Cascade Use and Optimal Control of Solar Thermal Energy for Hybrid Solar Energy System

Masashi Ohkura[1*] and Shunsuke Mori[2]

[1] Department of Industrial Administration, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba, Japan

[2] Department of Industrial Administration, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba, Japan

[*] Corresponding Author, ohkura@rs.noda.tus.ac.jp

Abstract

Solar energy is a promising technology for reduction of CO2 emission with amenity of life. The use of solar energy is divided to two methods: electricity conversion and thermal energy conversion. In this paper, the authors describe about the combination use of photovoltaic and solar heat collector. The authors investigated the effect of operating condition of hybrid solar energy system on energy saving potential in Japan. Thermal output from the heat exchanger was 26.1% of total demand of room heating. The low supply point decreased the effect of reduction of room heating to 66%. The additional thermal energy for hot water supply also decreased. The reduction of room heating demand by hot water will be effective when the heat source of room heating has high environmental load or the efficiency of room heating apparatus is low. The total amount of surplus PV electricity in a day was 4147.0kJ on a holiday and was 2523.4kJ on a working day. The use of surplus electricity for hot water supply is effective for reduction of electricity in the evening.

1. Introduction

Energy consumption in Japan of a household was 42277.2MJ/year in 2008. The 46.6% of energy consumption was electricity and 53.4% of energy was heat supplied by utility gas, LPG, kerosene and other heat sources [1]. The amount of electricity consumption for household energy demand is increasing due to increase of implementation of electrical heat pump for air conditioning and hot water supply. On the other hand, kerosene remains a capital heat source for room heating. To replace kerosene with other renewable energy heat sources is an effective solution for reduction of CO2 emission.

Solar energy such as photovoltaic and solar heat collector is a promising technology. The effectiveness of solar energy varies by energy demands. The effectiveness of solar energy supply without energy storage becomes small for households which have a few inhabitants. The kinds of inhabitants also affects the effectiveness of solar energy. For example, worker is not home and does not consume energy in daytime in spite of higher solar irradiation.

Solar energy is converted to 2 kinds of energy: electricity and thermal energy. Photovoltaic can convert solar irradiation to electricity. The electricity can be used for several energy demands. However, electricity storage requires high cost and implementation rate is still low. Solar heat collector can supply thermal energy by using air or water. The efficiency of solar heat collector is higher than photovoltaic. Furthermore, solar thermal energy can store easily by using water storage. On the other hand, solar heat collector for household can supply low temperature heat. The use of low level heat is limited to hot water supply and room heating.

In this paper, the authors describes about hybrid solar energy system. The hybrid solar energy system consists of photovoltaic and solar heat collector. This hybrid system has hot water storage tank as thermal energy storage. Thermal energy supply by the water storage for room heating and room cooling is also investigated. Finally, we investigate optimal configuration and operating condition of the hybrid system to reduce energy supply from utility.

2. Hybrid solar energy system

2.1. System configuration and energy flows

Fig.1 shows the energy flows of hybrid solar energy system for household energy demands. Demands for electricity, hot water, room heating and room cooling are generated by action of inhabitants and by ambient condition. Electricity supplied by utility and solar irradiation are energy sources for this system. Photovoltaic (PV) supplies electricity and electricity is used for electricity demand directly and is supplied to heat pumps. The heat pump air conditioner supplies cooled air or warmed air. The other heat pump supplies hot water and hot water is stored to heat storage. Utility also supplies electricity to the same apparatuses. Solar irradiation is also supplied to solar heat collector (SHC). The solar heat collector heats water. The hot water is stored to heat storage tank. Hot water in the water storage tank is used for hot water demand directly. Hot water is further used as heat source for room heating and room cooling. The hot water warms air and the warmed air is supplied for room heating or desiccant cooling process. The desiccant cooling process dehumidifies and cools air in the room.

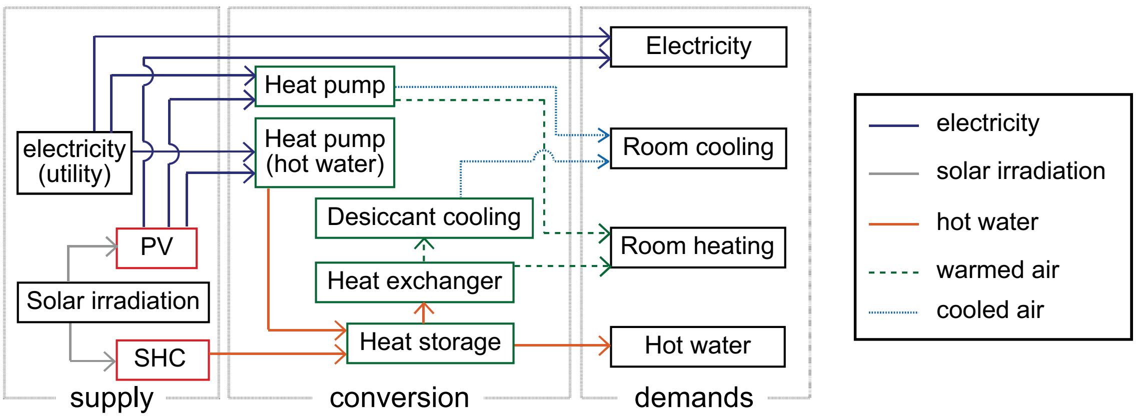

Fig.1 Energy flows of the hybrid solar energy system

2.2. Modelling of the system

We investigated energy saving potential of the hybrid solar energy system basing on water temperature in the system. The amount of electricity supplied by PV was calculated by solar irradiation and efficiency and surface area of PV. The ambient temperature affects PV efficiency.

Thermal energy supply by heat storage and the amount of water in the water storage used for hot water demand and demands of room heating and room cooling were defined by hot water temperature. Fig.2 shows the schematic of hot water supply process in the hybrid solar system. The heat pump supplies water which prescribed water temperature. Electricity demand for the hot water supply D_{E_HP} by electrical heat pump was calculated by Eq.1, where, m_2 is flow rate of water, c_{WTR} is specific heat of water. θ_{HP} and θ_2 are prescribed temperature of water and water temperature numbered in Fig.2, respectively. Note that flow rate of water supplied by electrical heat pump is limited by capacity of the heat pump.

$$D_{E\_HP} = m_2 \cdot c_{WTR} \cdot (\theta_{HP} - \theta_2) \tag{1}$$

Hot water temperature supplied by solar heat collector θ_{3_SHC} was estimated by Eq.2, where S_{SHC} is surface area of SHC, J is solar irradiation, W_2 was thermal flow rate of water and η_{SHC} is efficiency of SHC estimated by Eq.3, where, η_{SHC_MAX} is maximum efficiency of SHC, r_o and r_c are thermal penetration of SHC, T_{AMB} is ambient air temperature. Flow rate of water supplied to SHC was determined by surface of SHC. In this study, flow rate of water was 0.001m^2/ (min · m^2-SHC).

$$\theta_{3\_SHC} = \theta_2 + S_{SHC} \cdot J \cdot \eta_{SHC} / W_2 \tag{2}$$

$$\eta_{SHC} = \eta_{SHC\_MAX} - (r_o + r_c) \cdot (\theta_2 - T_{AMB}) \tag{3}$$

The heat storage tank stores hot water supplied by SHC or electrical heat pump. The thermal storage tank is first filled with water supplied from water line and the water is replaced by hot water. Temperature of water in the water storage tank has temperature distribution. We calculated temperature distribution in the water storage tank. The basic calculation model was mentioned by Yokoyama et al [2]. Temperature of water at the top of water storage tank is highest and decreases gradually into the bottom of water storage tank. The Yokoyama's model assumed that hot water is supplied only by heat pump. Thus, temperature of water is higher than that in the water storage tank and it is suitable that inlet point of hot water to water storage tank is top of water storage. In this model, there is no guarantee that temperature water supplied by SHC becomes higher than that in the water storage tank. We assumed that temperature of hot water supplied by SHC and that in the water storage tank affects inlet point of hot water due to density of water. The heat storage tank has two water supply points. Therefore, water flow rate in the water storage tank is calculated by supply flow rate of water in

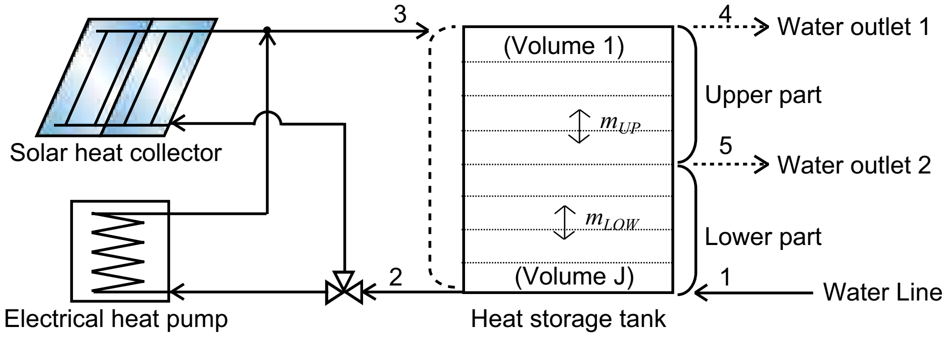

Fig.2 Schematic of the water heating and storage process

each position and inlet point (inlet temperature) of hot water. The water flow rate in the upper part and lower part of water storage tank is calculated from Eq.4 and Eq.5, respectively. Symbols of θ_{j_UP} in Eq.4 and θ_{j_LOW} in Eq.5 are water temperatures in each volume in the water storage.

$$m_{UP} = m_3 - m_4, \theta_3 < \theta_{j\_UP} \Rightarrow m_3 = 0 \tag{4}$$

$$m_{LOW} = m_3 - m_4 - m_5, \theta_3 < \theta_{j\_LOW} \Rightarrow m_3 = 0 \tag{5}$$

Hot water is supplied to heat exchanger for room heating or room cooling. Thermal output of the heat exchanger HS_{HEX} is calculated by temperature of hot water and air and heat exchanger efficiency η_{HEX} in Eq.6.

$$HS_{HEX} = \eta_{HEX} \cdot W_{AIR} \cdot (\theta_{WTR} - T_{ROOM}) \tag{6}$$

The warmed air is supplied to room directly for room heating. The hot air is also used as heat source of the desiccant cooling process. The warmed air temperature T_{OUT_HEX} is estimated by Eq.7.

$$T_{OUT\_HEX} = T_{ROOM} + HS_{HEX} / W_{AIR} \tag{7}$$

Cooling effect of the desiccant cooling system strongly depends on its driving temperature. Temperature of warmed air is calculated by Eq.6. In this study, we estimated cooling effect of the desiccant cooling process from examination results [3-5]. Demands of room heating and room cooling are influenced by inhabitants. When thermal output from the heat exchanger becomes surplus against room heating demand, thermal output of heat exchanger is adjusted to room heating demand by changing efficiency of heat exchanger due to changing flow rate of water from the water storage [6]. Cooling effect of the desiccant cooling process is also adjusted to room cooling demand by changing thermal output of the heat exchanger and by driving temperature of the desiccant cooling system.

3. Simulation case study

3.1. Operating parameters

In this paper, we describe energy saving potential of the hybrid solar energy system in a week in winter. The surface area ratio of PV and SHC is main operating parameter in this hybrid solar energy system. The use of hot water in the water storage can reduce electricity for room heating. High temperature water can supply a large amount of thermal energy and requires a large amount of electricity for heat pump. The authors further consider operating condition: the amount of hot water supplied by heat pump and the temperature level of hot water for room heating.

Table.1 indicates efficiency of apparatuses in the hybrid system and operating condition of the case study. Surface area ratio of PV and SHC is 2:3 in the hope that high reduction of energy demand is achieved by hybrid solar energy system [7]. Total surface area for solar irradiation collecting is $25m^2$. Case0 is a base case. The hot water in the water storage is not supplied for room heating or room cooling in Case0. Heat pump supplies 60^oC of hot water. The stoppage point of hot water means the amount of stored water in the water storage. The stoppage point describes as a relative position of water storage tank and the value of 0.0 is the top and 1.0 is the bottom of water storage. The heat pump stops when water temperature at the stoppage point reaches the stoppage temperature. Case1 supplied hot water to heat exchanger for room heating. The other condition is same as Case0. Water

Table.1 Efficiency of apparatuses and operating condition in each case

Parameters	Case0	Case1	Case2	Case3
Efficiency of PV [-]	0.108			
Volume of water strage tank [m^3]	0.30			
Capacity of heat pump for water heating [kW]	4.50			
COP of heat pump for water heating [-]	3.00			
COP of heat pump for room heating [-]	2.50			
Surface area of SWH [m^2]	10.0	10.0	10.0	10.0
Surface area of PV [m^2]	15.0	15.0	15.0	15.0
Stoppage temperature of heat pump [^oC]	42.0			
Stoppage point of heat pump [-]	0.975			
Hot water supply temperature [^oC]	60.0	60.0	50.0	60.0
Supply temperature of hot water for room heating [-]	-	30.0	30.0	30.0
Supply point of hot water for room heating [-]	-	0.25	0.25	0.75

temperature supplied from heat pump is lower in Case2. In Case3, supply point is located in lower part of water storage tank. Therefore, Hot water will be not supplied to heat exchanger until water storage tank will be filled with hot water.

3.2. Energy demands

Energy demands were calculated from the action of the inhabitants and ambient condition. In this study, the kind of day, which is working day or holiday, changes the action of inhabitants. The actions of the inhabitants and ambient condition are defined by documents [8-9]. Fig.3 shows time variations of electricity demand and room heating demand and Fig.4 is the required amount of heat for hot water supply. The room heating demand increases in early morning and decreases in the daytime due to increase of solar irradiation and ambient temperature. Absence of inhabitants further decreases room heating demand. This paper investigates the amount of energy required in a winter week inclusive four

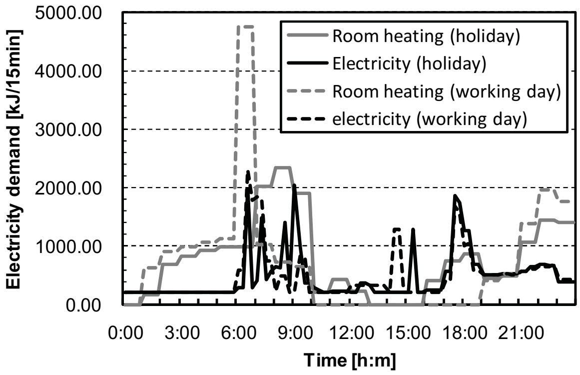

Fig.4 Time variations of electricity demand in a working day and a holiday

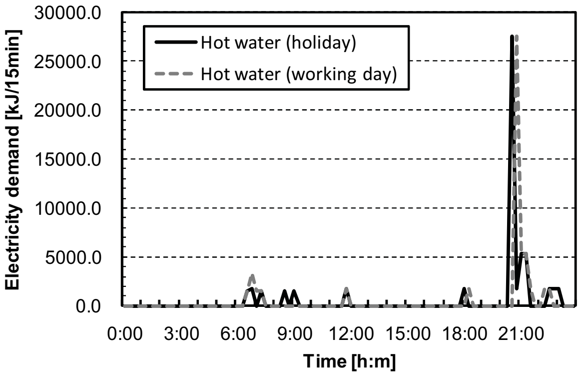

Fig.5 Time variations of electricity demand for hot water supply in a working day and a holiday

holidays and three working days. Total electricity demand in a week is about 88.34kWh and thermal energy demand for hot water in a week is 391MJ. Thermal energy for room heating in a week is 1360.2MJ.

4. Simulation results and discussions

4.1. Energy supply from the hybrid solar energy system

Table.2 summarizes the amount of energy supplied from the hybrid solar energy system and electricity demand for the system. Surface area of PV was set to same in every case. PV electricity was not used for heat pump hot water supply in Case1, Case2 and Case3. As a result, the amount of electricity from the PV became same value. In Case0, PV electricity was used for room heating in the early morning.

Thermal output for room heating by heat exchanger in Case1 was 355.1MJ in a week and was 26.1% of total room heating demand in a week. The thermal output in Case2 was 253.8MJ and was lower than Case1 since water temperature in the water storage tank was low (50^{o}C). Electricity demand of heat pump for hot water supply was also low in Case2. However, the additional thermal energy for hot water supply became highest in Case2. Therefore, 50^{o}C of water temperature was not enough for demands of hot water and room heating. The supply point of Case3 was lower than other cases. Thermal output from heat exchanger in Case3 decreased to 236.4MJ and was 66.6% of Case1. The additional thermal energy for hot water in Case3 was 71.98MJ and can be reduced 45.3% compared to Case1 since the amount of hot water stored in the water storage was larger than that in Case1. Electricity demand for heat pump hot water supply became small in Case0. In Case0, water temperature at the stoppage point reached the stoppage temperature and the working time of heat pump became short. The worth of the reduction of room heating demand by water storage tank is influenced by the heat source of room heating. The reduction of room heating by hot water will be effective when the heat source of room heating has high environmental load or the efficiency of room heating apparatus is low.

Table.2 The amount of energy supplied by the hybrid solar energy system and electricity demand

Parameters	Case0	Case1	Case2	Case3
Electricity demand in a week [kWh]	88.34			
Efficiency supplied by PV [kWh]	32.51			
PV electricity used for electricity demand [kWh]	20.27	22.40	22.40	22.40
Surplus electricity of PV [kWh]	12.25	10.11	10.11	10.11
Thermal energy demand for room heating [MJ]	1360.2			
Thermal output from heat exchanger [MJ]	-	355.1	253.8	236.4
Additional thermal energy for room heating [MJ]	1360.2	1005.1	1106.40	1123.8
Electricity demand for heat pump of hot water supply [kWh]	45.93	78.44	62.96	78.44
Additional thermal energy for hot water supply [MJ]	22.19	131.5	203.6	71.98

4.2. Behaviour of the hybrid solar energy system in a day

Operating condition also affects energy saving potential of the system. Fig.6 shows the time variations of electricity demand for hot water supply, room heating and electricity demand and electricity supplied from PV in Case1 and Case3. Electricity is required for heat pump for hot water supply in the midnight and early morning. This means heat pump is working in this time. The working time of the heat pump was same as the scheduled time. Therefore, water temperature at the stoppage point did not reached the stoppage temperature in both cases. Electricity for room heating was not required from 0:00 to 6:00 on holiday in Case1 since high temperature water, which was almost 60°C, was supplied to heat exchanger. On the other hand, in Case3, 720.6MJ of electricity was required from 1:00 to 2:00 since water temperature at the supply point did have not reached supply temperature. Electricity demand from 2:00 to 6:00 varied from 0MJ to 981.5MJ intermittently. This behaviour is attributable to decreasing of water temperature at the supply point. The cold water from the water line was supplied from the bottom of water storage. Therefore, low supply point influenced temperature of water supplied to heat exchanger. Higher supply point had a high temperature of water under the supply point. Therefore, thermal energy supplied from heat exchanger was stable. However, the same fluctuation of thermal energy output had been seen in Case1 on working day due to increase of room

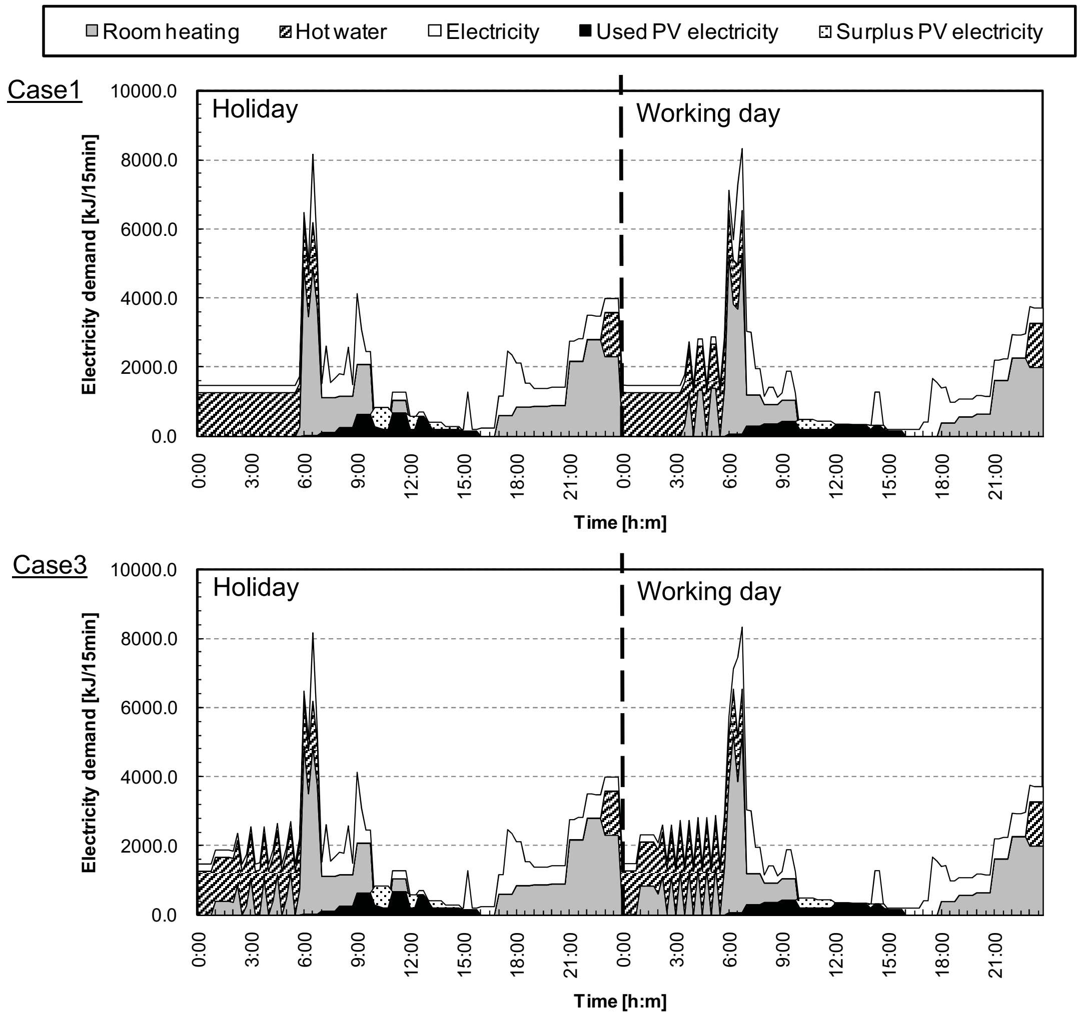

Fig.6 Time variations of electricity for room heating, hot water supply by heat pump and electricity demand and the amount of electricity supplied by PV.

heating demand. Case1 could reduce thermal energy for room heating. However, Thermal energy for room heating was required in the night in both cases. Hot water demand generates in the evening. Temperature of water became low in the night. No hot water was stored in the water storage at 22:45. Therefore, additional thermal energy was required to satisfy hot water demand (as shown in Table.1).

PV electricity became surplus at 10:00 and in the daytime due to decrease of room heating demand. The maximum amount of surplus electricity in 15 minutes in both cases was 289.3kJ. On the other hand, electricity was required for hot water supply and room heating after 18:00. Therefore, the surplus PV electricity can be used for hot water supply. The total amount of surplus PV electricity in a day was 4147.0kJ on a holiday and was 2523.4kJ on a working day. Lower surplus electricity on a working day was caused by low solar irradiation.

5. Conclusions

The authors investigated operating condition and energy saving potential of the hybrid solar energy system. 50^{o}C of hot water could not satisfy room heating and hot water demand. In this case, electricity for room heating and additional thermal energy for hot water supply increased. The lower supply point decreased the effect of reduction of room heating. However, additional thermal energy for hot water supply also decreased. The effect of the reduction of each demand strongly depends on energy source of each demand. Hot water room heating is effective when thermal energy for room heating demand is supplied by low efficiency apparatuses.

System behaviour and energy thermal energy output varied with operating condition. Higher supply point stabilized thermal output of heat exchanger. On the other hand, additional thermal energy for hot water supply increased at the higher supply point. Surplus PV electricity is mainly generated in the morning. The use of surplus electricity for hot water supply is effective for reduction of electricity in the evening.

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