Evaluation of Photovoltaic System in Detached Houses with All-electrified Residential Equipment

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Abstract: - Two detached houses with photovoltaic energy systems and all-electrified residential equipment were chosen as the research object to clarify the hourly operating situation of electricity generation and electricity consumption. The combination using of the photovoltaic system with the high efficiency equipment, CO2 heat pump hot water heater, also has been examined. The introduction effect of the photovoltaic system in Japan 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: - All-electrified residential equipment, Photovoltaic system, CO_2 heat pump hot water heater, Field study, Detached house, Electricity generation amount.

1 Introduction

Japan imports most of the primary energy resources from oversea and declared to reduce 6% of its greenhouse gas emission with the1990 level in 2008 to 2012. Therefore 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.

On the other hand, the Japanese energy consumption in residential sector is increasing, but in other sectors, slightly decreasing or keeping up in the same level after the oil crisis. It 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. 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 in Japan. The advantages of this system are 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. However, very little research has been spent on the combination effect of the renewable system, the high efficiency equipment and the all-electrified system.

Two detached houses with all-electrified residential equipment and 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 this system have been clarified. The combination of photovoltaic system with the high efficiency equipment, CO2 heat pump hot water heater, has also been examined. 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 Outline of Photovoltaic Systems

The details of the two photovoltaic systems are listed in Table 3. They are installed in typical detached house locating in Kyushu, the southern region of Japan as illustrated in Fig.1, 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 energy demand is satisfied by the electricity from the power company or the photovoltaic system. In Japan, a bathtub is filled with hot water almost every evening throughout the year and is used by the whole family. This is the large portion of hot-water supply load of dwelling. Hot water supply consumes about 30% of the total energy consumption in dwelling. 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), the lowest electricity price period (refer to Table 1).

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.

3 Generated and Consumed Electricity

3.1 Hourly Electricity Generation and Consumption

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.2, Fig.3 and Fig.4, 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.

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 photovoltaic 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)

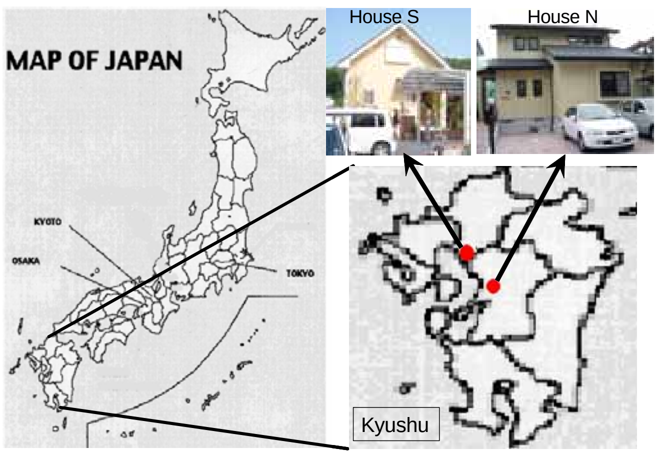

Fig.1 The location of these two detached houses

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 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. The maximum value of the hourly electricity generation in October was 0.4kW larger than that in August.

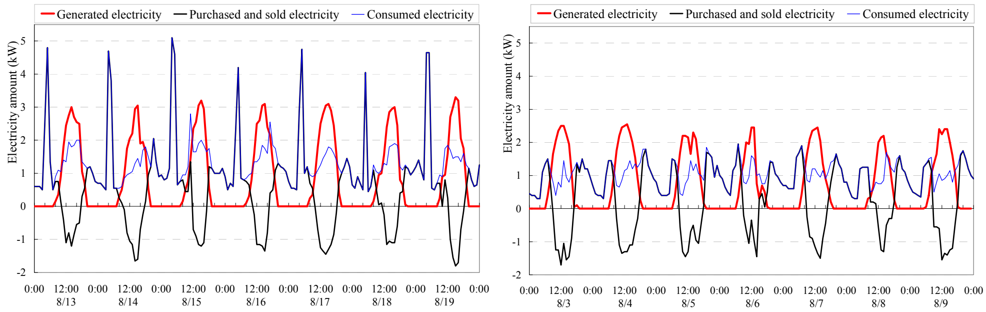

Fig.2 Hourly electricity variation of House S (left) and House N (right) in August

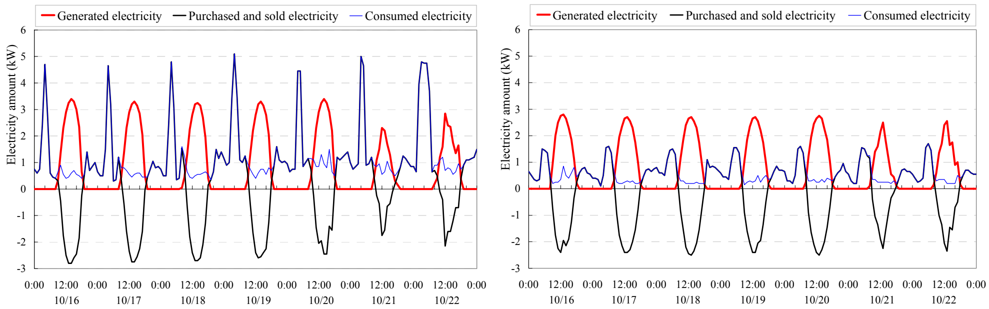

Fig.3 Hourly electricity variation of House S (left) and House N (right) in October

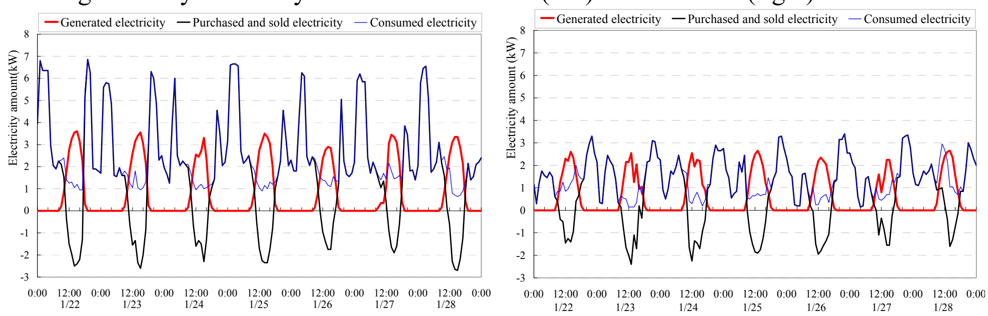

Fig.4 Hourly electricity change of House S (left) and House N (right) in January

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. In addition, the electricity selling almost occurred in daytime, the highest electricity price period, and the purchasing occurred generally at lower electricity price periods.

House S had remarkable rising of electricity consumption in early morning, from 5:00-8:00 AM according to the operation of the electric hot water heater. 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 storage amount in early morning and can not satisfy all day's hot water demand; the hot water heater needed to operate at about 20:00 PM, the bathing time. Therefore, two electricity consumption peaks appeared in early morning and at about 20:00 PM in January.

3.2 Monthly Electricity Situation

The monthly electricity situation of August, October and January is shown in Fig.5. In each month, both the electricity consumption and generation in House S were larger than those 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. As for the sold electricity, the largest value occurred in October, it were about 288kWh/month in House S and 290kWh/month in House N.

3.3 Annual Electricity Situation

The monthly values of electricity generation, electricity consumption and the ratio of electricity generation to consumption were shown in Fig.6 (House S) and Fig.7 (House N) from January 2005 to January 2006. In House S, the data of March, April and May in 2005 were not available, due to the breakdown of the measuring instrument,

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

The electricity consumption in House S was remarkably rising in winter due to the operation of air-conditioners for all rooms and the normal hot water heater. On the other hand, the air-conditioner was operated only when somebody in room in House N. Although in House N, the electricity consumption was rising in winter, it was not so remarkable.

4 Energy Consumption Analyses

In House N, classified electricity consumption during two days were measured in summer and winter. The hourly electricity consumption are shown in Fig.8 (summer) and Fig.10 (winter). The classified electricity consumption for categorized usage are shown in Fig.9 (summer) and Fig.11 (winter). Since the isolated 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 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 electricity consumption for hot water heater was included in other category.

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

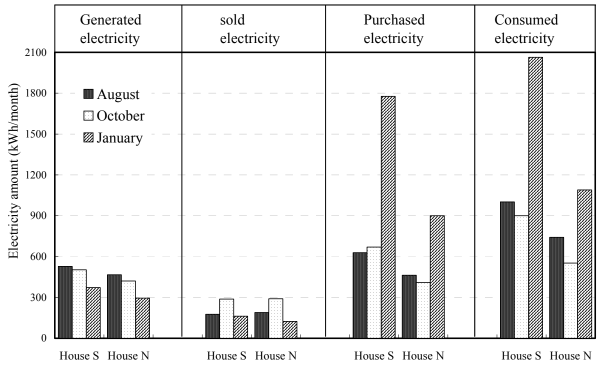

Fig.5 Monthly electricity situation

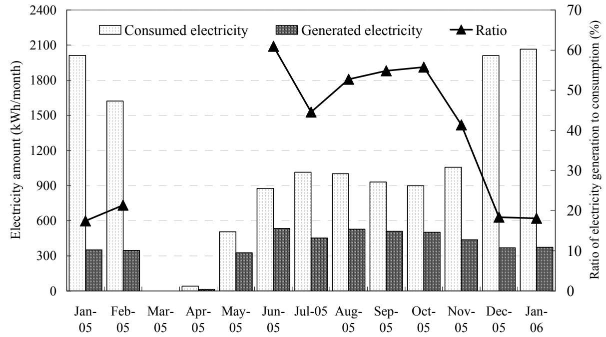

Fig.6 Monthly electricity variation in House S

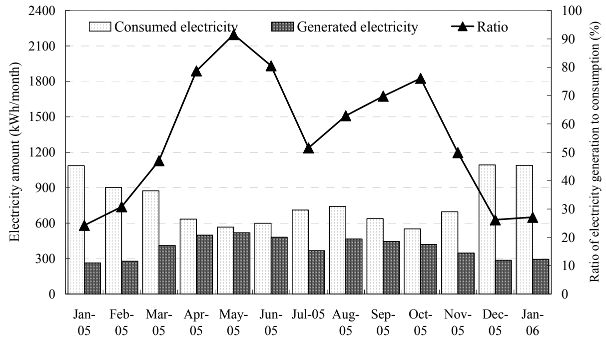

Fig.7 Monthly electricity variation in House N

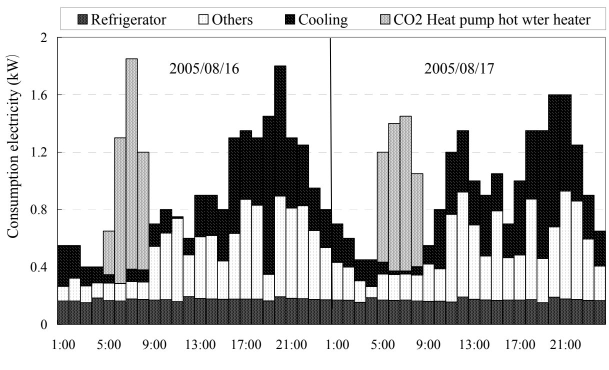

Fig.8 Hourly electricity consumption in summer

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 (see Fig.10 and Fig.11), 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, CO_2 heat pump hot water heater and other appliances consumed 70% of electricity. 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.

5 Evaluation of the Photovoltaic system

5.1 Energy Saving

Because the electricity generated by photovoltaic system will reduce the primary energy consumption in power because it does not consume any fossil energy. By using the power generation efficiency 39.3% of power plant and the measured electricity generation amount of photovoltaic system, the primary energy saving was calculated and shown in Fig.12 in every month.

The monthly energy saving in House S is larger than that in House N because the electricity generation in House S is larger than that in House N. The maximum energy saving amount occurred in June 2005 by 4,892 MJ in House S. On the other hand, the maximum energy saving amount in House N occurred in May 2005 by 4,754 MJ. According to the measured data, the annual 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.

5.2 Environmental Effect

Monthly CO_2 reduction amount due to the electricity generated by photovoltaic system is used to evaluate environmental effect. Fig.13 shows the monthly CO_2 reduction amount in these two Houses. The CO_2 reduction amount has a similar tendency to the energy saving. The annual CO_2 reduction was 2,879kg in House S and 3,083kg in House N.

5.3 Economic Effect

According to the electricity price listed in Table 1, the details of electricity cost in August 2005, October

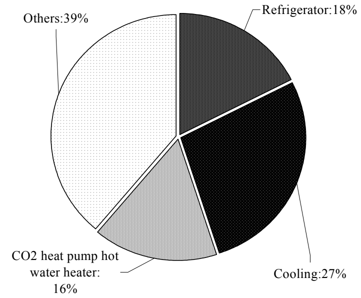

Fig.9 Classified electricity consumption in summer

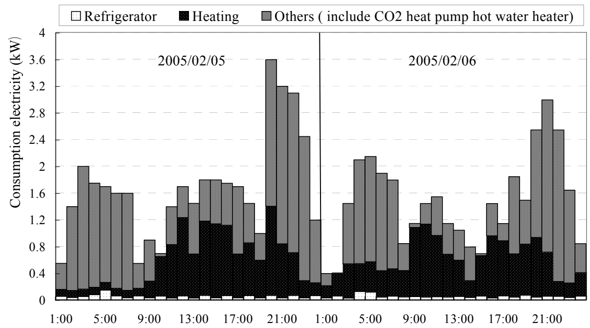

Fig.10 Hourly electricity consumption in winter

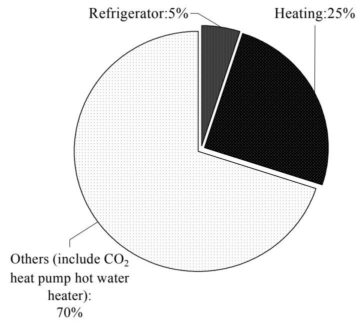

Fig.11 Classified electricity consumption in winter

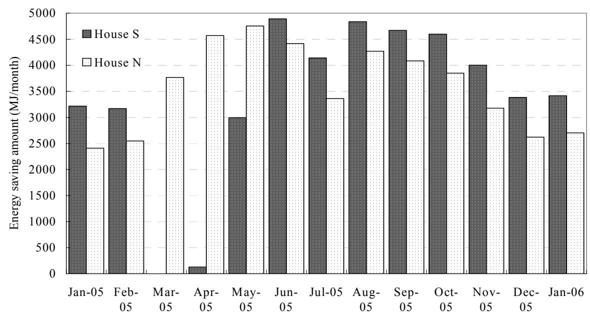

Fig.12 Monthly energy saving amount

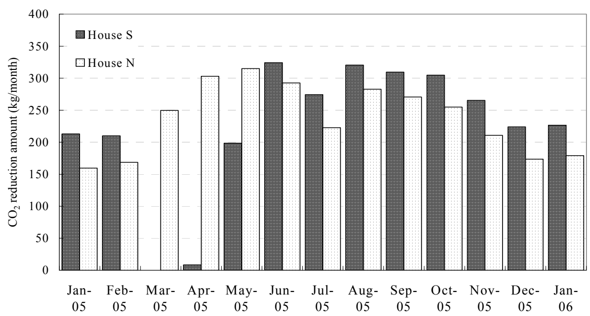

Fig.13 Monthly CO_2 reduction amount

2005 and January 2006 was calculated and listed in Table 4 assuming the price of selling electricity is the same as the purchase price. The cost reduction in House S was larger than that 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. 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 cost for purchased electricity. This implies the user can achieve 1,701 Yen benefit in this month for introducing the photovoltaic system.

6 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 evaluated the introduction effect of photovoltaic systems. The obtained results can be summarized as follows:

1) The optimized azimuth and inclination angle are important for the photovoltaic system.

2) The energy consumption for air-conditioning accounted for 27% in summer and 25% in winter against whole energy consumption. In summer, about 55% energy was used for hot water heater and other appliance except for refrigerator and air-conditioner. However, it was 70% in winter because of the increase of hot water demand.

3) 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.

Acknowledgements

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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

*Note: Electricity user should pay 1155 Yen/month initial cost, refer to Table 1