shows the temperatures of the storage tank, purchased power, and sold power respectively. Fig. 9(a) shows the goal temperatures of storage tank at 6 a.m. and 7 p.m. are fulfilled by HP and SC heating. Also, Fig. 9(b) shows that the fixed battery is charged during the time where the electricity tariff price is cheap and discharges during the time when the electricity tariff price is high. Therefore, a higher amount of power is used during the time when the electricity tariff price is reduced so that the electricity bill is lower.

CONCLUSION

In this paper, an electricity bill and the regulation effort of a smart house, which is participating in a RTP system, are minimized. An electric consumer can reduce their electricity bill by performing regulation effort at times in order to use shiftable loads for an announced electricity tariff price. In the simulation results, if a fixed battery with a large storage capacity is used, the consumer can reduce the electricity bill with a small regulation effort. However, since a fixed battery with a large storage capacity is costly, the consumer needs to determine the capacity of the fixed battery considering their own feasible regulation effort.

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