Field Study on Photovoltaic System and All-electrified Residential Equipment in Detached Houses

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In this paper, two detached houses with photovoltaic system and all-electrified residential equipment were chosen as the research object. The hourly operating situation of electricity generation of photovoltaic system and electricity consumption were investigated. Based on the recorded data, the combination using of the photovoltaic system with the high efficiency equipment, CO_2 heat pump hot water heater, also has been examined. The introduction effect of the photovoltaic system was evaluated from the view of energy saving, environmental and economic effect based on the electricity situation such as price, greenhouse gas emission and so on.

Key words: *Photovoltaic system, All-electrified Residential Equipment, Detached House, CO_2 heat pump hot water heater*

1. Introduction

Residential sector's energy consumption accounted for 26.4% of total primary energy [1]. Moreover, the total CO_2 emissions from the residential sector in FY2005 were 174 million tons, 36.7% increase to the base year FY1990 [2]. Based on above mentioned background, the energy conservation and the new energy introduction in the residential sector is very important to achieve the reduction target of greenhouse gas for Japan. On the other hand, the application of renewable energies is very important for Japan to reduce the consumption of the fossil energy and the emission of the greenhouse gas. Photovoltaic system is inexhaustible, environmental friendly system and has advantages such as efficiently integrated in buildings, high reliability and long lifetime, low maintenance cost and low environmental load. Thus the photovoltaic system must be an effective option in helping Japan to meet greenhouse gas reduction and renewable energy introduction. The introduction target of the photovoltaic system is 4.82 million kW in 2010 with 3.9 million kW for residential house according to the new energy law of Japan [3]. However, it has been accomplished only 0.6 million kW until 2003. As the initial cost of the photovoltaic system was decreased to 661,000 Yen/kW in 2005 according to the statistical data of the New Energy Foundation of Japan [4], it is competitive compared with other energy systems. With these backgrounds, it is necessary to accelerate the introduction of the photovoltaic system in residential house.

In addition, the high efficiency appliance, such as CO_2 heat pump hot water heater, high efficiency refrigerators and air-conditioner, have been developed to improve the energy conservation of residential buildings in Japan. Also, the all-electrified residential equipment is widely adopted recently as an option of the energy supply and using system in residential sector in Japan. The advantages of this system are the low running cost, convenience and safety to use. Table 1 shows the electricity price for all-electrified system user and the electricity price for normal user is shown in Table 2 for the reference. Nevertheless, according to the previous research[5], the energy-saving and environmental effects of the all-electrified residential equipment system are obviously dependent on the COP/efficiency performance of electric appliance. Hence, high efficiency appliance should be introduced in such an energy supply system. However, very little research has been spent on the combination effect of the renewable system, the high efficiency equipment and the all-electrified system.

In this paper, two detached houses with all-electrified residential equipment and

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photovoltaic system have been chosen as the research object. The hourly electricity generation amount of the photovoltaic system and electricity consumption of the houses were investigated. By analyzed these recorded data, the operational situation of the photovoltaic systems have been clarified. The combination of photovoltaic system with the high efficiency equipment, CO_2 heat pump hot water heater, has also been examined. Moreover, based on the power situation (electricity price, greenhouse gas emission and so on) of Japan, the introduction effect of the photovoltaic system has been evaluated from the view of energy saving, environmental and economic effect.

2. Energy Systems of Two Detached Houses

The details of the energy systems of two detached houses listed in Table 3. These two typical detached houses locating in Kyushu, where the annual solar radiation amounts are about 1398kWh/m^2 (Oomuta) and 1330kWh/m^2 (Kumamoto). The houses adopted all-electrified residential equipment, which means all of the domestic appliances are the electric things and the energy demand is satisfied by the electricity from the power company or the photovoltaic system. Because the hot water supply consumes about 30% of the total energy consumption in dwelling, the hot water system is very inportant for the energy conservation. The hot water in these two family are provided by a electric hot water heater in House S and a CO_2 heat pump hot water heater (COP is 3.0) in House N, respectively. Both of the hot water supply systems operate at early morning (5:00-8:00 AM) to make thermal storage.

As for the photovoltaic system, in House S, the solar cells has the capacity of 4.8kW with 35.6m^2 area, its azimuth angle is southwest 45° and the inclination angle is 38.7°. In the same manner, House N is 4.2kW with 31.1m^2, southwest 77° and 21.8°, respectively. The power generation efficiency of both systems is 13.48%.

3. Research Method

In this paper, the monthly electricity generation and electricity consumption were recorded from Jan. 2005 to Feb. 2006. In addition, the hourly electricity situation was measured in Aug. 2005, Oct. 2005 and Jan. 2006 in order to clarify the details of the electricity situation.

Based on these recoded data, the evaluation of photovoltaic systems has been done from the view of energy saving, environmental and economic effect. By using the power generation efficiency 39.3% of power plant, the CO_2 emission unit of the electricity from utility power and photovoltaic system and the measured electricity generation amount of photovoltaic system, the primary energy saving and the environmental effect were evaluated in this paper using equation (1) and (2). Referencing the discussion of paper [6], the CO_2 emission unit used for utility electricity was the average value for fired power plants. The economic effect was evaluated using the index of running cost reduction amount calculated by equation (3). The systems none-introduced photovoltaic system are the energy systems which are not introduced photovoltaic system with the same domestic appliances as factual systems.

Energy saving amount:

$$PE_{save} = \frac{E_{Ge-PV} \times 3.6}{\eta_{up}} \quad (1)$$

CO_2 reduction amount:

$$CO2_{save} = E_{Ge-PV} \times (C_{unit-fire} - C_{unit-PV}) \quad (2)$$

Table 1 Electricity price served all-electrified user from a main electric power company in Kyushu, Japan.

Period		Price (Yen/kWh)
22:00-8:00		6.93
8:00-10:00; 17:00-22:00		20.48
10:00-17:00	In summer	32.60
	other seasons	27.25
Initial fee (Yen/month)		1155

Table 2 Electricity price served normal user from a main electric power company in Kyushu, Japan.

Consumption amount (kWh)	Price (Yen/kWh)
0-120	15.54
120-300	19.95
More than 300	21.40
Initial fee for 40A (Yen/month)	1134

Table 3 the outline of two energy systems.

Detached house	House S	House N
Location	Oomuta, Kyushu	Kumamoto, Kyushu
Total floor area (m^2)	137.46	140.16
Family size	3 persons	5 persons
Equipment	all-electrified residential equipment	All-electrified residential equipment
Capacity of Photovoltaic system (kW)	4.8	4.2
Azimuth angle	Southwest 45°	Southwest 77°
Angle of inclination	38.7°	21.8°
Area of solar cell (m^2)	35.6	31.1
Power generation efficiency (%)	13.48	13.48
Hot water equipment	Electric hot water heater	CO2 heat pump hot water heater (COP=3.0)

Running cost reduction amount:

$$RC_{save} = RC_{Cost-PV} - RC_{Cost-NonePV} \quad (3)$$

Where,

PE_{save} : Energy saving amount (MJ);

E_{Ge-PV} : Electricity generation amount of photovoltaic system (kWh);

η_{up} : Power generation efficiency of utility power (%);

$CO2_{save}$: CO_2 reduction amount (kg-CO_2);

$C_{unit-fire}$: CO_2 emission unit of utility power (0.66kg-CO_2/kWh, the average value of fired power plant [6],[7]);

$C_{unit-PV}$: CO_2 emission unit of photovoltaic system (0.053kg-CO_2/kWh[7]);

RC_{save} : Running cost reduction amount (Yen);

$RC_{Cost-PV}$: Running cost amount of systems introduced photovoltaic system (Yen);

$RC_{Cost-NonePV}$: Running cost amount of systems none-introduced photovoltaic system (Yen);

The running cost of the energy system was calculated using equation (4) and (5). Although, the trade price system of surplus electricity from photovoltaic system is different in the different power company and region, for the sake of simplicity, the sold price of surplus electricity from photovoltaic system was assumed same as the purchased price in this paper.

$$RC_{Cost-PV} = C_{connectfee} + E_{purchased} \times P_{price} - E_{sold} \times P_{price} \quad (4)$$

$$RC_{Cost-NonePV} = C_{connectfee} + E_{consumed} \times P_{price} \quad (5)$$

Where,

$C_{connectfee}$: The connect fee that the electricity user must to pay to power company as long as they connect to power company grid, refer to Table 1 (Yen/month);

$E_{purchased}$: The purchased electricity amount of the energy system with photovoltaic system from power company (kWh);

E_{sold} : The sold electricity amount of the energy system with photovoltaic system to power company (kWh);

$E_{consumed}$: The electricity consumption amount of these two houses (kWh);

P_{price} : The electricity price, refer to Table 1 (Yen/kWh).

4. Generated and Consumed Electricity

4.1 Hourly Electricity Variation

In this section, the measured hourly data of the two systems in August 2005, October 2005 and January 2006 were analyzed. The hourly electricity variation for one week in mentioned three months was shown in Fig.1, Fig.2 and Fig.3, respectively. In these figures, the negative value in the purchased and sold electricity means the surplus electricity from photovoltaic systems sold to a power company. Conversely, the plus value means the electricity purchased from the company.

As for the electricity generation of photovoltaic system, House S was more than House N because former has larger capacity of photovoltaic system. The maximum value of the hourly electricity generation occurred in October; it was 3.4kW in House S and 70% of the photovoltaic system capacity. In House N, the maximum hourly electricity generation amount was 2.8kW and 67% of the photovoltaic system capacity. The main reason of the low electricity generation under the capacity was that the azimuth angle and the inclination angle of the solar cell were not optimal values for these two sites. Assuming August represents summer, October for spring or autumn and January for winter, the electricity generation in spring or autumn is larger than those of other seasons. The lowest hourly electricity generation amount occurred in January in winter.

About the purchased and sold electricity, the electricity selling happened in both photovoltaic systems in daytime. The reason is the electricity consumption of the dwelling almost occurs in morning and night; the electricity generated by photovoltaic system cannot be consumed on site in daytime. The maximum hourly electricity selling value was 2.7kW occurred in January in House S. However, because the electricity generation can not happen in night, all of the electricity was purchased from the power company, thus, the purchased and sold electricity curves superposed on the consumed electricity curves in night. In addition, the electricity selling almost occurred in daytime, the highest electricity price period, and the purchasing occurred generally at lower electricity price periods.

In August and October, House S had remarkable rising of electricity consumption in early morning, from 5:00-8:00 AM (the cheapest electricity price period) due to the operation of the electric hot water heater to make thermal storage. Although the electricity consumption in House N was rising in the same period, it is only about 1/3 of that in House S because of the adoption of CO_2 heat pump hot water heater with 3.0 COP. In winter, not only bathing but cooking and washing use hot water. The increase of hot water demand leaded the deficiency of the thermal storage amount in

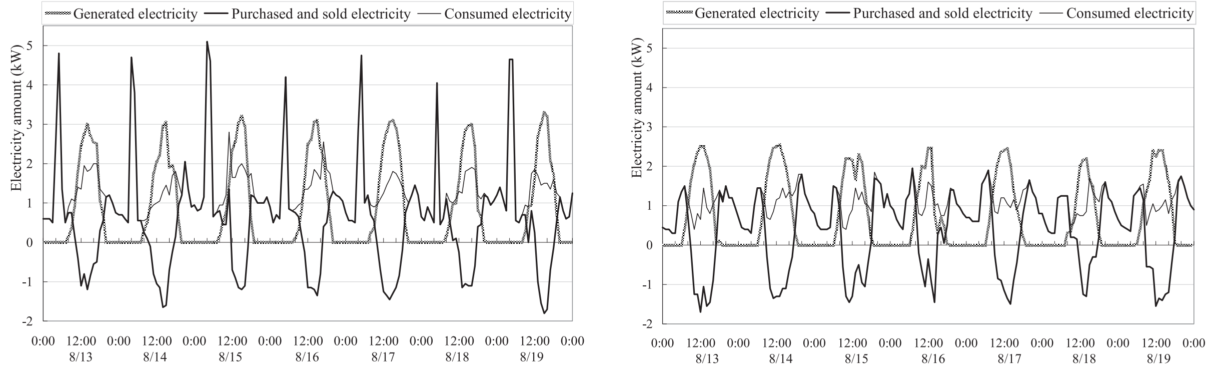

Fig.1 Hourly electricity variation of House S (left) and House N (right) in August.

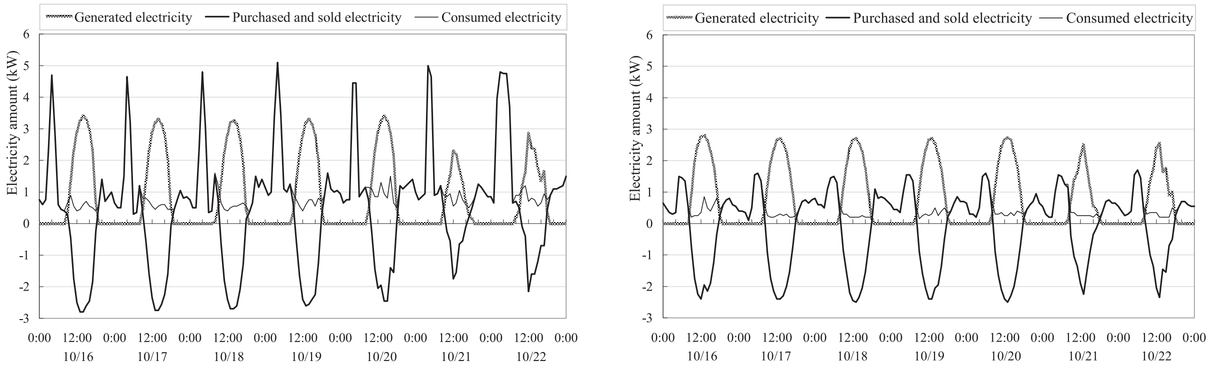

Fig.2 Hourly electricity variation of House S (left) and House N (right) in October.

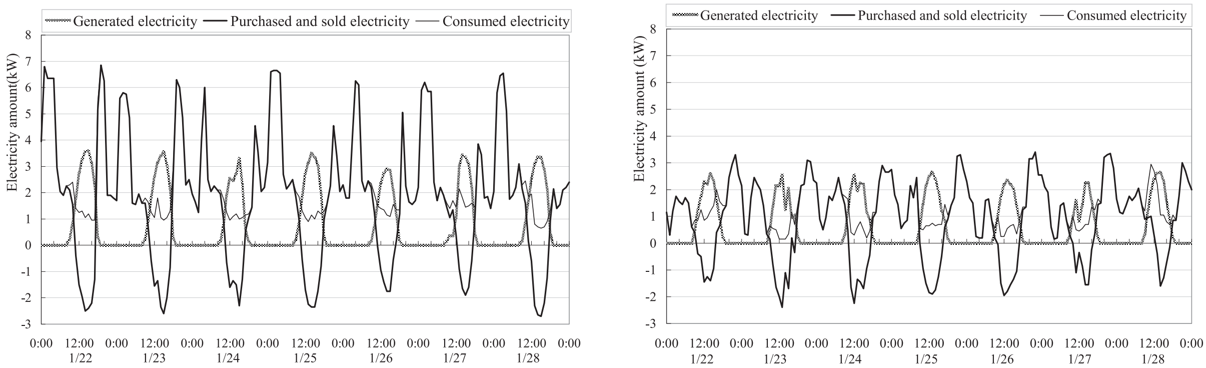

Fig.3 Hourly electricity change of House S (left) and House N (right) in January.

early morning; the hot water heater needed to operate at about 20:00 PM, the bathing time, in both houses. Therefore, two electricity consumption peaks appeared in early morning and at about 20:00 PM in January.

4.2 Monthly Electricity Situation

The monthly electricity situation of August, October and January is shown in Fig.4. In each month, both the electricity consumption and generation in House S were larger than those in House N. the electricity generation amount in August was the largest among these three months. They were 528kWh in House S and 466kWh in House N. As for the sold electricity, the largest value occurred in October, it were 288kWh/month in House S and 290kWh/month in House N. The electricity consumption in January was the largest among these three months for the heating load and increasing hot water load. In House S, the electricity consumption in January was 2.3 times higher than that in October and 2.1 times higher than that in August. The electricity consumption of House N in January was 1.9 times higher than that in October and 1.4 times higher than that in August. Accordingly, the purchased electricity in January was also the largest value among these three months.

4.3 Annual Electricity Situation

The monthly values of electricity generation, electricity consumption and the ratio of electricity generation to consumption is shown in Fig.5 (House S) and Fig.6 (House N) from Jan. 2005 to Jan. 2006. In House S, the data of

Mar., Apr. and May in 2005 were not available, due to the breakdown of the measuring instruments.

The electricity generation was lower in winter because of the shorter sunshine time and the weaker intensity solar radiation than other seasons. In July 2005, rainy season in Japan, the electricity generation amount was also lower than other months.

The electricity consumption in House S was remarkably rising in winter due to the operation of air-conditioners for all rooms and the adoption of normal hot water heater. However, the air-conditioner was operated only when somebody in room in House N and the high efficiency hot water heater (COP 3.0) was adopted. Although in House N, the electricity consumption was rising in winter, it was not as remarkable as that in House S.

The maximum values of the ratio of electricity generation to consumption were 61% in June in House S and 91% in May in House N and the minimum values were 17% in House S and 24% in House N in January 2005.

5. Electricity Consumption Analyses

In House N, hourly classified electricity consumption during two days were measured in summer and winter. The hourly electricity consumption are shown in Fig.7 (summer) and Fig.8 (winter). The daily classified electricity consumption percentage for categorized usage is shown in Fig.9. Since the isolated hourly electricity consumption for CO_2 heat pump hot water heater was not measured, it was calculated as the subtraction of the electricity consumption amount including refrigerator, cooling and the midnight average value for other appliance in summer from the total electricity consumption amount in early morning. However, the hot water heater was operated not only in early morning but also in evening in winter; the hourly electricity consumption for hot water heater was included in others category. Because the daily electricity consumption amount of other appliances (exclude hot water heater) almost constant all of the year, the daily electricity consumption amount of hot water heater in winter was estimated as the subtraction of the daily average electricity consumption amount of other appliances in summer from the daily amount of others including hot water heater in winter. By using the estimated electricity consumption value of hot water heater, the daily percentage of hot water heater and others were calculated and

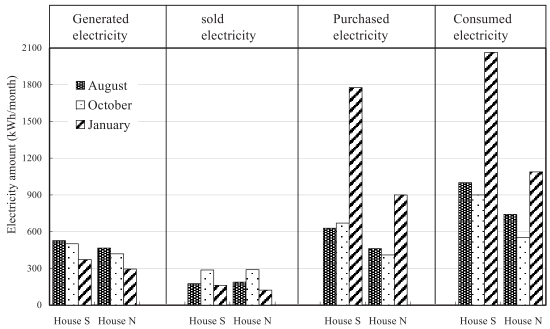

Fig.4 Monthly electricity situation.

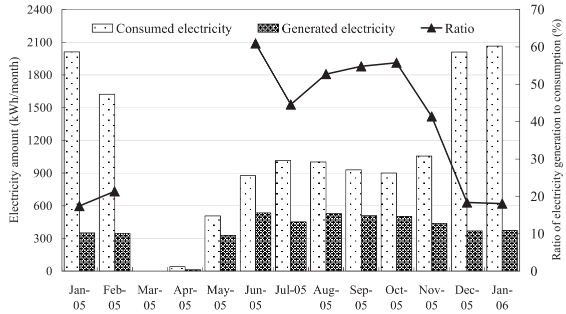

Fig.5 Monthly electricity variation in House S.

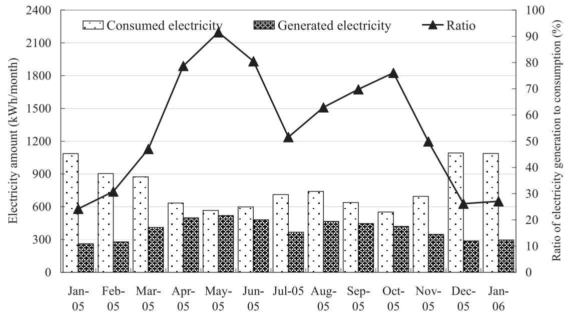

Fig.6 Monthly electricity variation in House N.

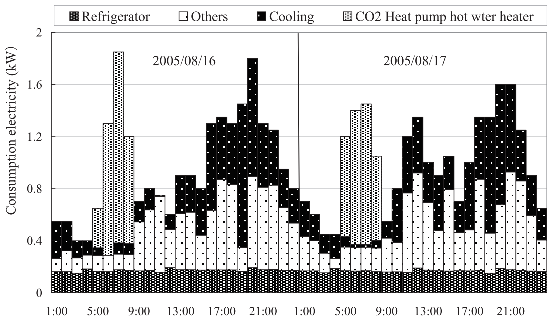

Fig.7 Hourly electricity consumption in summer.

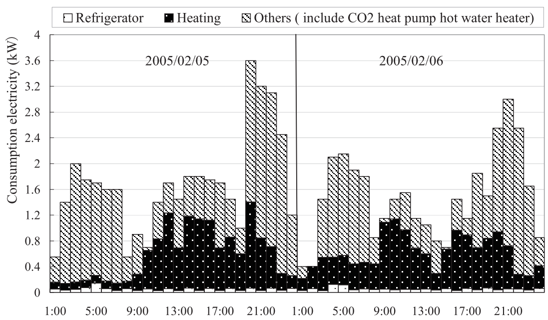

Fig.8 Hourly electricity consumption in winter.

shown in Fig.9.

From the figures of summer, the peak electricity consumption occurred in early morning when the CO_2 heat pump hot water heater was operated to make thermal storage. In addition, electricity consumption was rising in evening when all family members were at home. The electricity consumption for refrigerator was almost constant throughout a day. From the data in Fig.9, in summer, the percentage of electricity consumption was about 16% for CO_2 heat pump hot water heater, 27% for cooling, 18% for refrigerator and 39% for other appliances.

From the corresponding figures in winter, the increasing hot water consumption leads the CO_2 heat pump hot water heater to operate not only in early morning but also in evening around 20:00 PM in winter. Thus, the daily percentage of CO_2 heat pump hot water heater electricity consumption was increased remarkably to 41% in winter from 16% in summer. Reversely, the percentage of refrigerator electricity consumption was decreased significantly to 5% in winter from 18% in summer. The electricity consumed for heating accounted for 25% of total amount.

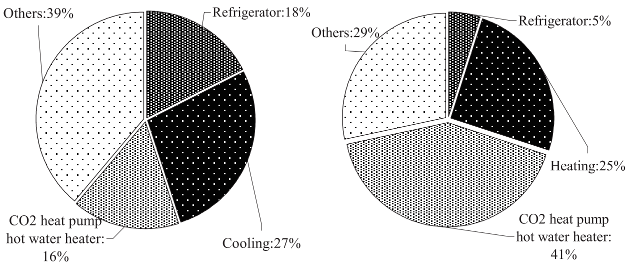

Fig.9 Classified electricity consumption in summer (left) and winter (right).

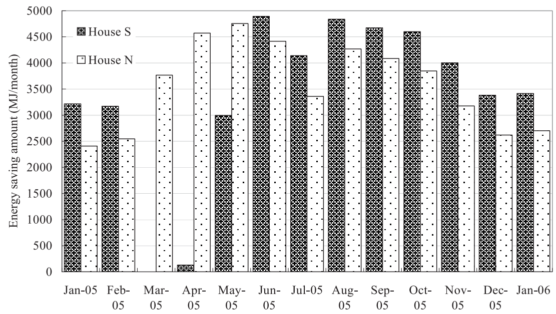

Fig.10 Monthly energy saving amount.

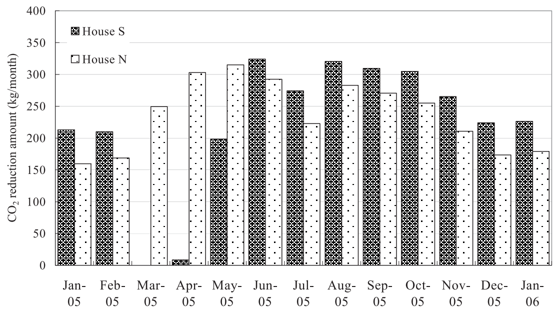

Fig.11 Monthly CO_2 reduction amount.

6. Evaluation of Photovoltaic System

6.1 Energy Saving

According to equation (1), the primary energy saving was calculated and shown in Fig.10 in every month from January 2005 to January 2006.

The monthly primary energy saving in House S is larger than that in House N excluded March, April and May (the unavailable data months) because the electricity generation in House S is larger than that in House N. The maximum primary energy saving amount occurred in June 2005 by 4,892 MJ in House S. On the other hand, the maximum primary energy saving amount in House N occurred in May 2005 by 4,754 MJ. The annual primary energy saving in House S amounted to 40,324MJ, which excluded the amount of March, April and May. In House N, the photovoltaic system saved 46,525 MJ in 2005

6.2 Environmental Effect

The monthly CO_2 reduction amount due to the electricity generated by photovoltaic system is used to evaluate environmental effect. Fig.11 shows the monthly CO_2 reduction amount in these two Houses. Compared with the figure of energy saving, it can be found that the CO_2 reduction amount has similar tendency as the primary energy saving. The annual CO_2 reduction amounts were 2,879kg in House S and 3,083kg in House N in the measured year.

6.3 Economic Effect

According to the electricity price listed in Table 1, the details of electricity cost in August 2005, October 2005 and January 2006 was calculated and listed in Table 4. The photovoltaic system user only paid about the connect fee for the electricity cost in August in House N and in October in House S. It is noted that the cost for electricity in House N was -1,701Yen in October when introducing photovoltaic system. This is because that the income from selling electricity exceeded the sum of the cost for purchased electricity and connect fee. This implies the user can achieve 1,701 Yen benefit in this month for introducing the photovoltaic system. The cost reduction in House S was larger than that in House N. House S reduced more than 10,000Yen/month

Table 4 Cost comparison of the introduced /none-introduced photovoltaic system.

Month		August, 2005		October, 2005		January, 2006	
House		House S	House N	House S	House N	House S	House N
Electricity consumption amount (kWh/month)		965	723	871	527	2002	1082
Introducted photovoltaic system	Cost for Purchased electricity (Yen/month)	7270	5890	8235	4757	21353	12715
	Income from selling electricity (Yen/month)	5686	5885	7767	5885	4406	3312
	Cost for electricity (Yen/month)	2739	1160	1623	**-1701**	18103	10559
None-introducted photovoltaic system	Cost for total electricity consumption (Yen/month)	17204	13470	12195	7676	27343	17470
	Cost for electricity (Yen/month)	18359	14625	13350	8831	28498	18625
Reduction cost (Yen/Month)		15621	13465	11726	10532	10396	8066

in every month. The maximum cost reduction amount occurred in August and they were 15,621Yen in House S and 13,465Yen in House N. The average reduction cost of these three months was 12,581Yen/month in House S compared with the none-introduced photovoltaic system. It was 10,688Yen/month in House N.

7. Conclusion

The field study was carried out on two existing detached houses with all-electrified residential equipment and photovoltaic system. Based on the measured data, we clarified the operating situation of electricity generation of photovoltaic system and electricity consumption of such energy system. The introduction effect of photovoltaic systems also was evaluated. The obtained results can be summarized as follows:

1) The optimized azimuth and inclination angle of solar cell are important for the photovoltaic system to achieve excellent electricity generation result. The electricity generation of the photovoltaic system in spring or autumn is larger than those of other seasons.

2) Because the electricity consumption of the dwelling almost occurs in morning and night, the electricity generated by photovoltaic system cannot be consumed on site in daytime, the electricity selling happened in both photovoltaic systems in daytime

3) The air-conditioning electricity consumption accounted for 27% in summer and 25% in winter against whole electricity consumption. In summer, about 16% electricity was used for hot water heater; however, the value was remarkably increased to 41% in winter because of increasing hot water demand. Other appliances except for refrigerator consumed about 39% in summer and 29% in winter against daily total electricity consumption amount. The hourly electricity consumption for refrigerator was almost constant throughout the day and the daily percentages were 18% in summer and 5% in winter.

4) In these two houses, the system achieved excellent energy saving, environmental and economic effect with the introduction of photovoltaic system. Especially, the user gained 1701 Yen benefit from the electricity selling in October in House N.

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