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Development of an Operation Control System for Photovoltaics and Electric Storage Heaters for Houses Based on Information in Weather Forecasts*

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Abstract
An all-electric home using an electric storage heater with safety and cleaning is expanded. However, the general electric storage heater leads to an unpleasant room temperature and energy loss by the overs and shorts of the amount of heat radiation when the climate condition changes greatly. Consequently, the operation of the electric storage heater introduced into an all-electric home, a storage type electric water heater, and photovoltaics was planned using weather forecast information distributed by a communication line. The comfortable evaluation (the difference between a room-temperature target and a room-temperature result) when the proposed system was employed based on the operation planning, purchase electric energy, and capacity of photovoltaics was investigated. As a result, comfortable heating operation was realized by using weather forecast data; furthermore, it is expected that the purchase cost of the commercial power in daytime can be reduced by introducing photovoltaics. Moreover, when the capacity of the photovoltaics was increased, the surplus power was stored in the electric storage heater, but an extremely unpleasant room temperature was not shown in the investigation ranges of this paper. By obtaining weather information from the forecast of the day from an external service using a communication line, the heating system of the all-electric home with low energy loss and comfort temperature is realizable.

Key words: Operation Control, Electric Storage Heater, Weather Forecasts, Photovoltaic, All Electrification Equipment, Information Aided Operating

1. Introduction

The spread of all-electric homes has expanded due to the importance of safety and limiting the emission of gases [1]. In an all-electric home in a cold region, an electric storage heater is often introduced into each room [2] . Because the midnight power is used as a power source for the electric storage heater, it contributes to the load leveling of the power generation equipment of the power company. When cheap midnight power is used, there are many examples of the advantageous cost compared to oil heating. Moreover, heating during the day is possible for the electric storage heater, and there is also no discharge of an exhaust

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gas from a house. The typical structure of a cold region house in recent years has excellent air leakage efficiency and insulation efficiency. If an electric storage heater is installed in such a cold region house, energy savings and comfortable residential space can be obtained. However, the amount of heat storage of a popular electric storage heater is manually set by the resident or is microcomputer control using an easy temperature sensor. In these cases, if the change in climate conditions is large, overs and shorts in the amount of heat radiation will occur, and an unpleasant room-temperature change and large energy loss will occur. For example, opening a window in the midwinter and taking the open air into the room and the use of an oil portable stove simultaneously occur frequently. Recently, the installation of communication lines, such as ADSL (asymmetric digital subscriber line), and optical cables in houses has expanded. Therefore, in this paper, the operation of cold region houses with electric storage heaters, a storage type electric water heater, and photovoltaics is planned based on the weather forecast information distributed by a communication line. When the system is operated based on this operation plan, there are few overs and shorts in the amount of heat radiation when the climate condition changes, and the realization of an all-electric home with a comfortable room temperature environment is expected.

A control computer receives weather forecast information for one day by 0:00 am of the target day. Accordingly, photovoltaic power and the load of the electric storage heater are predicted using the weather forecast information for the day received at 0:00 am of the target day. Moreover, the photovoltaic power is supplied for the power load of a household appliance and a cooking heater, an electric storage heater, and a storage type electric water heater. The insufficient electric power of photovoltaics is supplemented with the purchase of commercial electric power. However, the insufficient electric power of an electric storage heater and a storage type electric water heater requires night power. In this paper, the room temperature error when the proposal operation control system is introduced into an all-electric home of a cold region, the amount of daytime electric power and night power purchased, and the influence of the capacity of photovoltaics are clarified.

2. Proposed System

2.1 System configuration

Figure 1 shows the scheme of the proposed system. The electric power from photovoltaics is converted into an alternating current from the direct current by a power conditioner, and it is also adjusted to the frequency within regulation. This electric power can be distributed to various household appliances and a cooking heater, an electric storage heater, and a storage type electric water heater through a distribution board. Electric power and heat equipment shown in Fig. 1 are operated by the adjustment of SW1 to SW3 by a system controller. Moreover, weather forecast information using a communication line is periodically inputted into the controller. The controller plans the system management in the procedure described in Section 3 using this information. In addition, in this paper, in order to prevent the influence of the commercial power system of the installation of the proposed system, the electricity sale to utilities of the surplus power of the photovoltaics was not taken into consideration.

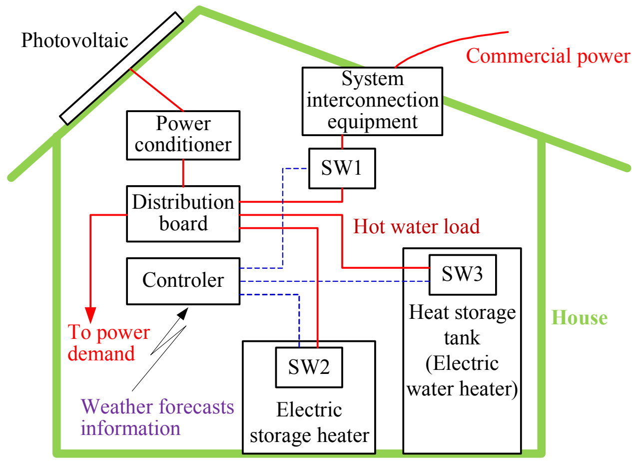


Fig. 1 System scheme

2.2 Operation of system

Figure 2 is a chart showing the relation between the schedule of the operation plan by the system controller, the power load, and the power supply. Figure 2 shows the system management for two days, Day n and Day $n+1$. The controller obtains weather information (outdoor air temperature $T'_{\infty,u}$, the amount of global solar radiation $q'_{s,u}$, where $u=0,1,2,...,23$) with a constant time interval using a communication line. An algorithm installed in the system controller plans the operation of the system shown in Fig. 1. In detail, the system controller predicts the power of the photovoltaics, the load of the storage type electric water heater, and the electric storage heater based on weather information for every time. If each value (the production of the electricity of the photovoltaics and the load of the storage type electric water heater and the electric storage heater for every time) described above is found correctly, the amount of night power supplied to the storage type electric water heater and the electric storage heater can be planned to be the minimum required.

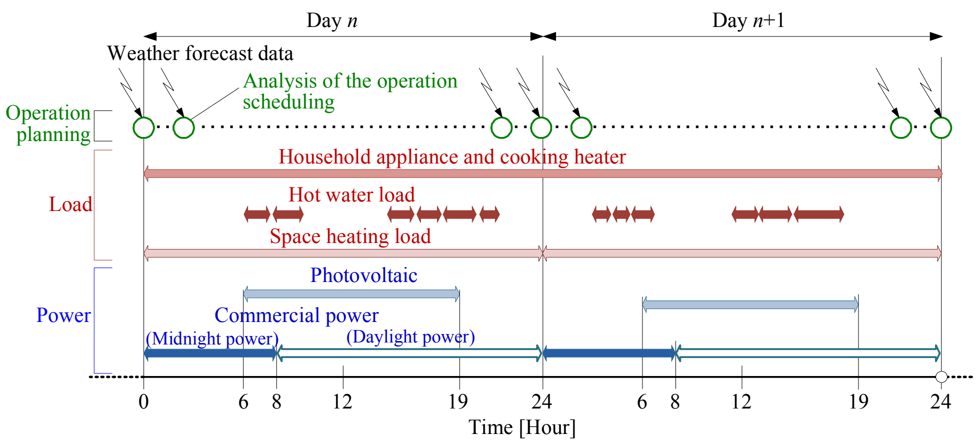
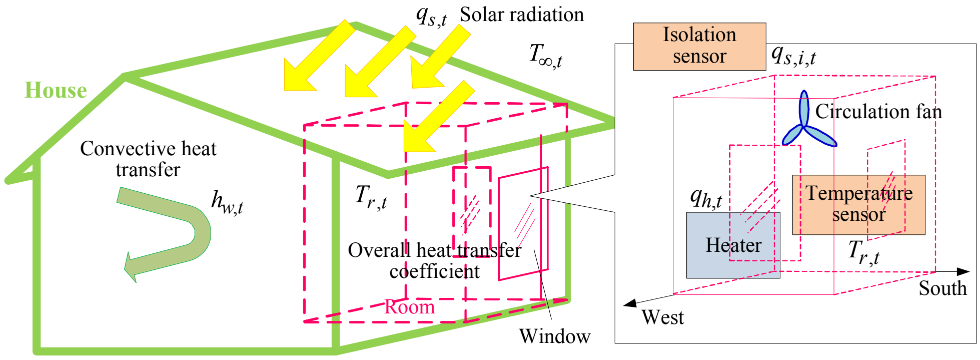


Fig. 2 System operation method in winter

3. Planned Method of Operation

3.1 Balance of space heating load

In order to obtain the space heating load of individual houses correctly by numerical



(a) Heating system for house (b) Instrumentation system

Fig. 3 Heating system and room model

analysis, it is necessary to know the specifications and the property values of all the structural members. In addition, in order to estimate the space heating load correctly by experiment, it is necessary to investigate many environmental conditions, such as outside air temperature, amount of insolation, and heat transfer rates. The space heating load of the house shown in Fig. 3 (a) is represented by the room model shown in Fig. 3 (b).

Equation (1) is the heat balance expression of the room model. The left side of Eq. (1) is heat entering the room model by solar radiation and heat transfer. The right-hand side is each term of the electric storage heater and elements with heat generation. The amount of insolation is $q_{s,i,t}$ at time t. However, solar radiation reaches the roofs and outer walls of $i=1$ to N_{ws}. Each area of these acceptance surfaces is $a_{ws,i}$, and heat enters the room model at the rate of r_i in proportion to the magnitude of solar radiation. On the other hand, on roofs and outer walls $j=1$ to N_{ws}, heat enters the room model by heat transfer. δ_j and λ_j express the thickness of the outer wall and the heat conductivity, respectively. $a_{wh,j}$ is the area of the roofs and outer walls j. $h_{\infty,j,t}$ and $h_{r,t}$ are the heat transfer rates of roofs or outer walls and the room walls of the room model, respectively. Furthermore, $T_{\infty,t}$ and $T_{r,t}$ are the outside air temperature and the mean temperature of the room model. $q_{hs,t}$ on the right-hand side is the amount of heat radiation of the electric storage heater at time t, and $q_{e,k,t}$ is the heat generation of a human body or electric appliances. The number of heat generation terms is expressed as N_e, and all the terms are calculated.

$$-\sum_{i=1}^{N_{ws}}\left(a_{ws,i}\cdot q_{s,i,t}\cdot r_i\right)+\sum_{j=1}^{N_{ws}}\left(a_{ws,j}\cdot\frac{1}{1/h_{\infty,j,t}+\delta_j/\lambda_j+1/h_{r,t}}\cdot\left(T_{r,t}-T_{\infty,t}\right)\right)=q_{hs,t}+\sum_{k=1}^{N_e}q_{e,k,t} \quad (1)$$

3.2 Estimation of the space heating load

The calculation of the space heating load of the room model uses the simple method described below in this paper. In order to use this simple method, the experimental equipment shown in Fig. 3 (b) is installed in the room model. The space heating load is varies with the outside air temperature $T_{\infty,t}$ and the amount of insolation $q_{s,i,t}$ measured with this experimental equipment. Indoor air was heated with an electric heater, and the indoor temperature characteristics in this case were investigated. During this experiment, the indoor air was always agitated with a fan. By investigating many combinations of outside air temperature $T_{\infty,t}$ and amount of insolation $q_{s,i,t}$, the relation between the space heating load of the room model and the climate conditions can be found. Accordingly, predictors of the outside air temperature and the amount of insolation ($T'_{\infty,t}$, $q'_{s,i,t}$) are given by this relation, and the space heating load of the room model can be found. If the method described above is used, although it is not very precision, the space heating load under various environmental conditions of the room model can be obtained.

3.3 Space heating load characteristics of the room model

Figure 4 shows an example of experimental results for the relation between the space heating load of the room model, the amount of insolation, and the outside air temperature as described in Section 3.2. The specification of the house and the room model that were used for this experiment are shown in Tables 1 and 2. The experimental result of Fig. 4 is the space heating load to maintain the room temperature at about 25℃. Figure 4 shows that the influence of the outdoor air temperature is strong, although the space heating load of this room model is slightly influenced by the amount of insolation. Therefore, in the next analysis, the heat load of the room model was calculated by installing an approximate linear line between the space heating load and the outside air temperature shown in Fig. 4.

Although the representative room is investigated in the next analysis example, approximate lines of the space heating load for all rooms in the individual house can be obtained by the method described in Sections 3.1 to 3.3. Accordingly, if the space heating loads of all rooms of individual houses are considered, the detailed operation method of the proposed system can be obtained.

Table 1 House model

Two-story wooden house
All-electric hose, Airtight and thermally insulated house
Floor space : 143 m^2 (6 rooms, 1 bath room, 2 rest rooms)

Table 2 Model room

Floor space : 9.72 m^2, Room volume 23.5 m^2
Window : South face 0.54 m^2 and west face 1.94 m^2
Electric storage heater :
Heat storage type with natural-convection system
The amount of heat storage capacity 49000 kJ/8 hour

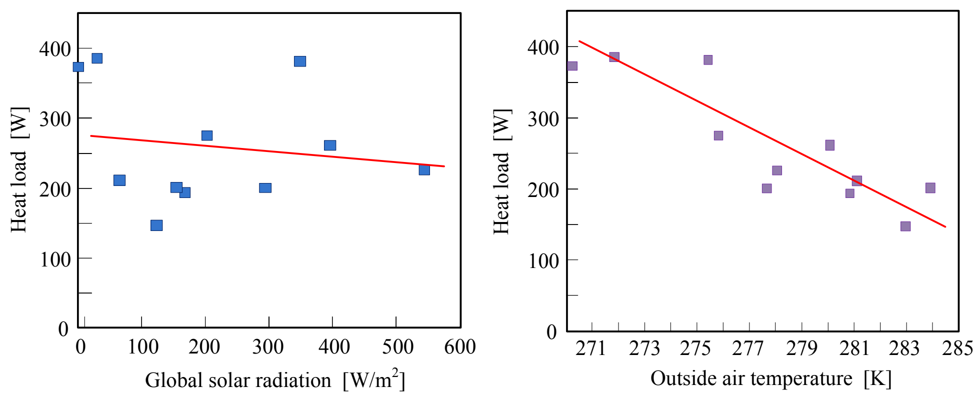


Fig. 4 Experimental result of the heat load on a model room.
Heating value Required to raise the room temperature to 293 K.

4. Analysis Example

4.1 Housing model and room model

This analysis estimates the performance of the operation control of an individual house (a housing model) in Sapporo, as shown in Table 1, with the space heating load characteristics described in Fig. 4. According to measurement results of power consumption, the space heating load of the whole housing model is about 8 times the load (Fig. 4) of the room model shown in Table 2. The housing model has high airtightness and insulation properties, and mechanical ventilation is installed in all rooms. Accordingly, this housing model is typical of cold region specifications. In addition, electrical equipment and heat equipment shown in Fig. 1 were installed in the housing model.

4.2 Meteorological model

In the analysis of this paper, the actual meteorological data in March, 2007 for Sapporo, Japan were used. Because the outside air temperature and the amount of insolation in March change sharply, weather prediction in this month is difficult compared with other months. Figure 5 shows March 1, 2007 average outside air temperature [3]. In this paper, the proposed system shown in Fig. 1 was installed in the period of March 5 to 9 when the outside-air-temperature change was large. The average outside air temperature on March 19 was the nearest to the monthly average outside air temperature in March. Consequently, the analysis result on March 19 was compared with the results of March 5 to 9. It is thought that the operation method based on March 19 simulates a setting method for the heat storage amount of the present electric storage heater because many setting methods for the heat

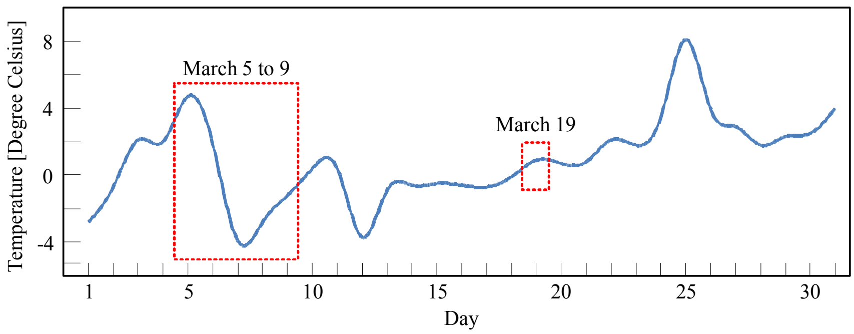


Fig. 5 Outside temperature of March, 2007 Sapporo

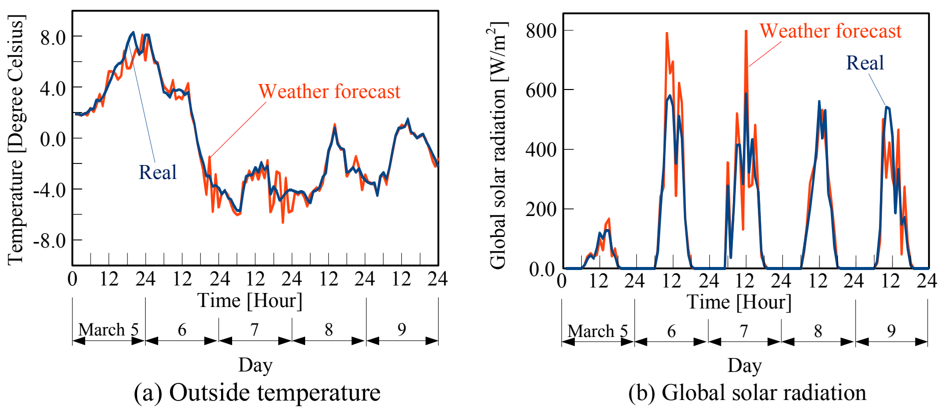


Fig. 6 Weather data and weather forecast data in Sapporo in March 5 to 9, 2007.

storage amount of the present electric storage heater involve manual operation.

4.3 Weather forecast information

Figure 6 shows an example of the measured data [3] of the outside air temperature, the amount of global solar radiation, and the weather forecast data of the period on March 5 to 9, 2007. An error is included in the weather forecast data. There is an example of the investigation of the error between weather forecast data and actual meteorological data [4-6]. After 24-hours the forecast accuracy of the outside air temperature by publication of the Japanese Meteorological Agency is about 20% in an annual average [6]. However, because changes of the outside air temperature in mid season are sharp, it is expected that the weather forecast error becomes even worse. Therefore, in this paper, the inaccuracy 24 hours after the receiving time (0:00 ($t=0$) is assumed at midnight) ($t=24$) of the weather forecast information ($T'_{\infty,t}$) of the outside air temperature was set to 60%. On the other hand, the predicted value of the amount of global solar radiation ($q'_{s,t}$) was set to include the maximum 100% error at the time of sunset. Weather forecast information ($T'_{\infty,t}, q'_{s,t}$) will increase error, if the elapsed time increases from the receiving time $t=0$ of the weather forecast information. The weather forecast information used in the analysis was calculated from Eqs. (2) and (3) such that the error characteristics described above may be expressed. Here, $T_{\infty,t}$ and $q_{s,t}$ are the actual measured outside air temperature and the amount of global solar radiation, e_t and e_q are coefficients decided from the inaccuracy 24 hours after the receiving time of the weather forecast information, and R is a random number, $0 \le R \le 1$.

$$T'_{\infty,t} = T_{\infty,t} \cdot \left(1 + t \cdot e_t \cdot (0.5 - R)\right) \tag{2}$$

$$q'_{s,t} = q_{s,t} \cdot \left(1 + t \cdot e_q \cdot (0.5 - R)\right) \tag{3}$$

4.4 Water-heating load and power load

Figure 7 shows an example of measurement of the water-heating load and power load in an individual house in Sapporo [7, 8]. The load of hot water supplied for housekeeping, drinking, and bathing is included in water-heating load, and this hot water is supplied from the storage type electric water heater. On the other hand, the power load expresses the load of a household appliance and a cooking heater. The value of the storage type electric water heater and the electric storage heater are not included in the power load.

Electric power can be supplied to the power load and the storage type electric water heater, and the electric storage heater can use commercial electric power (night power) and a solar

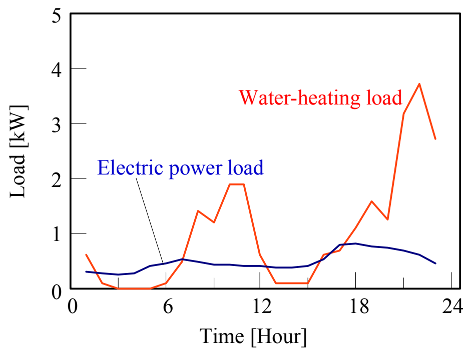


Fig. 7 Energy load of an individual house in Sapporo [7,8]

photovoltaic system. Furthermore, these power supplies can be changed at any time.

5. Procedure of the Operation Plan

Figure 8 shows the flow of the operation planning of the proposed system and the operation control of the proposed system. This control flow consists of an operation plan and system management. Operation of the proposal system was planned based on the weather forecast data.

However, the following conditions were set in the system management of this paper.

(1) The weather forecast data (outside air temperature and the amount of global solar radiation) can be obtained through a communication line by 0:00 of the target day.

(2) The electric power of photovoltaics and the supply for the power load (household appliance), space heating load (electric storage heater), and water-heating load (storage type electric water heater) were set.

(3) In the purchase of commercial electric power, 9:00 am to 12:00 pm, is daytime power, and 0:00 am to 8:00 am is midnight power.

(4) The insufficient electric energy of the photovoltaics for the space heating load (electric storage heater) and water-heating load (storage type electric water heater) were covered by the purchase of midnight power. Here, the purchase electric energy of midnight power was equally planned at each time (from 0:00 am to 8:00 am).

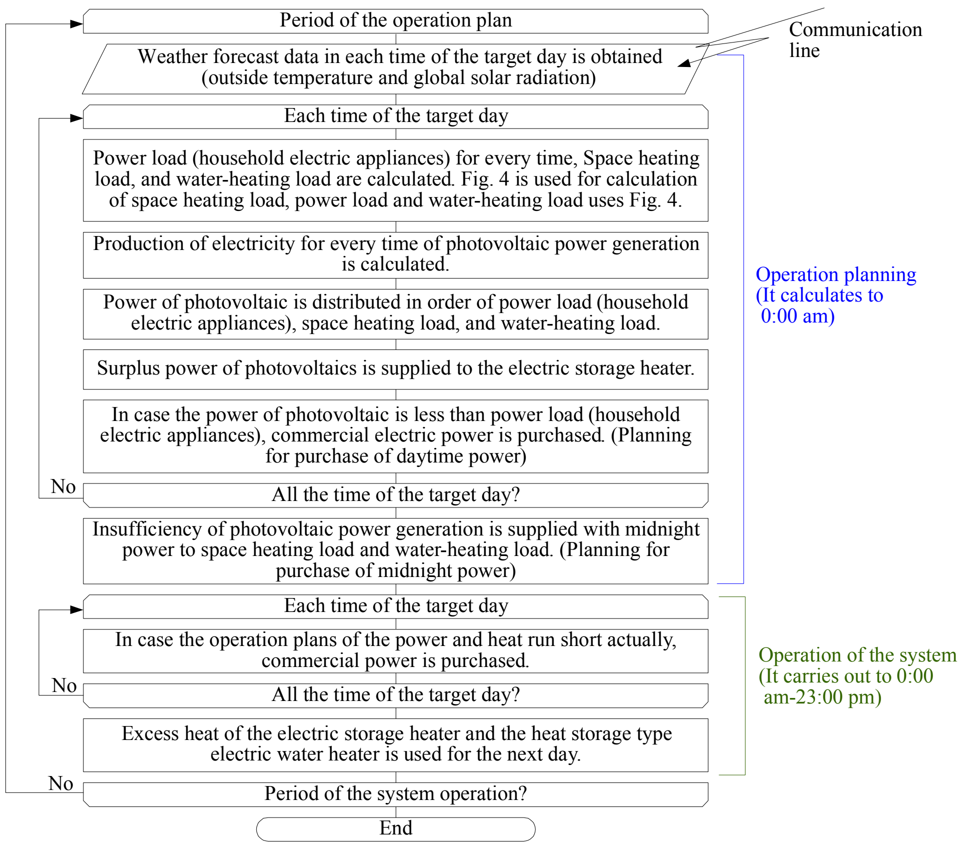


Fig. 8 Control flow of the operation planning and system operation

6. Analysis Results

6.1 Weather forecast data and actual weather data

Figure 9 shows the measured data [3)] and weather forecast data of the outside air temperature and the amount of global solar radiation of the period from March 5 to 9, 2007. All weather forecast data were calculated using the method described in Section 4.3. The weather forecast data of outside air temperature and the amount of global solar radiation change with the values of the random number R included in Eqs. (2) and (3). Therefore, in the analysis of this paper, the weather forecast data of Fig. 9 obtained with random numbers was used. Compared with the measured data of the outside air temperature and the amount of global solar radiation, for each forecast data of late time, the difference becomes large. If the measured data and forecast data of the outside air temperature and the amount of global solar radiation are compared, the difference of the data will become large over time.

6.2 Change of room temperature

Figure 10 shows the difference of the room-temperature target of the room model and the room temperature obtained for the operation results in the operation analysis of the proposed system. Figs. 10 (a) and (b) show the effects of installing a solar photovoltaic system. The area of this solar cell module was 40 m^2, and the power generation efficiency was 19%. Figures 10 (a) and (c) show the operation results of the proposed system based on the meteorological data (the outside air temperature and the amount of global solar radiation on March 19) for the average temperature in March. This operation method assumes continuous running every day of the electric storage heater using the monthly mean outside air temperature. On the other hand, the results of Fig. 10 (b) and (d) relied on the weather forecast data of the same day by a communication line at 0:00 a.m. of that day and uses

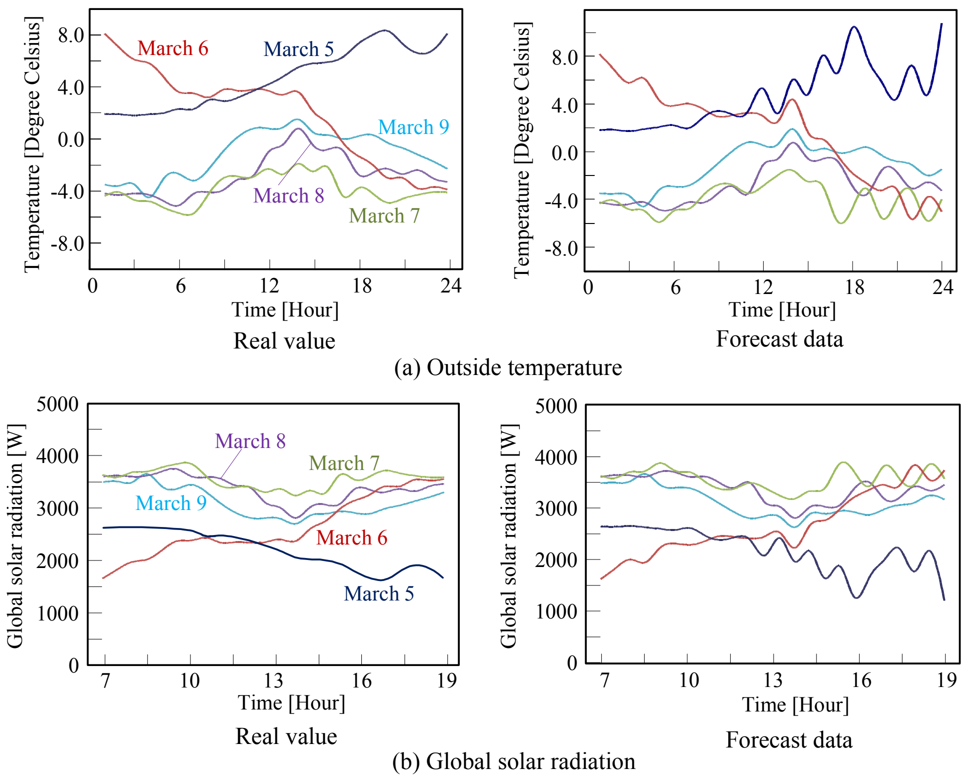
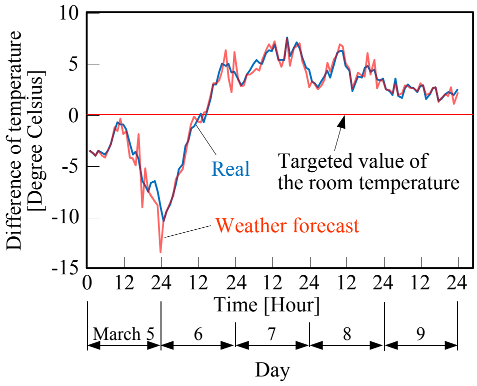
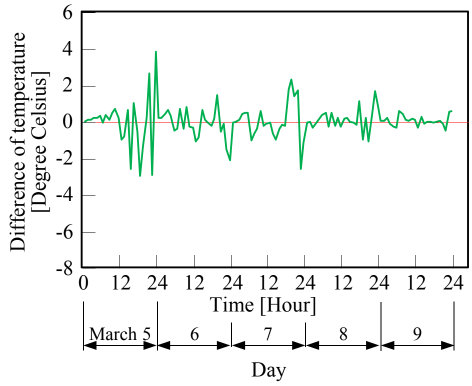


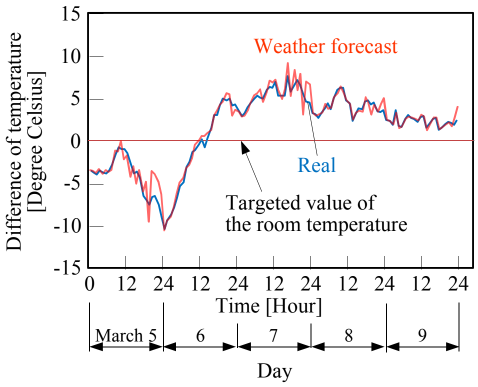
Fig. 9 Outside temperature and global solar radiation in Sapporo in March 5 to 9, 2007



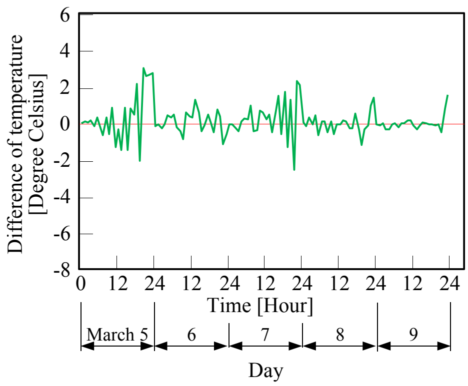
(a) Change of the room temperature when operation of the electric storage heater is planned according to the weather data on March 19 (average temperature in March). Area of the solar cell module 40 m^2.



(b) Change of the room temperature when operation of the electric storage heater is planned at 0:00 midnight according to a weather forecasts. Area of the solar cell module 40 m^2.



(c) Change of the room temperature when operation of the electric storage heater is planned according to the weather data on March 19 (average temperature in March). Without photovoltaics.



(d) Change of the room temperature when operation of the electric storage heater is planned at 0:00 midnight according to a weather forecasts. Without photovoltaics.

Fig. 10 Analysis results of the room temperature

system management based on this forecast data. When installing photovoltaics into a system (Figure 10 (a) and (b)), two prediction errors in the outside air temperature and the amount of global solar radiation are included in the operation planning. As a result, compared with the system (Fig. 10 (c) and (d)) without photovoltaics, the difference between the temperature and the room-temperature target may be large. The differences between the room-temperature target of Figs. 10 (a) and (c) and the room-temperature results differ. If photovoltaics are not installed, the difference described above is small. Furthermore, if Figs. 10(a) and (b), and Figs. 10 (c) and (d) are compared, respectively, and the weather forecast data is used for the operation planning of the electric storage heater, the difference between the room-temperature target and the room-temperature result is small, and comfortable heating operation is obtained.

6.3 Amount of electric power purchased

Figure 11 shows the analysis results of the electric-power plan purchased when using the proposed system without a solar photovoltaic system. On the other hand, Fig. 12 shows the analysis results of the electric-power plan purchased in the case (the area of a solar cell module is 40 m^2, and power generation efficiency is 19%) of installing a solar photovoltaic system in the proposed system. From Figs. 11 (c) and 12 (c), the amount of electric power

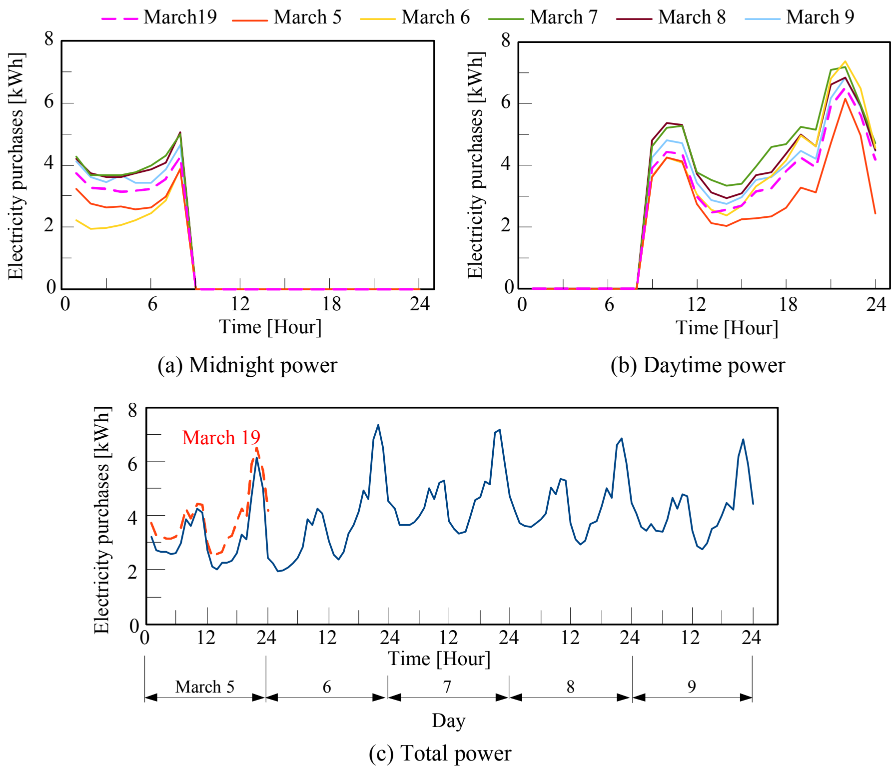


Fig. 11 The amount of electricity purchases. Without photovoltaics.

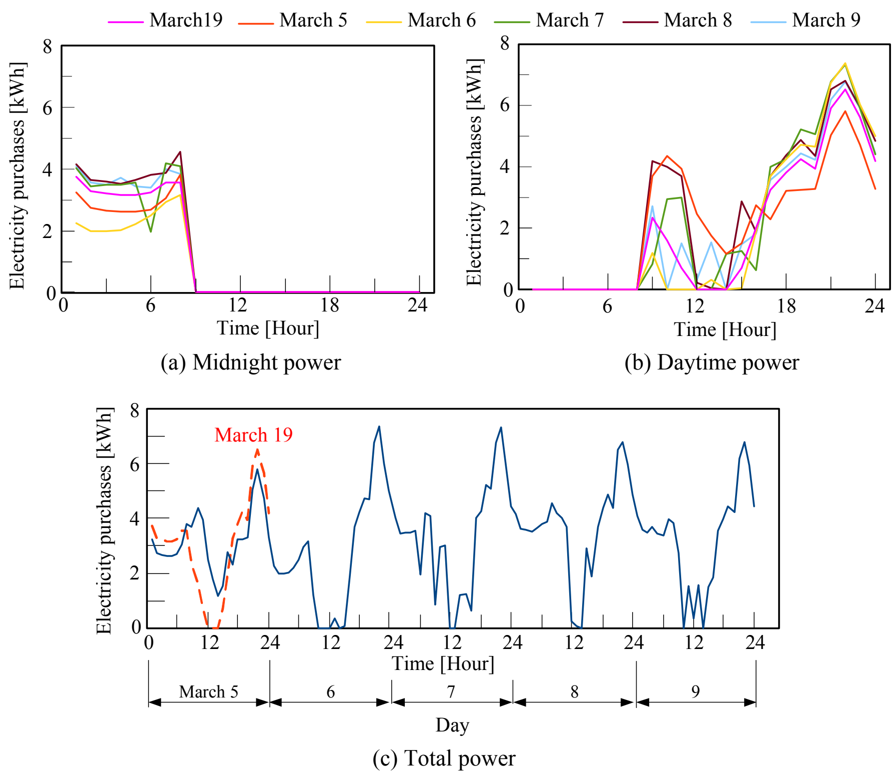


Fig. 12 The amount of electricity purchases. Area of the solar cell module 40 m^2.

purchased is reduced by 16% by installing photovoltaics in this analysis range. As found in Figure 11 (b) and Figure 12 (b), the reduction of the amount of purchased electric power during the daytime due to the introduction of photovoltaics, the amount of purchased daytime electric power decreases by installing photovoltaics. Therefore, the introduction of photovoltaics can lower the purchase cost of commercial electric power greatly.

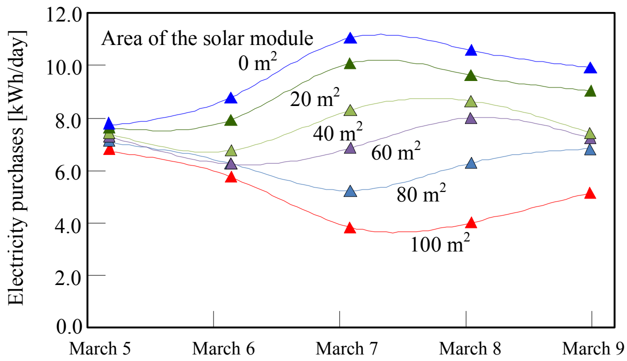
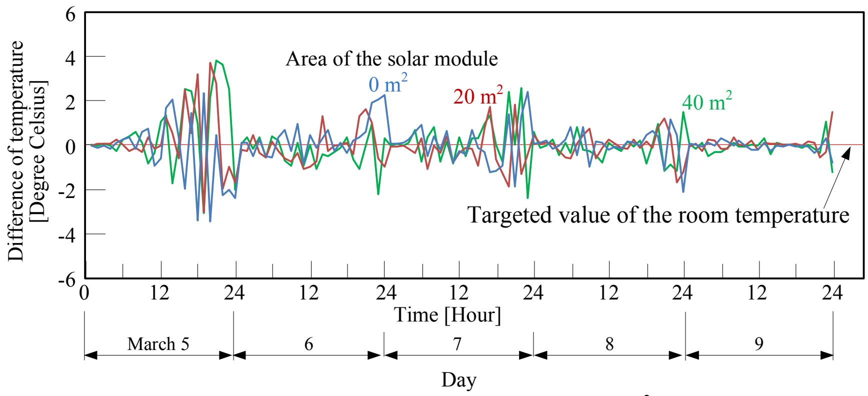
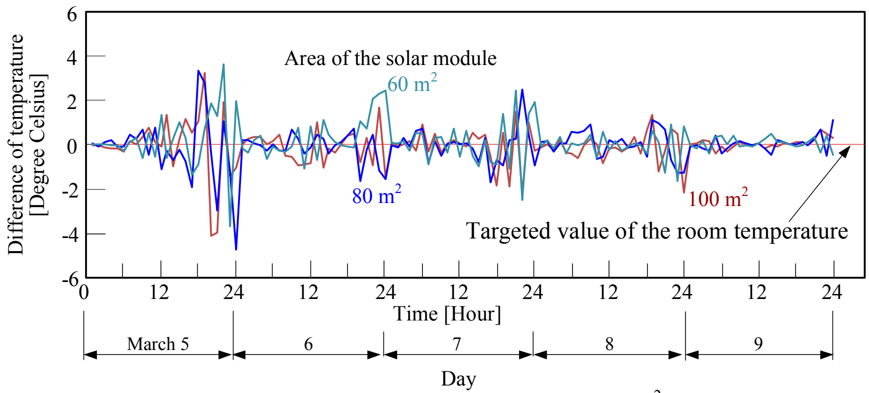


Fig. 13 Relation between the area of a solar cell and commercial-electric-power consumption



(a) Area of the solar module 0 to 40 m^2



(b) Area of the solar module 60 to 100 m^2

Fig. 14 Relation between the area of a solar cell and the difference of temperature

Furthermore, if the peaks occur with time change of the amount of electric power purchased can be cut, the receiving capacity of the power can be reduced substantially. Peak cut technology is a very important subject.

6.4 Capacity of the photovoltaics

Figure 13 shows the results of an investigation of the relationship between the area of the solar cell module installed in the proposed system and the amount of purchased commercial electric power each day. The amount of purchase of the commercial electric power in this figure is the total of daytime and night power. Although the effect of photovoltaics changes with the day, when the module area of the solar cell exceeds 60 m^2, the amount of purchased commercial electric power decreases rapidly. The surplus power of the proposed system is used for the thermal storage of the electric storage heater without selling it to a commercial system. Therefore, the excessive electric-power output by the photovoltaics may raise the room temperature of the room model uselessly. Consequently, as shown in Fig. 14, the relation between the area of the solar cell module and the difference between the room-temperature results and the room-temperature target was investigated. When the area of the solar cell module becomes large, the difference between the room temperature result and the room-temperature target in the period from the evening to midnight on March 5 is large. However, in the analysis results for other days, the relation between the area of the solar cell module and the difference between the room-temperature results and the room-temperature target has few differences. As Fig. 5 shows, the outside air temperature on March 5 is high compared with that on other days. Therefore, the relative error of the weather forecast data calculated by Eqs. (2) and (3) becomes large compared with the error of other days. The room temperature was controlled by installing the method of the operation planning described in this paper within the limits of plus-or-minus 2□ to 4□ to the targeted values.

7. Conclusons

In this paper, the operation of an electric storage heater, a storage type electric water heater, and photovoltaics installed in an all-electric home in a cold region was planned based on the weather forecast information distributed by a communication line, the influence of the room-temperature environment (difference between the room temperature results and the room-temperature target) when the system operated based on this planning, the purchase electric energy, and the capacity of the photovoltaics was investigated. As a result, the following conclusions were obtained.

(1) By using weather forecast data for the operation planning of an electric storage heater, the difference between the room-temperature target and the room temperature result was small, and comfortable heating operation was possible. On the other hand, when the system was planned with the monthly average value of meteorological data, it is predicted that the difference of the room-temperature target and the actual room temperature becomes large.

(2) If the capacity of the photovoltaics is increased, the daytime electric power decreases. Therefore, the introduction of photovoltaics lowers the purchase cost of commercial electric power greatly. On the other hand, the purchase of cheap midnight power hardly changes.

(3) The surplus power will be used for the thermal storage of then electric storage heater if the capacity of photovoltaics is increased without taking electricity sales to utilities into consideration. However, an extremely unpleasant room temperature is not obtained with the conditions in this paper.

If the method of operation planning described in this paper is installed in an individual house in a cold region, compared with the existing all-electric home, low energy loss and comfortable heating are realizable.

Nomenclature

a : Area [m^2]

h : Heat transfer coefficient [W/m^2K]

q_s		Amount of solar radiation [W/m^2]
q_s'		Amount of solar radiation by weather forecast [W/m^2]
N		Number
q_e	:	Heat generation from the elements [W]
q_{hs}	:	The amount of heat radiation of the electric storage heater [W]
r_i	:	Rate of the solar insolation that enters the room
T	:	Temperature [K]
T'	:	Outdoor air temperature according to weather forecast [K]
t	:	Sampling time [Hour]

Roman character

δ	:	Thickness of an outer wall [m]
λ	:	Heat conductivity [W/mK]

Subscript

e	:	Element of heat generation
r	:	Room model
s	:	Storage
ws	:	Roofs and exterior walls
∞	:	Outside air

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