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Optimization of Energy Use for Advanced Solar Houses

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ABSTRACT

Optimization of solar energy use for low-energy residential houses in Japan is proposed. In order to design rational solar energy systems, it is important to recognize the structure of energy consumption of the residential houses as well as the climatic conditions of the region. Using statistical data obtained from an energy survey of residences in Japan, it has been found that the three major portions of purchased energy are space heating, domestic hot water heating, and household appliances (including lighting and cooking). Therefore, the following strategies are proposed to be validated by the simulation study:

- *thermal insulation of building envelopes to reduce space-heating energy,*
- *solar hot water heating system to reduce hot water heating energy, and*
- *a photovoltaic (PV) system for reducing household energy.*

The rigorous simulation was carried out using the generalized computer program for energy and environmental simulation of buildings and the results showed a fairly high possibility of reducing total purchased energy to 50% of the energy consumption of the average Japanese residence, provided appropriate combinations of solar collector and PV arrays were used. From the results of the simulation, it is also noted that the use of solar hot water heating systems should be emphasized for reducing the purchased energy of the well-insulated houses in Japan.

INTRODUCTION

What we call an "advanced solar house" is a house providing a comfortable living environment while minimizing purchased energy with optimized solar energy use. In addition to passive and active solar thermal systems, recent development of photovoltaic (PV) technology is making it possible to use PV systems integrated into the energy system in advanced solar houses. Therefore, the optimum way to achieve advanced solar houses is to find appropriate combinations of passive systems, active solar systems, and PV systems.

When considering optimum solar systems, it is important to understand the structure of demand and supply of the purchased energy in residential houses as well as the climatic conditions of the region in which the houses are located.

This paper describes the results of a simulation study to determine optimum ways of achieving advanced solar houses for single families in Japan that might be applicable to cases in the U.S. The data from the energy survey were examined to design the model system for validating the simulation results.

ENERGY DEMAND AND SUPPLY

The results of a series of statistical data investigations on the energy use of residences in Japan, including both single-family and multi-family houses, conducted by Nakagami (1990) showed an average total purchased energy consumption value of 11.6 MWh/yr (39.6×10^6 Btu/yr) for a housing unit, and that domestic hot water heating (DHW), space heating, and household appliances comprise 40%, 24%, and 34% of the total energy, respectively.

Statistical surveys were conducted by distributing questionnaires to collect more detailed information on the energy consumption of Japanese residences. Sawachi et al. (1994) reported energy survey for approximately 2,000 samples of single- and multi-family houses located in both urban areas and the suburbs of several major cities in Japan. As a result of the study, the average total purchased energy for single-family houses in Tokyo was estimated to be 13.8 MWh/yr (47.1×10^6 Btu/yr). In this case, 46% of the energy is used for domestic hot water heating, while 30% and 22% are used by space heating and household appliances, respectively.

Collecting 1,700 samples of recently built single-family houses with industrialized construction systems, Ishida et al.

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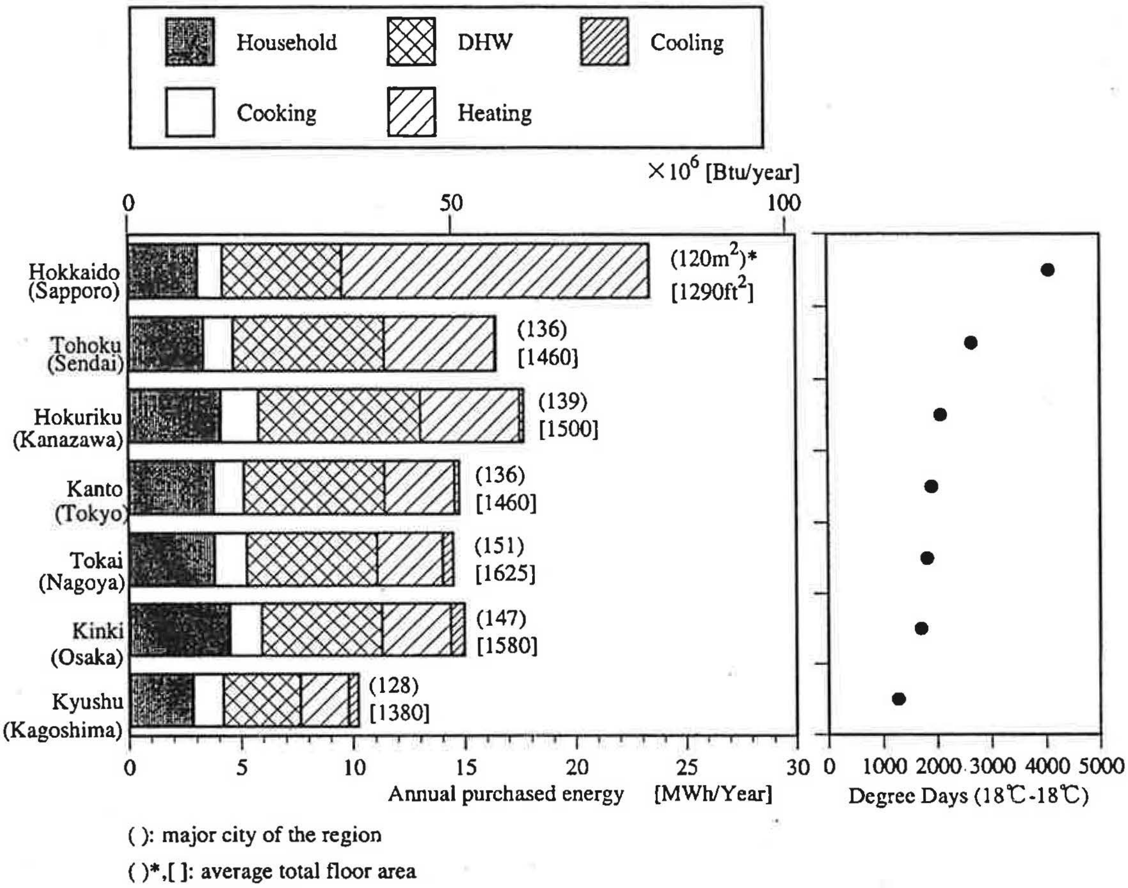


Figure 1 *Annual energy consumption of the single-family houses in Japan (Ishida et al. 1992).*

(1992) estimated the total energy consumption and uses of purchased energy from the monthly variation of purchased energy values. Figure 1 shows the results of the survey by region in Japan. The values of the heating degree-days in each region are also shown to express the climatic conditions for space heating. From Figure 1, it can be seen that the average total purchased energy is around 15 MWh/yr (51 × 10^6 Btu/yr) for a house, while, especially in colder regions such as Hokkaido, a greater amount of energy is consumed for a heavy space-heating load.

In Figure 1, the largest portion is shared by domestic hot water heating, except in the Hokkaido area, where space heating shares 60% of total energy. In most areas, approximately 5 MWh/yr (17 × 10^6 Btu/yr) is used for domestic hot water heating; for example, it amounts to 40% of the total purchased energy in the Kanto area. The main energy source for heating domestic hot water is city gas in most areas, while kerosene is widely used in Hokkaido combined with space-heating systems.

Space heating consumes almost the same amount of energy as household appliances, except in Hokkaido. In Japan, central heating system with space heating for all rooms throughout the winter is not common, and intermittent operation of unitary heating equipment is widely used. It is predicted that in the near future, however, most houses will be heated by central heating systems, with higher thermal comfort levels expected in winter. For this reason, the energy consumption for space heating will inevitably increase if the insulation level of the houses is not improved appropriately.

While room air conditioners are commonly used in regions of rather mild climate, as shown in Figure 1, cooling energy is not a major element of the purchased energy consumption as far as the results of the energy survey show. However, a gradual increase in cooling energy for longer operation, with the number of air conditioners increasing in the near future, is predicted. Another subject is the effect of cooling on the peak demand of electricity, since the largest peak demand for utilities occurs on hot summer days when the cooling requirement is increased.

Household energy, including lighting, is estimated to be 4 to 5 MWh (14 to 17 × 10^6 Btu/yr). The major household appliances are washing machines, vacuum cleaners, refrigerators, TV sets, and dryers. Dishwashers are not commonly used at present but may become one of the major energy-consuming household appliances in the near future. While fluorescent lamps have been widely used in Japanese houses, the use of incandescent lamps is being introduced gradually. As the basic energy source for household purposes is electricity except for cooking stoves, use of the photovoltaic (PV) system is expected to reduce the net electric demand for appliances. Of course, efforts at developing more energy-efficient household appliances are important.

As a result of discussion on the energy survey studies, the following methods are considered effective for the reduction of energy consumption using solar energy for areas of mild climate in Japan:

- provision of enough insulation for building envelopes to reduce the space-heating load and to increase passive solar heating effects,
- use of solar hot water heating systems to reduce hot water heating energy, and
- use of PV systems to decrease the electric energy for household appliances and also to decrease the peak electric demand caused by space cooling.

SIMULATION MODEL

Simulation studies have been conducted to validate the strategies for reducing purchased energy for advanced solar houses (Udagawa 1992; Kimura and Udagawa 1993; Udagawa et al 1993). This paper describes the results of a simulation study using a model house designed for a project for IEA Task 13 (Kimura and Udagawa 1993). The climatic conditions of Tokyo were presupposed in designing the model system for the simulation.

Figure 2 shows the floor plan and elevation of the model house. The total floor area is 148 m^2 (1,593 ft^2) to approximate the average total floor area of recently built single-family houses, as shown in Figure 1. As an ordinary type of single-family house, the model house is assumed to be made of wood, while a 150 mm (5.9 in.) thick concrete floor slab is provided for the rooms on the first floor in order to increase thermal mass. The living and dining spaces and all bedrooms except for the one facing south to utilize solar heat gain in winter. The bedroom that faces north can be heated by natural convection of the warm air from the living space below, where the void space with a clerestory window is provided to take advantage of the passive heating effect by increasing direct solar gain. The south slope of the roof is designed to have a solar collector array and a PV array mounted as shown in Figure 2.

A high thermal insulation level of the building envelope is assumed as one of the basic requirements for the advanced solar

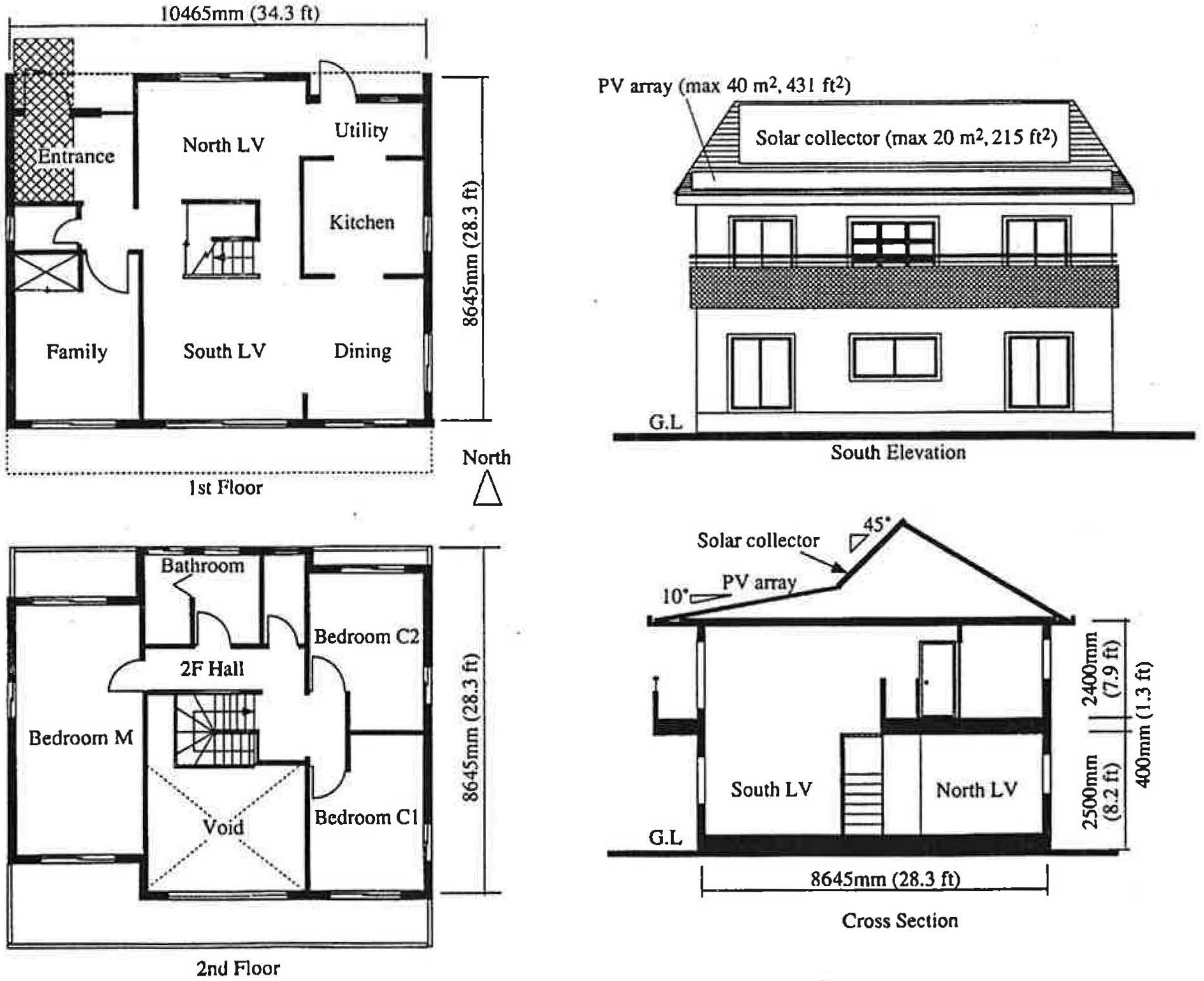


Figure 2 Floor plan and elevation of the model house.

house. The insulation thickness of the exterior walls and the ceilings below the roof are 150 mm (5.9 in.) and 300 mm (11.8 in.), respectively. Below the concrete floor slabs of the first-floor rooms, 100 mm (3.9 in.) of insulation is provided. Low-emissivity double-pane windows with an overall heat loss coefficient of 1.8 W/m^2·K (0.31 Btu/ft^2·h·°F) are basically assumed. During winter nights for all windows except a clerestory window in the south LV room, movable insulation panels with 30 mm (0.12 in.) insulation are assumed to be used. The overall heat loss coefficient of the combined insulation window is 0.71 W/m^2·K (0.13 Btu/ft^2·h·°F). Using these well-insulated building envelopes, the overall heat loss coefficient of the whole house per total floor area is 1.28 W/m^2·K (0.23 Btu/ft^2·h·°F) including a ventilation rate of 0.5 air change per hour (ACH).

The basic heating, cooling, and hot water heating systems are included in all simulations with or without the solar collector system. A fan-coil system with an air-source heat pump unit is used for space heating and cooling. A gas boiler is supposed to be used for domestic hot water heating. Table 1 shows the specifications of the system components used in the simulation.

The forced circulation type of solar domestic hot water (DHW) heating system and solar floor heating system combined with hot water heating are assumed for the active solar heating systems. While active solar heating seems less feasible in comparison with solar domestic hot water heating systems, a simplified active solar heating system using the concrete floors as heat storage floor panels (Udagawa and Tanaka 1981) is included in the simulation cases for heating the rooms on the first floor. A system diagram of the solar floor

TABLE 1 Systems and Components Used for the Models

Energy Demands	Systems	Main Components
Space heating/cooling	Basic system:	
	Fan coil system with an air-source heat pump chiller	Heat pump unit: • heating capacity 8.7 kW (29700 Btu/h), COP = 3.1* • cooling capacity 7.0 kW (23900 Btu/h), COP = 2.3*
	Active solar system:	
	Floor heating	(Combined with solar DHW heating system)
DHW heating	Base system:	
	Gas boiler system	Gas boiler 20 kW (68000 Btu/h) • system heating efficiency 70%
	Active solar system:	
	Forced circulation system	Solar collector • collector area 6, 10, 20 m^2 (65, 108, 215 ft^2) • flat plate with selective absorber and single glazing • tilt angle 45 degrees Heat storage tank • capacity 300, 600 L. (10.6, 21.6 ft^3) • heat exchanger for collector loop contained
Lighting, cooking, and househouse appliances	Base system:	
	Commercial utility line	
	PV system:	
	Grid connection without battery	PV models • mono-crystal silicon cell with module conversion efficiency 12%* • tilt angle 10 degrees Invertor • efficiency 90%

*At standard conditions

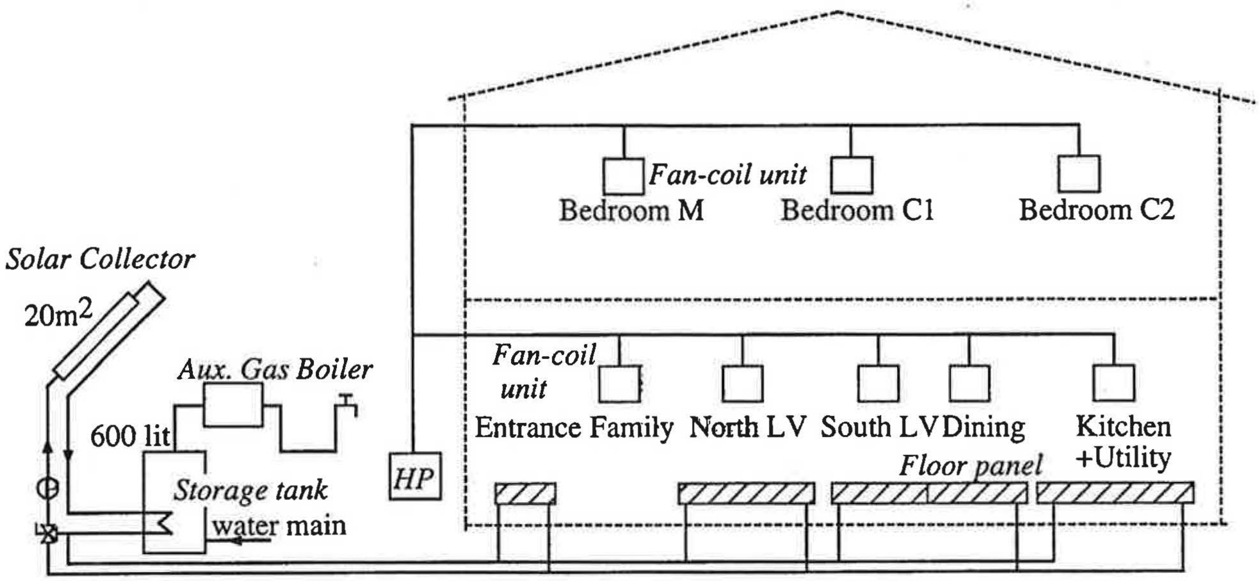


Figure 3 *Solar domestic hot water and floor heating system (HFW20, Cases 4 and 11).*

heating system is shown in Figure 3. The flat-plate solar collector with selective absorber surface is assumed for both systems of DHW-only and DHW combined with floor heating.

The grid connection type of PV system without batteries is assumed. Therefore, generated DC power by the PV array is converted into AC power by an inverter. Electric power is supplied from the utility line when the power generated by the PV array is not enough for the electric load. It is also assumed that the excess power generated by the PV array is supplied back to the electric utility line to be sold to the electric power company. A single-crystal type of PV cell with a module efficiency of 12% at the standard test condition is used.

Table 2 shows the combination of cases compared with each other in this study. The floor plan and the thermal insulation level of the house are identical for all cases. The total array areas for solar collectors and/or PV modules are supposed to be from 6 m^2 (65 ft^2) to 40 m^2 (431 ft^2). The base case is the model house without the active solar heating system or the PV system, while the building envelopes are well insulated.

The model house is assumed to be inhabited by a family of four. Figure 4 shows the daily schedules used in the simulation. The daily schedules of the occupants and the use of household appliances are applied to both internal heat generation data for heat load simulation and energy consumption data for household energy estimation. As electricity is assumed as the energy source of the stove in the simulation, the energy source of all the appliances shown in the schedule is electricity. The schedule in Figure 4 is a modification of the standard schedule set that was prepared for the standard single-family house designed to validate heat load simulation programs (Udagawa 1985). The daily

TABLE 2 Simulation Cases

	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
Total collector and PV area [m^2]	0	6 (65 ft^2)	10 (108)		20 (215)				30 (323)	36 (388)	40 (431)		
Solar heating system Type	N	HW6	HW10	N	HWF20	HW6	HW10	N	N	HW6	HW10	HWF20	N
Collector area [m^2]	—	6 (65 ft^2)	10 (108)	—	20 (215)	6 (65)	10 (108)	—	—	6 (65)	10 (108)	20 (215)	—
PV array area [m^2]	—	—	—	10 (108 ft^2)	—	14 (151)	10 (108)	20 (215)	30 (323)	30 (323)	30 (323)	20 (215)	40 (431)

Solar heating system type

N: None
HW6: DHW heating system with 6 m^2 (65 ft^2) collector and 300 L (10.6 ft^3) storage tank
HW10: DHW heating system with 10 m^2 (108 ft^2) collector and 300 L (10.6 ft^3) storage tank
HWF20: DHW and floor heating system with 20 m^2 (215 ft^2) collector and 600 L (21.2 ft^3) storage tank

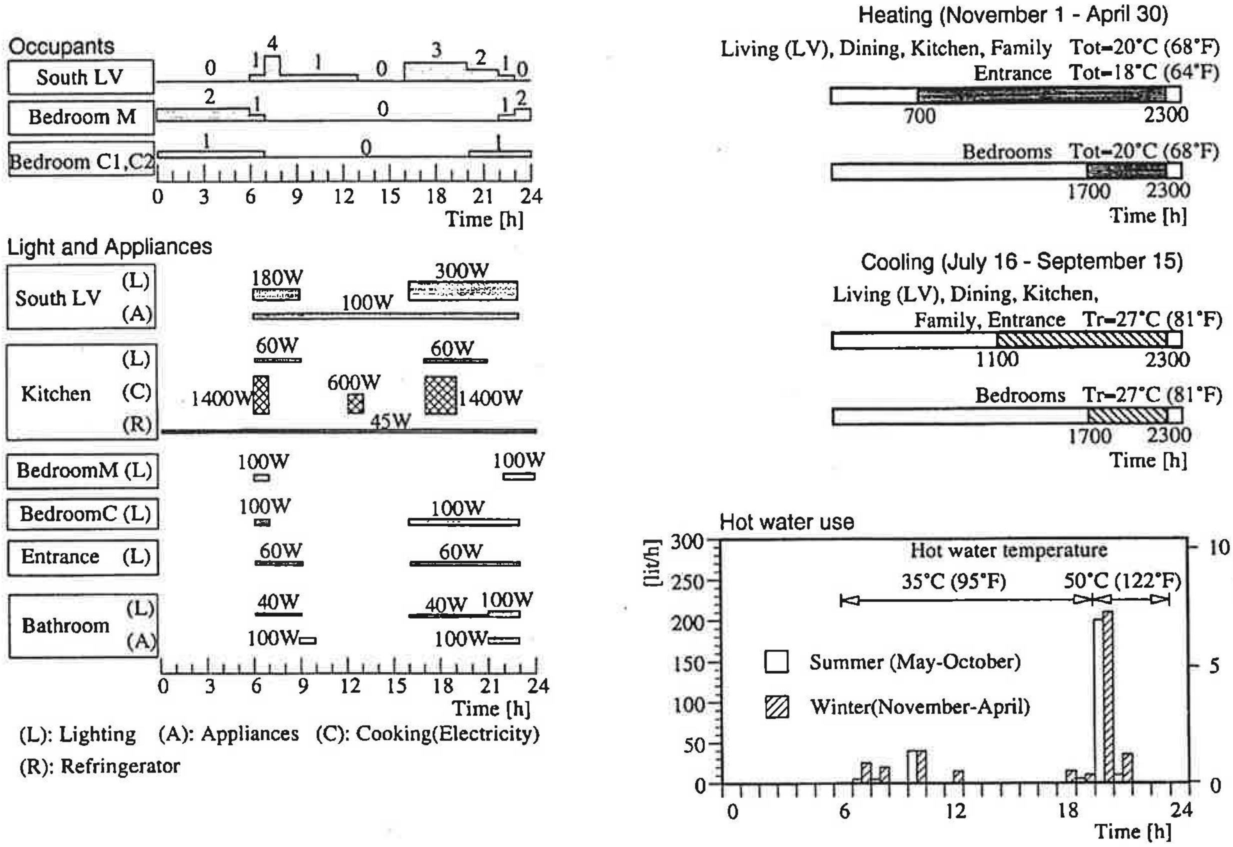


Figure 4 Daily schedules of occupants, household appliances, space heating, cooling, and hot water use.

total value of household energy is adjusted to meet the average value estimated from the energy survey study.

The daily schedules of the room air temperature setpoints are also shown in Figure 4. The heating season is designated from November 1 to April 30 and the cooling season from July 16 to September 15. The heating and cooling schedules used in this study are at a higher level than those of the average Japanese houses, in which intermittent operation of heating and cooling is common. The operative temperature approximated with the mean value of a room air temperature and a mean room surface temperature is used as the setpoint for the space heating, since the solar floor-heating system combined with the air heating is compared with the conventional air-heating system only by the fan-coil system.

The schedule for hot water use is also important in the energy simulation. Several types of use profiles have been proposed and used for the simulation studies. The hot water use schedule used in this study is selected from the standard hot water use schedule (JSTM 1992). As shown in Figure 4, the schedule is changed by season. The annual heat load of domestic hot water heating based on Figure 5 is 4.2 MWh/yr (14.3×10^6 Btu/yr), which is converted into purchased energy of 6.0 MWh/yr (20.5×10^6 Btu/yr) consumed by the boiler system with a system efficiency of 70%. The value is slightly greater than the energy consumption for domestic hot water heating in Figure 1. A higher acceptability level of hot water use is assumed, considering increased requirements for hot water.

The simulation was conducted using the generalized simulation program developed by Udagawa (1990, 1993, 1995). The program was prepared for energy and thermal environmental control system simulations composed of both the building thermal system and the mchanical system, including solar heat collection systems. A series of test case simulations was carried out as a task of IEA Task 13 to validate the simulation tools used for the energy estimation; this program showed one of the most reliable results (Poel 1993). The PV systems were simulated with the algorithm using the basic equation model using the voltage-current relationship of the PV cell (Udagawa and Kimura 1994). The hour-by-hour standard weather data set of Tokyo was used as the climatic data.

SIMULATION RESULTS

Hourly Variation of Thermal Environment, Loads, and Generated Power

Figure 5 shows examples of daily variation of the room thermal environment and the heat load of the living room obtained from the simulation for the base case. While Figure 5 is obtained from the results of the base-case simulation, Figure

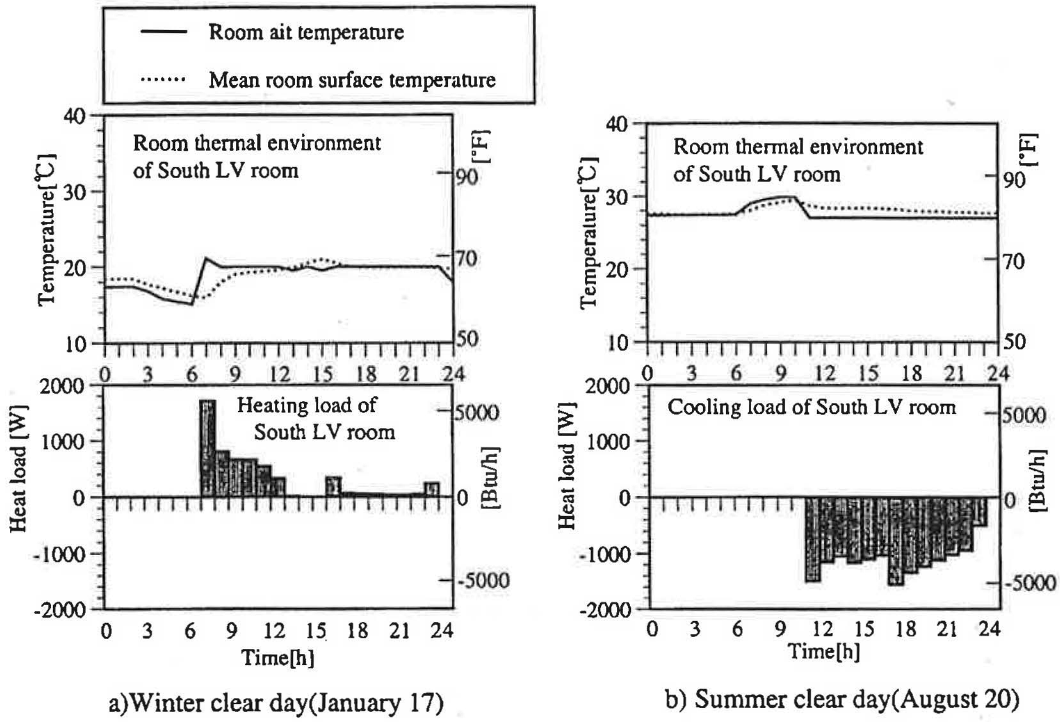


Figure 5 *Hourly variation of room thermal environment and heat load on typical clear days in winter and summer (base case).*

5a is commonly used for all cases except cases 4 and 11, in which the solar floor heating system (HWF20) is assumed. Figure 5b shows the common results for all cases, since an identical cooling system is used in all simulation cases.

In winter, since the room temperature is controlled to keep the setpoint operative temperature at a constant value, the mean of the room air temperature and the mean surface temperature are kept at the scheduled setpoint, as shown in Figure 5a. Because of the well-insulated envelopes, the room temperature is maintained above 15°C (59°F) even in the early morning when the heating system is switched off. The passive solar effect also helps reduce the heat load from noon to midnight.

Figure 5b shows results from a clear summer day. The room air temperature is maintained at the cooling setpoint as scheduled. It is shown from Figure 5b that the cooling load in the evening is larger than that in the daytime because of internal heat generation from lighting, as well as the daily cooling schedule for the bedrooms starting in the evening.

Figure 6 shows the daily variations of the electric loads of the house and the power generation by the PV array of 20 m^2 (215 ft^2) in case 7. Both in winter and summer, even with the 20-m^2 (215-ft^2) array area, the generated power at midday is greater than the electric load. The characteristics of the grid-connected PV system with a large array area are shown in Figure 6, in which a considerable part of the power generated by the PV system does not contribute directly to reduce the electricity load of the house itself and some excess power is supplied back to the utility line to be sold to the electric company.

Annual Heat Loads

Figure 7 shows the annual heat loads, including hot water heating for the system types, as noted in Table 2. The negative values show the heat loads covered by the solar heating systems. Therefore, the total length of each bar in Figure 7 is identified as the total heat load of each case. The cooling load is the same in all cases, since identical cooling systems are assumed for identical simulation model houses. The space-heating loads of type N, type HW6, and type HW10 are also the same for identical space-heating systems. The heating load of type HWF20 is less than the others, while the total load, including the heating load to heat the floor heating system by the solar collector, is greater than in the other cases. The excess heat supplied by the solar collector system contributes to a better room thermal environment, with higher mean radiant temperature and room air temperature when space heating is not scheduled. Due to the solar floor heating system, the heating load for the fan-coil system is 1.1 MWh/yr (3.7×10^6 Btu/yr), which is smaller than that for all other cases, 2.5 MWh/yr (8.5×10^6 Btu/yr).

Figure 7 shows that the largest portion of the heat load is domestic hot water heating. The differences in the hot water heating load are due to the effects of the solar hot water heating systems. Nearly half of the hot water heating load of the base case, type N, is supplied by solar energy even in the smallest collector area, 6 m^2 (65 ft^2), for type HW6.

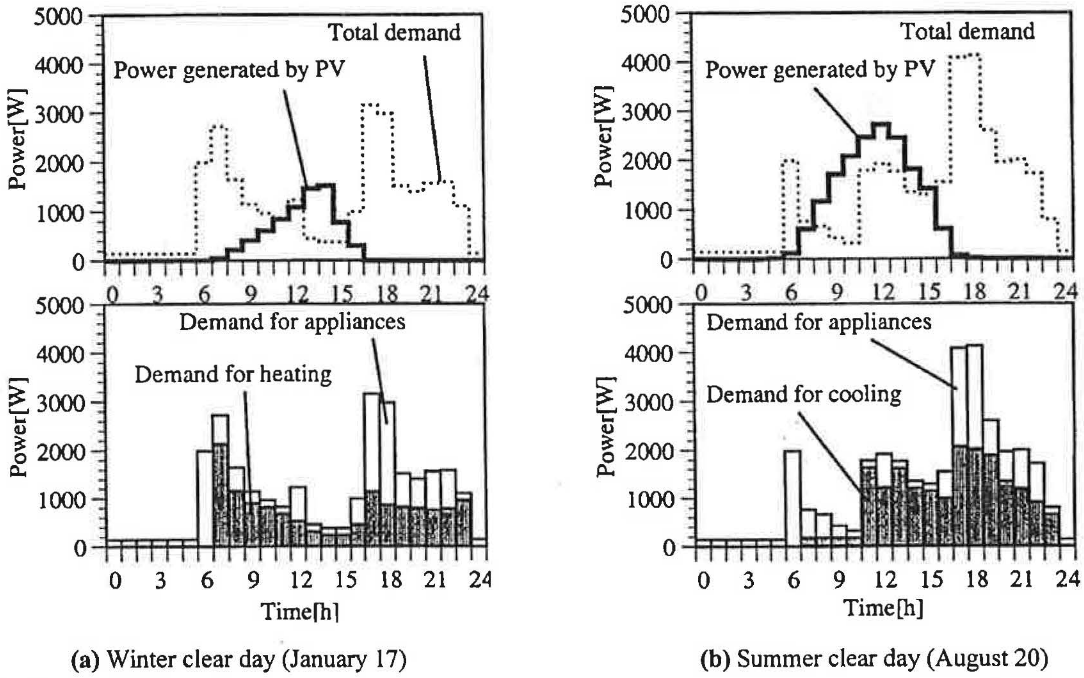


Figure 6 *Hourly variation of electric power load and power generated by PV system on typical clear days in winter and summer (case 7).*

Energy Consumption

The annual purchased energy obtained from the simulation is shown in Figure 8. The purchased energy consists of city gas used for the hot water heating boiler and electricity used for all other purposes, including space heating and cooling by the heat pump system. The contribution of the solar energy is included in each value. The differences between the values of the base case and the other cases can be recognized as the contribution of the solar system, excluding the sold electric power generated by the PV system. The values below the zero line show the power sold to the electric company.

In Figure 8 the survey data of the suburbs of Tokyo (Kanto area) in Figure 1 are added to the simulation results. The total purchased energy of the base case is less than the survey result by 10%. The amount of heating and cooling energy is less than the heating and cooling loads because of the use of the heat

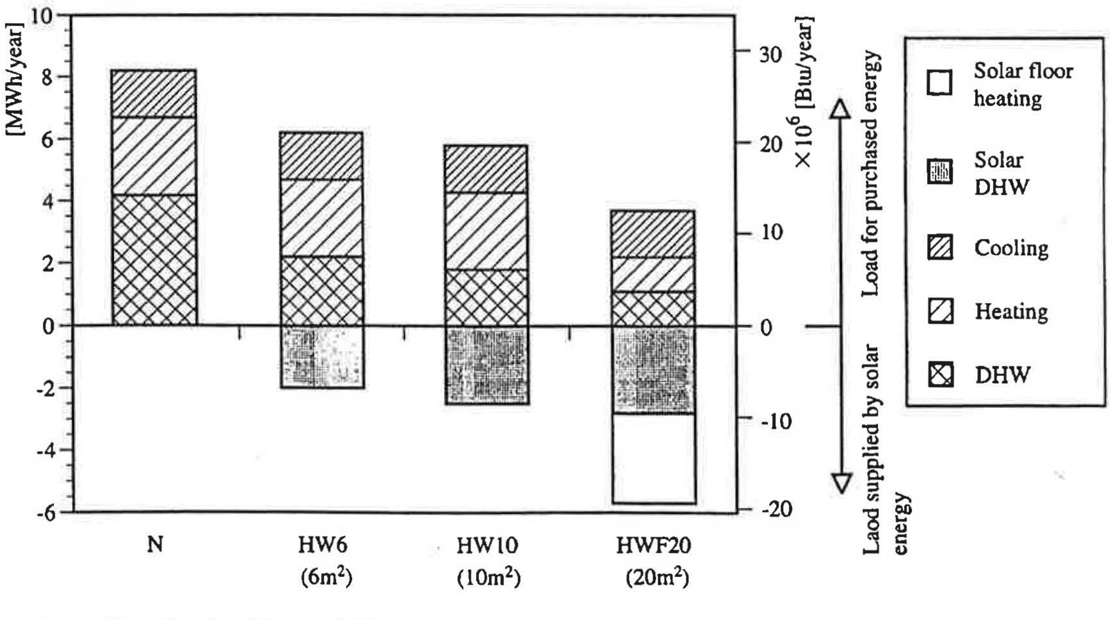


Figure 7 *Annual heat loads of the model house.*

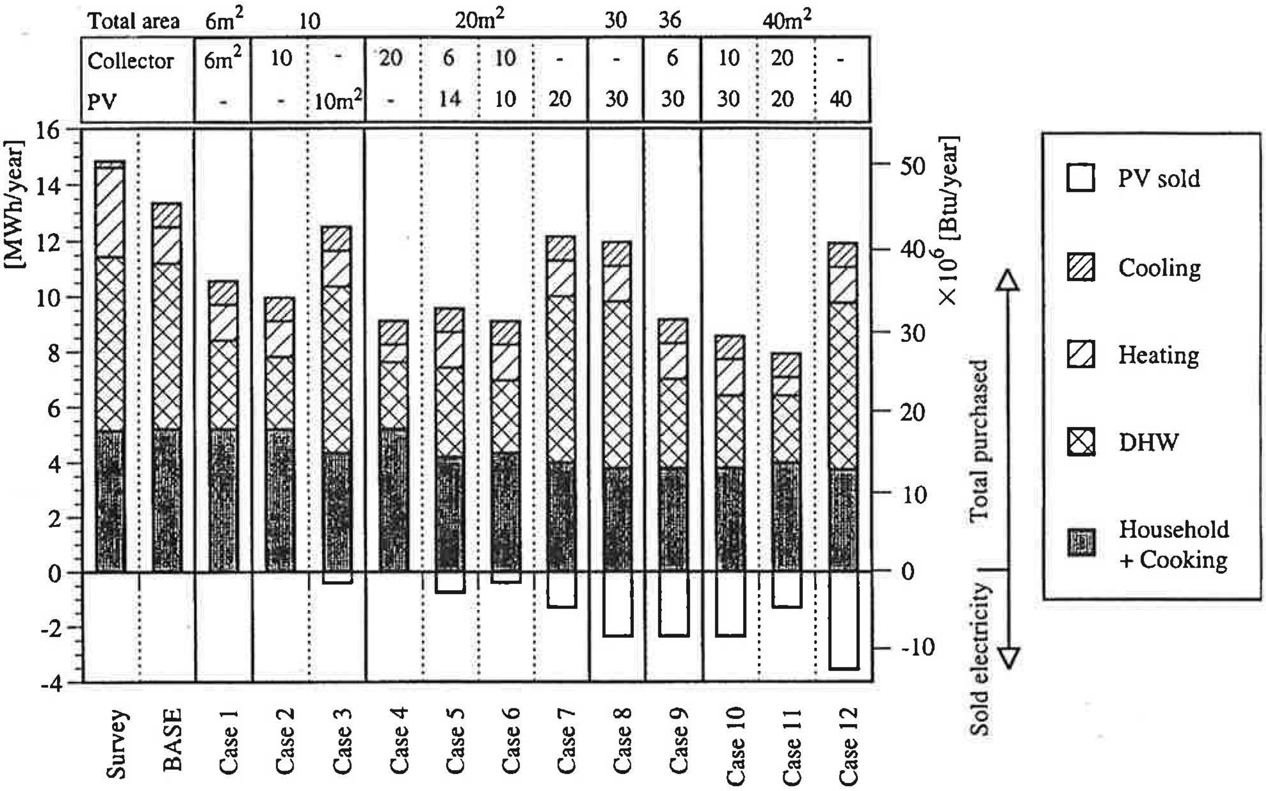


Figure 8 *Annual purchased energy.*

pump system. The simulated space-heating energy is reduced from 3.1 to 1.3 MWh/yr (10.6 to 4.4 × 10^6 Btu/yr), while the cooling energy increases due to a higher level of cooling demand assumed in the simulation. Although a higher comfort level in heating is also assumed in the simulation, the energy is reduced due to the superinsulation of the house and the heat pump system. The simulated hot water heating energy is found to be greater than the survey result, and the energy amounts for household appliances are the same because of the designated schedules (shown in Figure 4). The simulation result of the base case shows that a higher level of thermal comfort can be achieved with less energy consumption in well-insulated houses.

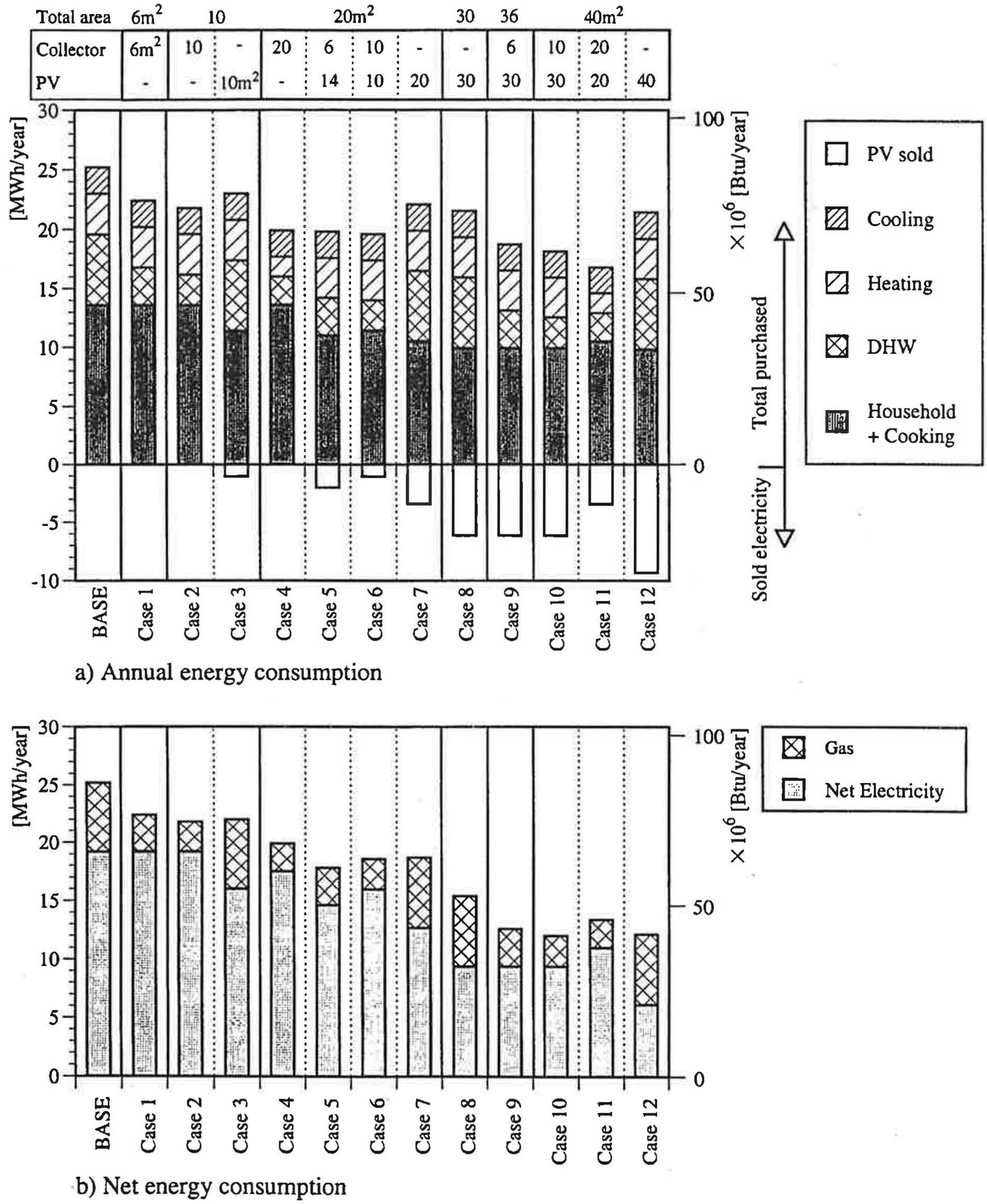
Excluding the amount of electricity sold from the PV system, a considerable reduction in the amount of energy is found in cases 1, 2, 4, 5, 6, 9, 10, and 11, in which solar thermal systems are used. This reduction is compared to reductions achieved in cases using the PV system only. Including the electricity sold, a larger PV array contributes to reduce the purchased energy, since the net purchased energy is expressed by subtracting the electricity sold from the total purchased energy above the zero line in Figure 8.

To evaluate the effects on the energy resources and the impact on the environment, comparisons of the energy consumption and supply to utility line expressed with primary energy are shown in Figure 9a. The conversion factors from purchased energy to primary energy are shown in the bottom of Figure 9. When using the primary energy scale, the weight for the electricity is emphasized; therefore, it appears that the PV system is more advantageous than the solar thermal system in these simulation cases. Nevertheless, the cases using the solar hot water heating system show smaller total values.

The net primary energy consumption in which the excess electricity sold to the utility is subtracted from the total energy consumption is shown in Figure 9b. The amount of gas in Figure 9b is the same as the energy consumption of the DHW in Figure 9a, since the gas boiler is used for the DHW heating in all cases. The differences between the systems with and without PV are small in comparison with the results in Figure 8 as expressed in the purchased energy scale.

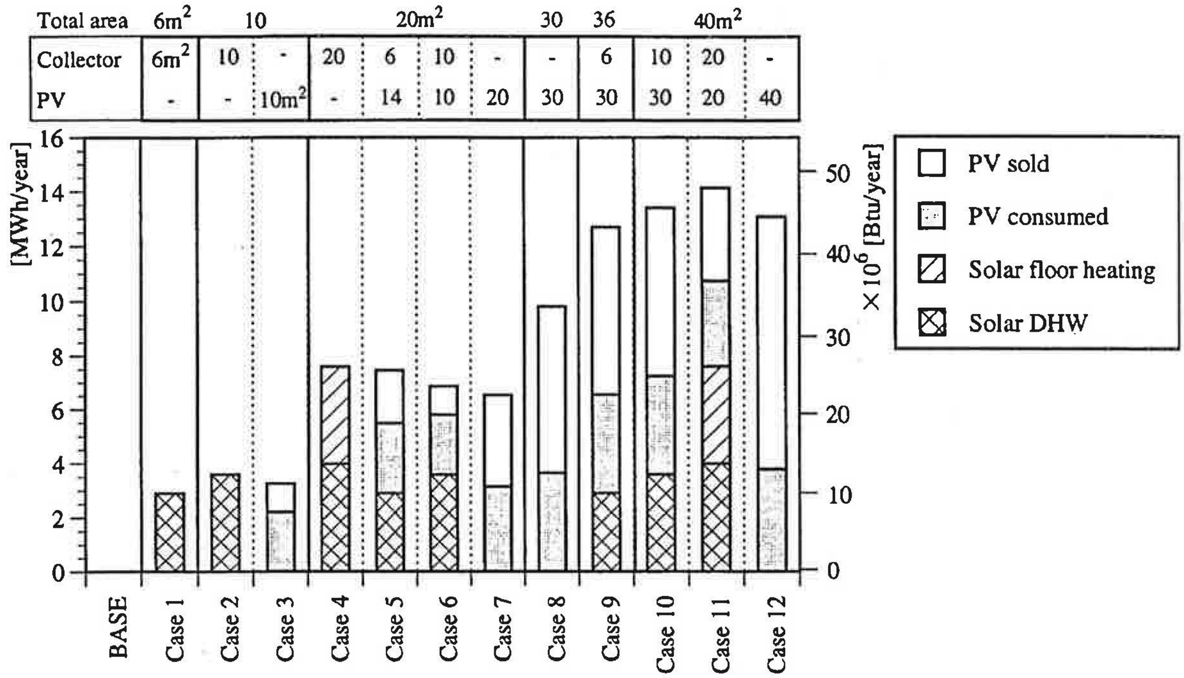
When using the net energy consumption as shown in Figure 9b, 30% and 50% of the base-case energy are saved using the solar collector and PV array with total areas of 20 m^2 (215 ft^2) and 40 m^2 (431 ft^2), respectively, for the cases with the solar collector system, the PV system, and the combined system.

The solar energy contribution to the DHW and solar floor heating by the solar thermal system and the generated electricity both consumed and sold to the utility for all cases are shown in Figure 10. The energy saved by the solar DHW heating and the solar floor heating is converted into the equivalent gas energy consumption with a boiler efficiency of 70% as assumed in the simulation, since the gas boiler is commonly used for the DHW heating system. While the auxiliary boiler is not assumed to be

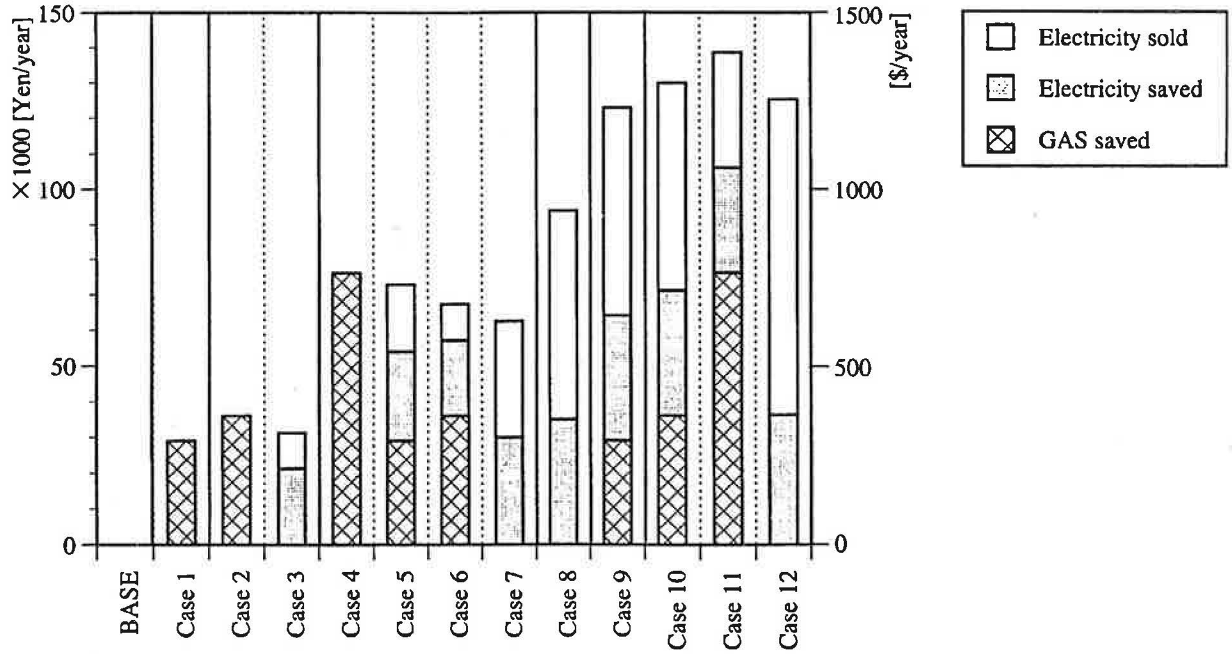


* Conversion of primary energy from purchased enerey (secndary energy)
Electricity : primary energy = 2.616 × purchased energy
Gas : primary energy = 1.0 × purchased energy

Figure 9 *Annual energy consumption in primary energy scale.*



a) Solar energy contribution in primary energy scale



b) Saved energy cost

* Energy cost
Electricity : 25 yen/kWh (approx. 25 cents/kWh)
Gas : 10 yen/kWh (approx. 10 cents/kWh or 3 cents/1000Btu)

Figure 10 *Annual cost saved and primary energy by solar collector and PV systems.*

used for the solar floor heating system, as shown in Figure 3, the amount of gas consumed is used in evaluating the solar contribution of the floor-heating system.

The solar contribution on the primary energy basis is shown in Figure 10a, from which it can be pointed out that the PV system with a large PV array increases the supply power to the utility, as already shown in Figures 8 and 9a. The power consumed in the house is maintained at the basic amount of approximately 4 MWh/yr (13.6×10^6 Btu/yr). This tendency can be inferred from Figure 6. As the electricity load in the daytime is not so great in comparison with the power-generating capacity of the PV system with a large array area on clear days, more than half of the generated power is supplied back to the utility in cases with a PV array area of more than 20 m^2 (215 ft^2).

The solar contribution is also expressed using the energy cost scale. The energy costs saved were estimated using the conversion factors for electricity and city gas as shown at the bottom of Figure 10. For power generated by the PV system, the amount of contribution is expressed in terms of the electricity cost. The same rate is assumed for purchasing and selling. The conversion factor of the city gas is used for the contribution by the solar DHW heating system and the solar floor heating system. The results are shown in Figure 10b. Though the difference in the total areas of the collector and/or PV arrays should be taken into account, a significant contribution to the saved energy cost is considered mainly due to the electricity sold in the cases of large PV area.

The cost of the saved energy is not enough to recover the installation costs of the systems with a payback period of 10 years, which might be considered a reasonable period in general.

DISCUSSION ON OPTIMUM SOLAR ENERGY USE

There are many features for optimization of solar energy systems. From the viewpoint of saving energy resources, it may be appropriate to examine the results expressed with primary energy. While the impact on the global environment is often measured using the equivalent amount of carbon dioxide emissions, the primary energy converted using the factors in Figure 9 shows the values corresponding to the carbon dioxide emissions. It implies that the effect of the environmental impact can be considered on the basis of primary energy as shown in Figures 9 and 10.

For a direct reduction in the energy requirements of residences, it is important to use solar hot water heating systems as much as possible, since the hot water heating load shares the largest portion of the energy, as shown in Figure 1. For a smaller application with less than 10 m^2 (108 ft^2) of area for solar collectors or PV array, the amount of reduction in energy consumption with the solar heating system is greater than that with the PV system, as shown in cases 1 and 2 of Figure 9a. The net energy consumption values of case 1, with 6 m^2 (65 ft^2) of collector area, and case 3, with 10 m^2 (108 ft^2) of PV area, are almost the same. The use of a solar hot water heating system is recommended from the viewpoint of system installation cost.

For a larger application, with more than 20 m^2 (215 ft^2) of total area of solar collector and PV array, the differences related to energy consumption based on primary energy are not as significant, while the cases without solar heating systems show greater total energy consumption values. The larger PV array area (more than 20 m^2 [215 ft^2]) contributes to producing the increased amount of excessive electric power supply to the utility rather than the case of increasing the power supply to the house in which the PV system is provided.

As shown in Figure 9b, while the solar floor heating system (HWF20) with 20 m^2 (215 ft^2) of collector area in cases 4 and 11 shows slightly greater energy consumption than the other cases with the same total collector and PV array area, the differences are small considering such a high thermal comfort level. When a solar energy system with a large array area is possible, the combination of the solar heating system and the PV system in cases 9 and 10 shows the smallest net energy consumption. However, the difference is not so great. Subtracting power supply to the utility, it was found from Figure 9b that the net energy consumption of cases 10 and 12 is 50% of the base-case value, which is almost equal to the average energy consumption of houses in Japan.

When the total energy reduction governs the object function of the optimization within the maximum possible total area of collector and PV array—40 m^2 (431 ft^2) in this case study—the ratios of the collector area and the PV area did not show important effects on reducing the primary energy consumption, including the effects of power supply to utility as shown in Figure 10. However, from the viewpoint of direct reduction in the energy load and the installation cost of the systems, a certain combination of solar thermal system and PV system should be considered appropriate.

CONCLUSIONS

Using the results of the energy survey on existing houses and the simulation study with the model house, the optimum ways to achieve advanced solar houses are examined for mild climatic regions such as Japan. The results are summarized as follows.

1. Providing well-insulated building envelopes with a total heat loss coefficient of 1.28 $W/m^2{\cdot}K$ (0.23 $Btu/ft^2{\cdot}h{\cdot}°F$) and assuming the use of a heat pump system, the heating energy in the purchased energy scale can be reduced to be less than half of the average value estimated by the energy survey even if a higher level of room thermal environment is assumed.
2. Use of a solar hot water heating system is effective in reducing the energy requirements of a house since the hot water heating load shares the largest portion of energy consumption in Japanese houses.
3. The PV system is effective in reducing the electric load caused by household appliances and the heat pump system. An array area of 20 to 30 m^2 (215 to 323 ft^2) is considered appropriate for the grid-connecting type of PV system for an average household, when the direct reduction of electricity

consumption in each house is considered to be the main purpose of providing the PV system in the house.

4. The possibility of reducing energy consumption by 50% is shown with a total collector and PV array area of 40 m^2 (431 ft^2).

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