OPTIMAL OPERATION OF SMART HOUSE FOR REAL TIME ELECTRICITY MARKET

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ABSTRACT

Recently, a real-time electricity market has attracted attention for the purpose of reducing peak demand. In this market, the electricity price is normally made to be high when the electricity demand is large. The system is designed to motivate consumers to reduce their electricity use during peak electricity demand and therefore overall demand can be reduced. In Illinois state in USA, there is a real-time pricing (RTP) system in place, which is based on the electricity price of the real-time electricity market. The electricity price of the real-time electricity market is dynamic and changes hourly; likewise, the real-time electricity price for customers in the RTP system change accordingly. Therefore, for a cheaper electricity bill, an electricity consumer needs to reduce power consumption during the time that the RTP system price is high. So, in this paper, an all-electric smart house utilizing a photovoltaic generator, a solar collector and a heat pump with a fixed battery, and an electric vehicle is proposed. Finally, the simulation results show the reduction effect of the electricity bill by the smart house.

INTRODUCTION

Recently, in an effort to reduce CO_2 emissions causing global warming, a reduction of a peak electricity demand is recommended. So, a real-time electricity market, in which the price of electricity is decided at real time and the real time exchange of electric power, is proposed. In the real-time electricity market, the price of the electric power is normally high when the electricity demand is large. Therefore, the peak electricity demand can be reduced if consumers are aware of the real time price of electricity and adjust their electricity usage accordingly.

In Illinois state in USA, there is an electricity retail company which uses the electricity price in the real-time electricity market for a real-time pricing (RTP) system for electric consumers. The RTP system announces an hourly dynamic electricity tariff to the consumers during the day. The consumer responds to the electricity price and can reduce their electricity bill by lowering their power consumption. However, since the consumer only knows the electricity price after an hour, good planning for power consumption is difficult. Therefore, on the previous day of electricity supply, the electricity retail company announces a day-ahead pricing (DAP) to the consumer as a predicted price of the RTP. The DAP is based on the electricity market of the previous day, so the consumer can plan a schedule of the hourly power consumption using this price. However, the actual electricity payment is calculated by the RTP price of the day.

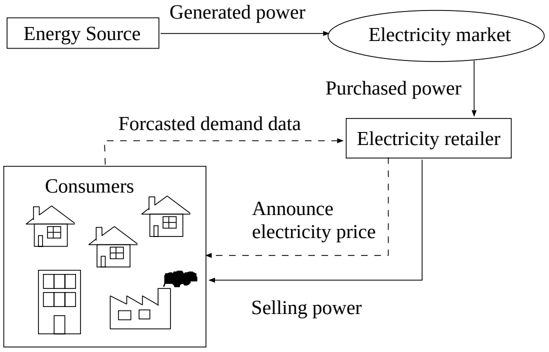


Figure 1 Framework of real-time electricity market

With regard to this system, in this paper, a smart house utilizing a photovoltaic (PV) generator, a solar collector (SC) and a heat pump (HP) with a fixed battery, and an electric vehicle (EV) is proposed. Here, the HP, fixed battery, and the EV are used as controllable loads. Also, by using the DAP price, the optimal operational method of the controllable loads is decided. Furthermore, the electricity bill for the day is calulated by applying the RTP price. Finally, the simulation results show the economic effects of the proposed smart house.

Real-time electricity market

The relationship among the electricity market, electricity company, and consumers is shown in fig. 1. The retail electricity market in the USA is liberalized where have a day-ahead market and a real-time market. A retail electricity company purchases electric power from the electricity market and supply to the consumers. Commonwealth Edison Company which is the retail electricity company in Illinois, USA, provides the real-time hourly electricity price as electricity rate price for residential consumers. The residential consumers can know only the current hour average price, but the price of the next hours are not known until after the hour has passed. So, Commonwealth Edison Company announces the day-ahead hourly electricity price to the consumers the day before. Therefore, the consumers are informed about the price of

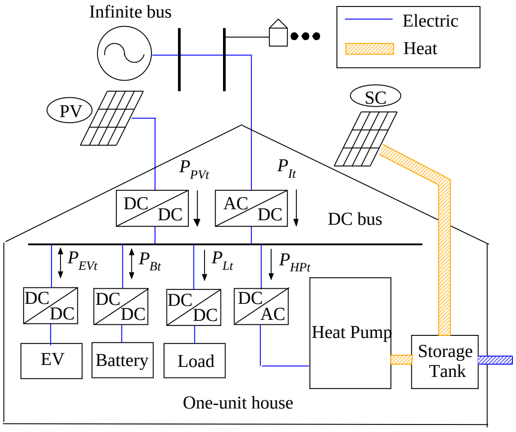


Figure 2 Smart house model

electricity rate beforehand.

Furthermore, it is thought that surplus power of a smart house can be sold to the company with the electricity market price by using FIP (Feed-in Premium) and Net Metering system in the future. In addition, for simplifying, the surplus power is can be sold with the electricity rate price.

ELECTRIC POWER SYSTEM

Smart house model

The smart house model assumed in this paper is shown in Fig. 2. 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. Current at the interconnection point between the power system and the smart house can be expressed with the current supplied to the smart house from the system in Fig. 1. In this paper, use of the hot-water 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 50 °C and 60 °C, at 6 a.m. and 7 p.m., respectively. 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 the fixed battery and the capacity of the EV are set to 1 kW/3 kWh, and 3 kW/16 kWh, respectively.

Photovoltaic system

In this paper, the parameters of the PV are as follows: The conversion efficiency η_{PV} is 14.4%, number of panels n_{PV} is 18 [panels], panel area S_{PV} is 1.3 m^2, and rated output is 3.5 kW. Moreover, PV output obtained from amount of insolation [kW] is calculated from the following equation.

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

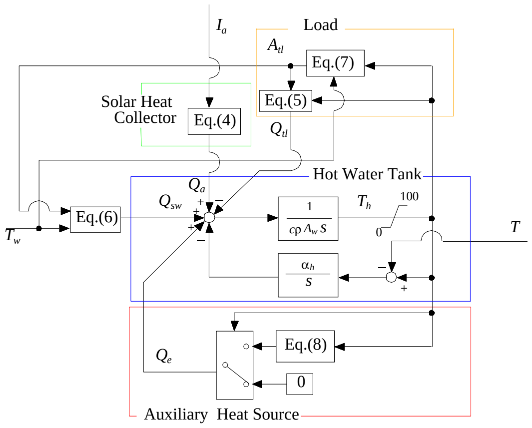


Figure 3 Model of solar collector

Here, I_{PV} is the amount of insolation [kW/m^2] and 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.3 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].

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

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

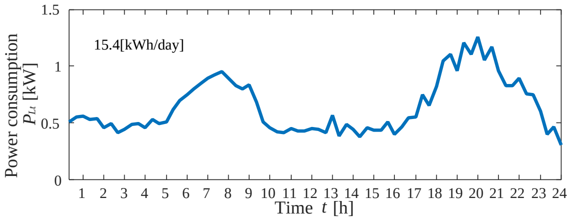
Here, η_h is the efficiency of conversion to heat, I_a is the solar radiation [J], n is the number of panels, and A_c is the heat collection area per panel [m^2].

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:

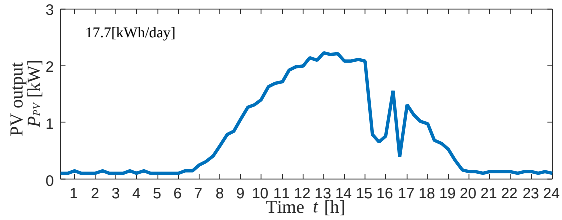
$$Q_{tl} = c\rho A_{tl} T_h \quad (5)$$

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

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



(a) Power consumpton



(b) PV output

Figure 4 Power consumpton and PV output

$$Q_e = c\rho A_w(T_e - T_h) \tag{8}$$

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

In this chapter, optimal planning of controllable loads in the smart house for one day is described. In this paper, the tabu search method, which is a optimization method, is used.

Objective function and actual cost

P_{It}, P_{Lt}, P_{PVt}, P_{Bt}, P_{EVt}, and P_{HPt} in Fig.1 are respectively the current at the interconnection point to the power system, 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 demand and supply balance of the smart house in Fig. 1.

$$P_{It} = P_{Lt} - P_{PVt} - P_{Bt} - P_{EVt} + P_{HPt} \tag{9}$$

In the optimal method used in this paper, the objective function is set by equation (9). The objective is to plan an optimal control method of the controllable loads for the purpose of minimizing the electricity bill by applying a DAP price. The DAP price is announced to the consumer on the previous day for the expected electricity supply. The electricity bill, is calculated using the objective function, and is called the " predicted operational cost " in this paper. Furthermore, the actual electricity bill using the operational method is calculated by applying a RTP price, which is announced to the consumer on the day the electricity is supplied. The electricity bill, which is calculated by the RTP price, is called the " actual operational cost " in this paper. Here, the surplus electric power can be sold at the retail electricity price through a net meter program.

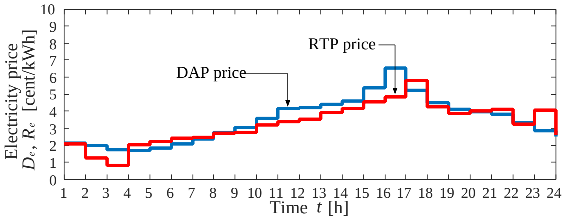


Figure 5 Electricity price

Objective function:

$$min\ C_{day}^{predict} = \sum_{t\in T} R_t^{DAP}\{P_{Pt} - P_{St}\} \tag{10}$$

Here, T is the set of hourly time, $C_{day}^{predict}$ is predicted operational cost of a day [cents], R^{DAP} is the DAP price [cents/kWh], P_{Pt} is purchased power [kWh], and P_{St} is sold power [kWh].

Actual operational cost:

$$C_{day}^{actual} = \sum_{t\in T} R_t^{RTP}\{P_{Pt} - P_{St}\} \tag{11}$$

Here, C_{day}^{actual} is actual operational cost of a day [cents], R^{RTP} is the DAP price [cents/kWh].

Constraints

Operation constraints of equipment in the smart house are shown in equations (12) ~ (16).

Constraints:

$$P_{Pt} < P_{Pt}^{contract} \tag{12}$$

$$|P_{Bt}| < P_{Bmax} \tag{13}$$

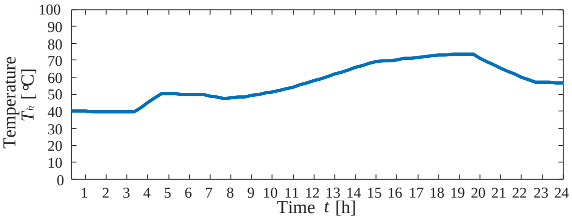
$$|P_{EVt}| < P_{EVmax} \tag{14}$$

$$0.2\ C_{Bmax} < C_{Bt} < 0.9\ C_{Bmax} \tag{15}$$

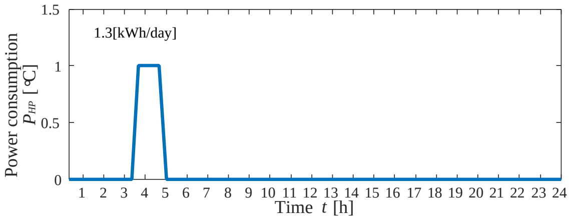
$$0.2\ C_{EVmax} < C_{EVt} < 0.9\ C_{EVmax} \tag{16}$$

Here, $P_{Pt}^{contract}$ is contracted maximum consumable electric power (4kW), P_{Bmax} is the maximum allowable value of discharge and charge power for the fixed battery (1kW), P_{EVmax} is the maximum allowable value of discharge and charge power for the EV (3 kW), C_{Bt} is the state of charge of the fixed battery, C_{EVt} is the state of charge of the EV, C_{Bmax} is the rated maximum storage energy of the fixed battery (3kWh), and C_{EVmax} is the rated maximum storage energy of the EV (16kWh).

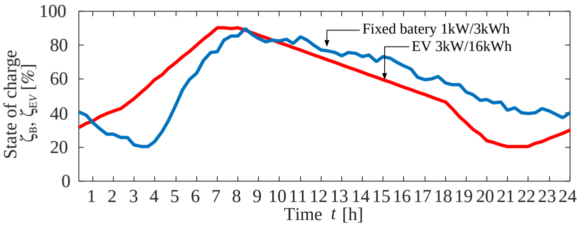
Equations (13) and (14) show the inverter constraints of the fixed battery and EV, respectively. Equations (15) and (16) show the state of charge constraints of the fixed battery and EV, respectively.



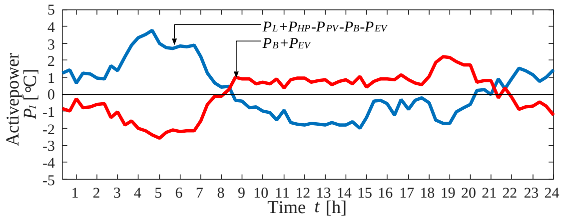
(a) Water temperature



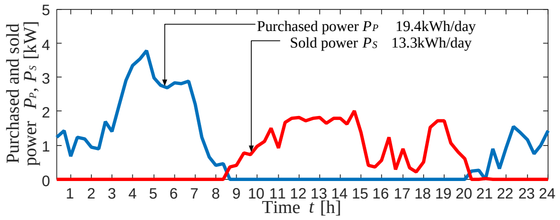
(b) Power consumption of HP



(c) State of charge for fixed battery and EV



(d) Supply power flow from infinite bus



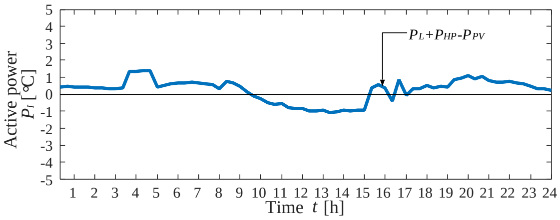
(e) Purchased and sold power

Figure 6 Simulation results of the smart house

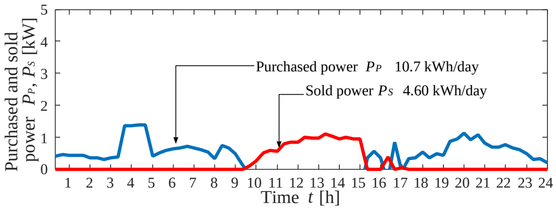
SIMULATION

Simulation conditions

The RTP price and the DAP price on the day in consideration are shown in Fig. 5. The RTP price and the DAP price are announced on August 7, 2012, and August 6, 2012, respectively. The power consumption excluding controllable loads and the PV output predicted on the previous day are shown in Fig. 5. The PV output is calculated by using equation (1). For the volume of hot water supply used in the smart house, 30L was used during the time period from 7 a.m. to 8 a.m. and 150L was used during the 3 hour period from 7 p.m. to 10 p.m. Also, if the temperature of the water in the storage tank dropped lower than 50 °C during the first time period, or lower than 60 °C during the second time period, the water was heated by the HP during the respective time period. The battery of the EV is assumed for an outdoor use of 700 Wh per hour for transportation from 8 a.m. to 6 p.m.



(a) Power consumpton



(b) PV output

Figure 7 Simulatin reslts of the traditonal house

Table 1 Comparison of electricity bill

	Predicted operational cost	**Actual operational cost**
Traditional house	12.3 [cent]	13.7 [cent]
Smart house	−17.6 [cent]	−11.5 [cent]

Simulation results

The simulation results for the proposed smart house are shown in Fig. 6. In Figs. 6(a) and (b), it can be observed that the goal temperatures of storage tank at 6 a.m. and 7 p.m. are fulfilled by HP and SC heating. Fig. 6(c) shows the state of charge for the fixed battery and EV, and it is found that the discharge and charge operations are performed within the terms of constraints. Figs. 6(d) and (e) show the current at the interconnection point between the power system and the smart house, and the purchased and sold power, respectively. From these figures, it can be seen that purchased power increases during times with a lower DAP price and sold power increases during times with a high DAP price. Therefore, benefits from selling electricity are obtained by supplying to the load and selling surplus electricity from the PV output and batteries.

Here, we compare the simulation results with those of a traditional house in order to show the economic effect of the smart house. In this paper, a smart house utilizing a PV generator, HP, and SC with an included fixed battery and EV is proposed. The traditional house is an all-electric house without a fixed battery or EV. The simulation results of the traditional house are shown in Fig. 7.

This figure shows that the amount of purchased power and sold power are small. Table 1 shows comparison results of the smart house and a traditional house. This table shows that the proposed smart house reduces the electricity bill in comparison to the traditional house. This shows that the smart house can obtain a larger profit than the traditional house by selling and buying the electric power.

CONCLUSION

Also, an optimal control method of the controllable loads, which minimizes the electricity bill, is planned by using a DAP price. The electricity bill is calculated by applying a RTP price when the plan is operated on a given day. Furthermore, the smart house is compared with the traditional house without the fixed battery or EV. The simulation results show the smart house reduced the electricity bill more than the traditional house, so that the economical effectiveness of the smart house is shown.

For future research, since only a prediction of the electricity bill by the DAP price only is insufficient, an RTP prediction method, such as the neural network method is proposed.

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