Evaluation of Photovoltaic Power Generation Systems in Residential Homes in Japan: A Partnership Program of Utility and Consumers' Cooperative

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ABSTRACT

A subsidy program for introducing photovoltaic (PV) power generation system to residential homes in Japan was launched by the Japanese government in 1994, with total capacity of the installed systems reaching 64.6 MWp in 1998. The cost of installation has been reduced to about \$9,000/ kWp[1] in 1999.

From 1997 to 1998, apart from the government program, the private-sector Seikatsu Club Consumers' Cooperative and the Tokyo Electric Power Company (TEPCO) granted average \$4,500/kWp to home owners who were planning to install PV systems in the Tokyo area. Out of 376 applicants, 132 households were selected through careful consideration, and grid-connected systems (total 412 kWp, mean 3.1 kWp) were installed on the rooftops of their houses.

According to measurement results from October 1998 to September 1999, the average PV electric output was 2,784 kWh/year (887 kWh/kWp/year), equivalent to 45% of monitored household electricity consumption. The average savings per household was \$641/year. Therefore the cost of installation is to be paid back in 42 years of savings. With consideration of subsidy, it is to be paid back in 23 years.

The electric output of PV system was 34% of total capacity during the TEPCO peak demand period. And electricity consumption for cooling was reduced 26% compared that of before installation. This might be brought by reduction in cooling load by PV arrays blocking roof sunlight and controlled air conditioner by monitored households.

From the result of measurement and estimated potential installation capacity mentioned on existing studies, the potential electricity generation by PV system in Japan would be 25.8 TWh/year, equivalent to 14% of the total residential electricity consumption in 1998.

Introduction

Along with the recent growing interest in global environmental issues, the need for developing renewable energy sources has increased. In particular, photovoltaic (PV) power generation systems, which do not emit carbon dioxide (CO_2) nor cause any air pollution as they generate electricity and for which the generation pattern matches the peak cooling demand in summer, is hoped to become one of the most reliable energy supplements in Japan. However, some stumbling blocks hinder the wider diffusion of the PV systems, such as its

[1] In this paper exchange rate we used was 1\$ = 110yen.

high dependency on the weather conditions, and also the relatively high cost of installation.

To promote the wider diffusion of PV systems, the Japanese government started subsidy programs for private residences in 1994. By this program, as shown in **Table 1**, the total capacity of installed PV systems has reached 64.6 MWp and is expected to exceed 100 MWp in 1999. **Figure 1** shows that the cost of installation has been reduced by about 25% to approximately $9,000/ kWp since 1993. In 1998, the Japanese government set its long-term energy outlook, in which the government aims at the total capacity of installed PV systems to be 5,000 MWp by 2010. This energy outlook meets the terms of the Kyoto Agreement, in which Japan promised a 6% reduction of greenhouse gas emissions from the 1990 level. In addition, electric power companies have started voluntarily buying surplus electric output of PV systems at the equal price of which each company sells. As PV systems for residential homes have become more widespread, the volume of electricity purchased by the electric companies reached a total of 17.4 GWh in 1998.

In 1997, apart from the government program, the Tokyo Electric Power Company (TEPCO) started a monitoring program which granted subsidies for the members of Seikatsu Club Consumers' Cooperative (CO-OP) in Tokyo/Kanagawa area who were planning to install PV systems. This partnership program of TEPCO and CO-OP is quite interesting because of their differing opinions; one is promoting nuclear power generation and the other is opposed to it. Since the 1980's, there have been always pros and cons on the use of nuclear power between the government/electric power companies and NGOs in Japan. NGOs believe a combination of energy conservation and the use of renewable energies could take the place of nuclear power. On the other hand, the government/electric power companies take up the position that nuclear power is an unavoidable choice for meeting the growing demand of electricity and for coping with the global warming issues.

TEPCO and CO-OP agreed upon a partnership based on mutual understanding of their differing opinions to tackle common energy problems. In 1996, they began a common study which explored energy efficiency experiments and surveyed monthly energy consumption among the members of CO-OP. This monitoring program concerning the installation of PV systems is another aspect of their common objective of investigating the availability of renewable energies. Although several assessment studies on PV systems had been done previously by the government, the actual measurements at more than 100 homes with installed PV systems is the first large-scale trial in Japan.

Outline of program

The program consists of the 3 parts for monitored households: subsidy for installation, measurement survey followed by complete installation, questionnaire surveys focused on consciousness of energy use and energy consumption (see **Table 2**).
TEPCO/CO-OP had subsidized the cost of installation for 2 years from 1997. During this period, out of 376 applicants 132 households had been appointed to monitored households as a result of initial survey. In the first year, the capacity of array limited to be more than 3 kWp, and 1.5 millions yen ($13,600) was subsidized across the board. However due to the small dimension of roofs, many of applicants cancelled their applications.

Table 1. Installation of PV systems by government subsidy program

F.Y.	Budget		Capacity	Mean Capacity	Number of
	(billion Yen)	(million $)*1	(MWp)	(kWp)	Installation*2
1994	2.03	18.5	1.86	3.45	539
1995	3.32	30.2	3.92	3.68	1065
1996	4.06	36.9	7.54	3.79	1986
1997	11.11	101.0	19.49	3.45	5654
1998	14.70	133.6	31.75	3.86	8229
1999	16.04	145.8	------	-----	14707
Total	51.26	466.0	64.55*3	3.69*3	32180

*1 exchange rate : 1$ = 110yen
*2 1998, 1999 : Number of applicants
*3 from 1994 to 1998
source : New Energy Foundation

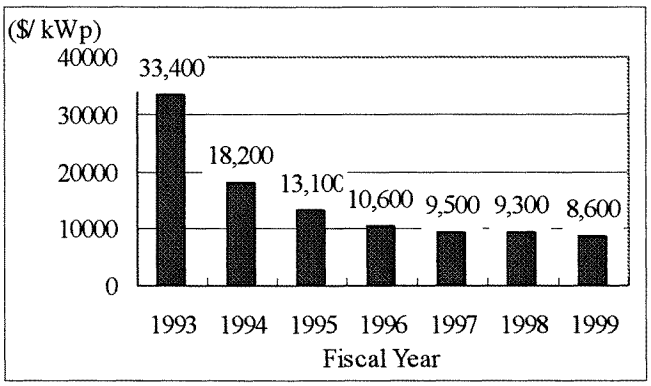

Figure 1. Cost of PV power generation system
source : Ministry of Industrial Trade and Industry
exchange rate : 1$ = 110yen

Therefore, in the next year, 1.5 millions yen was subsidized to households which had array with capacity of over 2.5 kWp, 1 million ($9,100) yen was subsidized to households which had array with capacity of 2-2.5 kWp.

After completion of the installations, measurements took place over 3 years. There were two types of measurement surveys. For 72 households, measured in detail, collecting the hourly data was done through telephone circuit everyday. This included PV electric output, electric output sold, electricity purchased, electricity consumption, global radiation, and array temperature. For the remaining 60 households, measured simply, hourly data was memorized into data logger (replacement every half year). This included PV electric output, electric output sold, electricity purchased, and electricity consumption.

Table 2. Outline of Program

Subsidy	1997	3kWp-	1.5 million yen ($13,600)
	1998	2.5kWp-	1.5 million yen ($13,600)
		2 - 2.5kWp	1.0 million yen ($9,100)
Measurement	detailed	PV output, electric output sold, electricity purchaced, electricity consumption, global radiation, array temprature	
	simple	PV output, electric output sold, electricity purchaced, electricity consumption	
Questionnaire	general description of households, conciousness of energy use, energy consumption, motive of installation		

State of Installation

The area of monitored households was Tokyo Metropolitan and Kanagawa prefecture in the south of service area of TEPCO (see **Figure 2**). The total capacity of installed PV systems was 412.2kWp, average 3.12kWp per household. All systems are connected to the grid, most of them were installed on the roof of single house dwellings. There are two types of cell, single crystal silicon cell for 125 systems and polycrystalline silicon cell for the remaining, depending on monitored households' choice of manufacture.

The average cost was 29.4 thousand dollars (U.S.) including tax, 9.4 thousand dollars per kWp[2]. Average amount of subsidy was 13.6 thousand dollars – 13.6 thousand dollars for 131 households and 9.1 thousand dollars for a household – therefore average expense to be paid by the individual was 15.8 thousand dollars, 5.1 thousand dollars per kWp.

The cost is composed of the cost of PV system (array, inverter, and attachments) and the cost of installation. Four households purchased only PV system and installed by themselves, the cost was downscaled to be 7.0 thousand dollars per kWp. On the other hand, the cost through vendors was 2.5 thousand dollars more per kWp (see **Table 3**). The difference between the former and the latter regarded as the cost of installation. According to New Energy Foundation, the average cost of installation in the government subsidy program was approximately 1.2 thousand dollars per kWp. Therefore, the cost of installation in this program seemed to be twice as high as the cost in the government program in which many of dwellings seemed to be constructed as PV dwellings, this meant that installing PV system with construction might lower the cost of installation. In this program most PV systems were installed after construction even with newly built houses.

To maximize the PV electric output, it is desirable to set it southerly tilted by 30-40 degrees in Tokyo area. In this program, 34% of total capacity was set southerly (due south ±15 degrees), and 11% were tilted by 30-40 degree (see **Table 4**).

[2] It seems to be a little expensive than the cost in the U.S.. According to "A consumer's Guide to Buying a Solar Electric System"(U.S. Department of Energy, Sep.1999), PV system cost is $8-$10/Wp for 2-kilowatt system, and $6-$8/Wp for 5-kilowatt system.

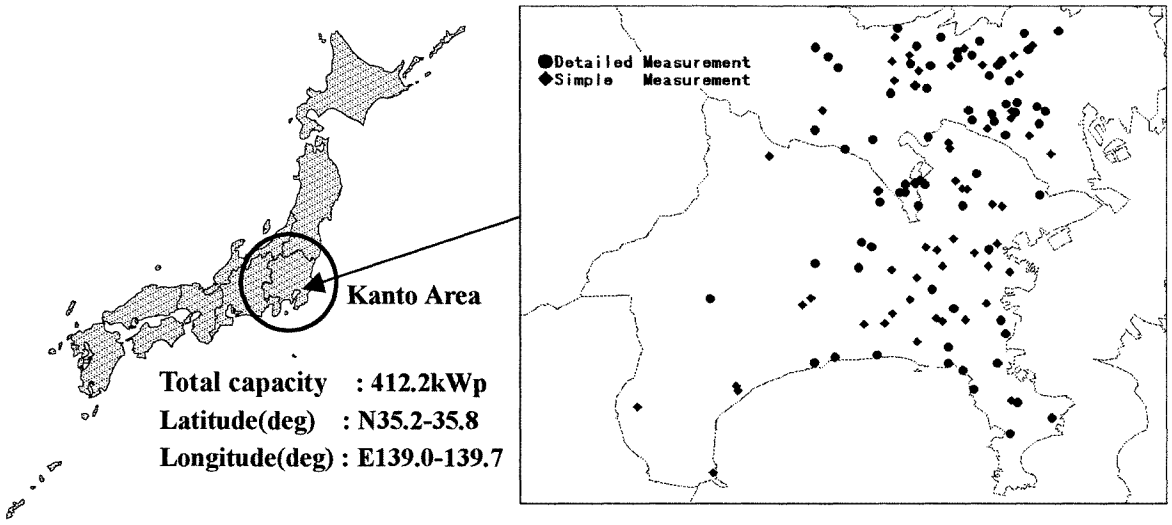

Figure 2. Location of Monitored Households

Table 3. Average Cost of PV system

		yen/kWp	$/kWp	Number
Installed by oneself		771,000	7,000	4
Installed by vendor		1,044,000	9,500	128
	Newly Built House	993,000	9,000	46
	Existing House	1,073,000	9,800	82
Average		1,034,000	9,400	132

Table 4. The share of capacity of installed PV systems by azimuth and tilt (degree)

azimuth \ tilt	0～10	10～20	20～30	30～40	40～50	50～60	Total
South±(0～15)	–	8.5%	14.4%	11.3%	–	–	34.1%
±(15～30)	–	8.9%	10.8%	5.3%	0.2%	0.6%	25.9%
±(30～45)	–	1.0%	5.9%	2.0%	–	–	8.8%
±(45～60)	–	1.9%	3.1%	1.9%	–	–	6.9%
±(60～75)	0.4%	0.4%	3.1%	1.8%	–	–	5.6%
±(75～90)	–	1.2%	2.7%	2.0%	0.4%	–	6.3%
±(90～105)	–	0.3%	3.3%	0.6%	1.0%	–	5.3%
±(105～120)	0.4%	0.2%	0.9%	1.1%	–	–	2.6%
±(120～135)	–	0.4%	1.3%	0.4%	–	–	2.2%
±(135～150)	–	–	0.3%	–	–	–	0.3%
±(150～165)	–	0.2%	0.5%	–	–	–	0.6%
±(165～180)	–	0.3%	0.6%	0.3%	–	–	1.2%
Total	0.7%	23.3%	46.9%	26.7%	1.7%	0.6%	100%

General Description of Monitored Households

General descriptions of monitored households determined by the questionnaire survey are as follows:

- 75% of these were composed by parents and children and average number of household members was 4.1, and was larger by 1.4 than that of Kanto area.
- The average floor space of monitored households was 136.1 m^2 (1,465ft^2), and was larger by 18% than that of Kanto area. The reason for it was that the house with PV system required to have large space of roof, therefore the house of small floor space was not selected in a result.
- As for the annual income, 60% of households earned 10 million yen ($90,900) per year, average income estimated to be more than 10 million yen. The average annual income of Kanto area was 7.33 million yen[3] ($66,600). A total of 87% of monitored households exceeded this average. Since, to install the PV system required much money, even though supported by subsidy, many of the monitored households were in upper income group.
- Monitored households have much concern about the global warming. 2/3 of these responded that they had much concern about it, 1/3 of these responded that they had a little concern about it (see **Figure 3**).
- The average annual energy consumption of single-family dwellings before installation of PV system was 60.6GJ (57 effective responses), and was 23% larger than the result of existing survey (IEEJ 1998) for households in Tokyo area. In addition, electricity consumption was 47% larger than (see **Figure 4**). This is because monitored households have relatively large members and lived in large houses as shown above.

State of power generation

From October 1998 to September 1999, total PV electric output was 2,784 kWh/year (887 kWh/kWp/year), and capacity factor[4] of PV system was 10.1% (see **Table 5**). Total global radiation was 1,138 kWh/m^2/year, 9% less than that of average year. Provided that PV electric output would be in proportion of global radiation, if global radiation would be the same value of average year, estimated total PV electric output would be 3,055 kWh/year (973 kWh/kWp/year), and capacity factor was 11.1%. The largest value of monthly PV electric output was 3.04 kWh/kWp/day indicated in May through year. Though global radiation was larger in summer season (July, August) than in May, PV electric output in summer season was smaller than that of May due to inefficiency caused by rise in array temperature.

PV electric output varies according to radiation and installation characteristics (azimuth and tilt). During the evaluated period, PV electric output measured in 78 households was distributed as **Figure 5**. The statistical mode was 900-950 kWh/kWp/year (22%). The PV system generating the largest amount of power was generating twice as large amount as that of the lowest amount of power. Due to the difference of the amount of

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[3] It was the average income of workers' households, excluding single households in 1998. source) Management and coordination Agency, Annual Report on the Family Income and Expenditure Survey 1998, June 1999.

[4] capacity factor(%) = {PV electric output / (Capacity * 8760)} * 100

radiation, electric output of PV system in Tokyo was 9% less than that of Kanagawa. According to New Energy Foundation, also the household subsidized by government, electric output of PV system in Tokyo was 10% less than that of Kanagawa. In addition, electric output of PV system installed separately into plural directions was 9% less than that of PV system installed in single direction. Especially, in winter, due to the lower sun's angle, difference between the former and the latter was greater.

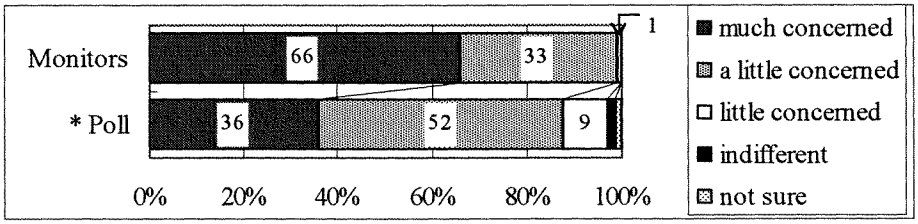

Figure 3. Degree of concerned for global warming issues
*) Prime Minister's Office, Public Opinion Poll (Feb. 1999)

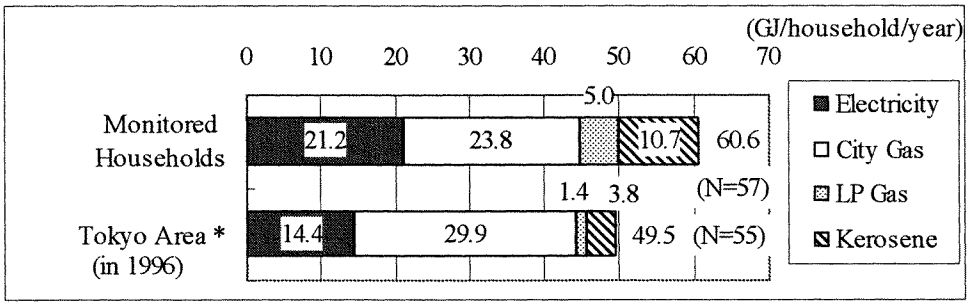

Figure 4. Annual energy consumption of monitored households before installation
note: excluding households who lived in multi-family dwellings before installation
* from existing survey (IEEJ 1998)

Table 5. Monthly PV electric output (Average of monitored households)

monthly	PV output(A) (kWh/day)	Capacity(B) (kWp)	(A)/(B) (kWh/kWp/day)	Capacity Factor (%)	N	global radiation (kWh/m^2/day)	N
1998/10	5.79	3.18	1.82	7.6	96	2.26	43
11	6.33	3.15	2.01	8.4	98	2.19	45
12	5.37	3.13	1.71	7.1	105	1.73	50
1999/1	7.48	3.14	2.38	9.9	107	2.30	51
2	8.96	3.15	2.84	11.8	110	3.04	53
3	6.53	3.15	2.07	8.6	113	2.58	56
4	8.30	3.14	2.64	11.0	117	3.48	58
5	9.53	3.14	3.04	12.7	121	4.27	61
6	7.66	3.12	2.45	10.2	127	3.68	67
7	9.05	3.13	2.90	12.1	128	4.28	68
8	9.45	3.13	3.02	12.6	123	4.44	63
9	7.19	3.12	2.30	9.6	124	3.15	64
Average	7.63	3.14	2.43	10.1		3.12	
Yearly	2,784	3.14	887	10.1		1,138	

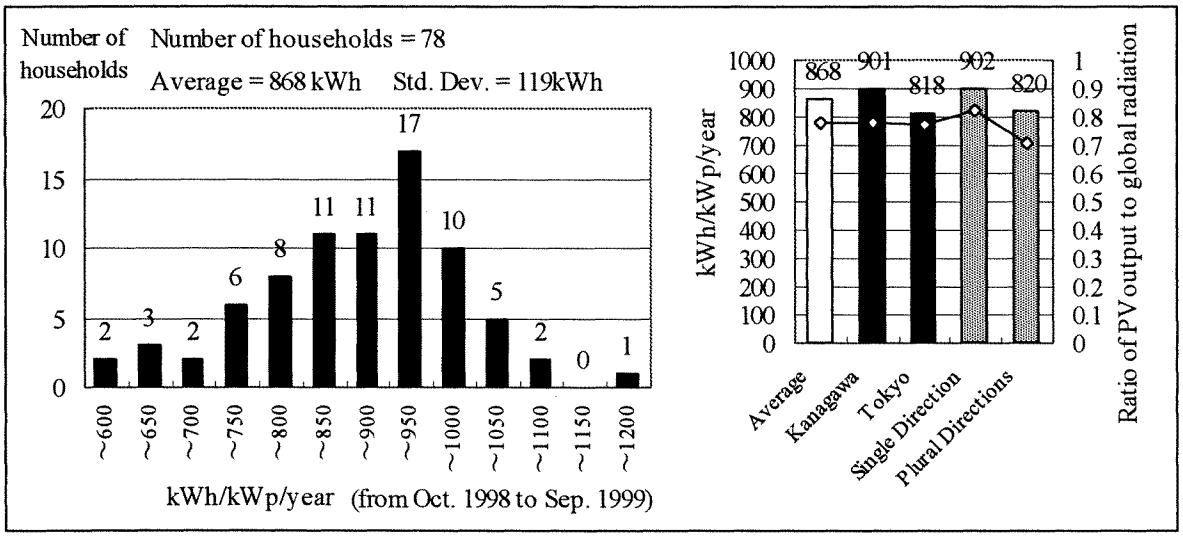

Figure 5. Distribution of annual PV electric output

PV system contribution

During the evaluated period, the average electricity consumption was 6,123 kWh/year, it was 34% higher than that of Kanto area (=4,560kWh/year)[5] because of large size of family and floor space. The 20% of these were generated by PV systems and electric power company supplied remains 80%. As for the total electric output of PV system, 45% of it was consumed by households, remains 55% of it was sold to electric power company (see **Figure 6**). The ratio of PV electric output to electricity consumption was 45%.

The savings of electric expenses by installation of PV system were $641/year, $291/year saved by reduction of electricity purchased from electric power company, $350/year saved by electric output sold. Noticed from the above, surplus electric output was sold by the same price ($0.23/kWh) as electricity supplied by electric power company.

Provided that global radiation would be the same value of average year, estimated total savings were $707/year. Therefore, pay back period is 42 years, without consideration of interest and cost for maintenance (replacement of inverter, etc). Monitored households were subsidized about $13,600, so in this case, pay back period is 23 years for them. Because the average residential electricity price for in Japan is higher than that of U.S., it is relatively economical, but it is still difficult to cover the cost of installation completely without subsidy.

As shown in **Table 6**, the savings of electric expense distributed in $376-778/year (median $602/year). Considering the savings adjusted by average year's radiation, pay back period is 30-65 years (median 45 years), which is longer than the duration of PV system. In view of subsidy, it is 12-37 years (median 24 years). However, assumed the duration of PV

[5] It was the average value of households excluding single households in 1998. source) Jyukankyo Research Institute," Residential Energy Statistics Year Book 1998", February 2000.

system would be 20 years, 16% of the above could be covered installation cost by savings. Additionally, 3 households installed PV system by themselves, so the pay back period for them is less than 16 years. It is necessary to reduce the cost of installation by 1/3 of current cost, to be less than $3,000/kWp for wider diffusion. The cost reduction of installation shall be needed as well as price reduction of PV module and inverter.

The ratio of PV electric output to the electricity consumption ranged 17-151% (median 48%).

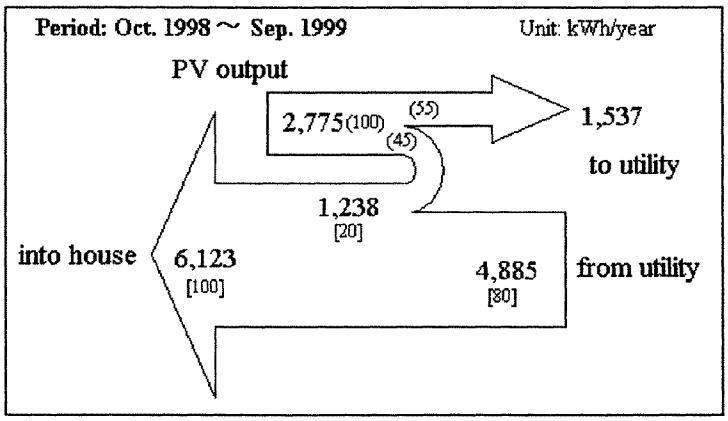

Figure 6. Flow of Electricity

Table 6. Distribution of savings and pay back period

[1] Savings of electric expense (dollars/year)

	-500	500-550	550-600	600-650	650-700	700-	N	Median	Max	Min
N	11	12	12	14	16	8	73	602	778	376
(%)	(15%)	(16%)	(16%)	(19%)	(22%)	(11%)	(100%)			

[2] Savings of electricity expense (adjusted by average year's radiation) (dollars/year)

	-550	550-600	600-650	650-700	700-750	750-	N	Median	Max	Min
N	12	12	10	14	13	12	73	656	861	416
(%)	(16%)	(16%)	(14%)	(19%)	(18%)	(16%)	(100%)			

[3] Pay back period (years)

	30-36	36-42	42-48	48-54	54-60	60-66	N	Median	Max	Min
N	5	21	18	13	11	5	73	45	65	30
(%)	(7%)	(29%)	(25%)	(18%)	(15%)	(7%)	(100%)			

[4] Pay back period (in consideration of subsidy) (years)

	12-16	16-20	20-24	24-28	28-32	32-	N	Median	Max	Min
N	3	9	25	13	13	10	73	24	37	12
(%)	(4%)	(12%)	(34%)	(18%)	(18%)	(14%)	(100%)			

[5]Ratio of PV output to Elctricity consumption(%)

	-20	20-40	40-60	60-80	80-100	100-	N	Median	Max	Min
N	1	22	25	8	8	9	73	48	151	17
(%)	(1%)	(30%)	(34%)	(11%)	(11%)	(12%)	(100%)			

Effect of peak load shaving

The peak load in TEPCO is recorded in the due summer when the load for cooling increases through year. Since the PV electric output increases when the cooling load is increasing, the PV system could shave the peak load. In 1999, average PV electric output of maximum 3 days and electricity consumption of monitored households indicated in **Figure** 7. PV electric output was 1.07 kWh/h (0.34 kWh/kWp/h), only 34% of capacity of PV systems, when peak load come into being on 3:00PM in TEPCO. Although electricity consumption in the afternoon was more increasing by using air conditioner than that of in May, PV electric output was more than electricity consumption from 7:00AM to 4:00PM.

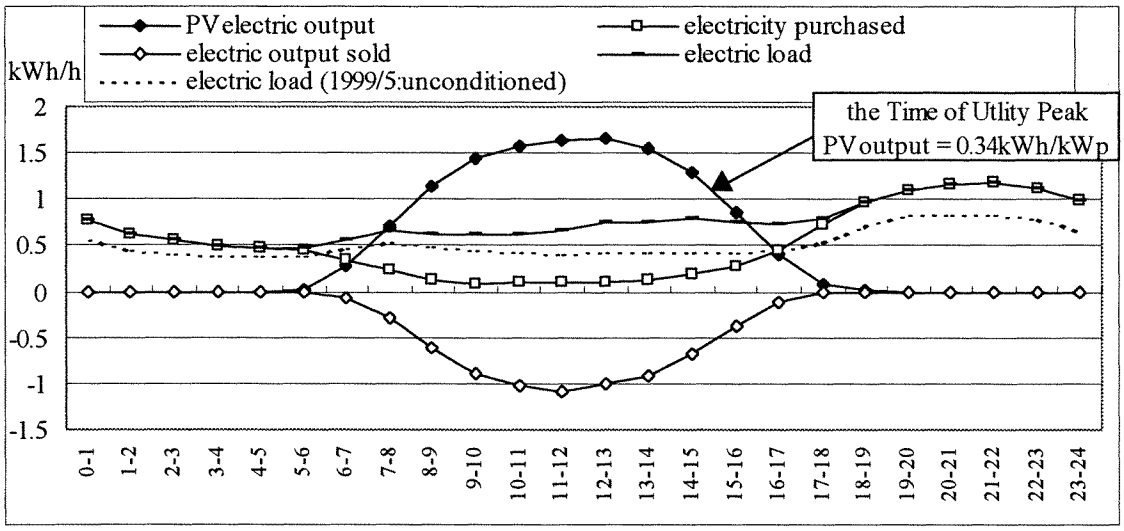

Figure 7. Hourly PV output and electricity consumption on the day of utility peak

Usage of electricity changed

For the monitored households whose house structure, family members, appliances (refrigerator and air conditioner) remained unchanged, an average of 3% of electricity consumption was saved than that of before installation of PV system (with consideration of climate condition). The savings by lighting and appliances was only achieved 4%, while savings by cooling was 26%. This might be brought by reduction of cooling load by PV array blocking the sunlight and by the households' intention to control air conditioner (see **Figure 8**).

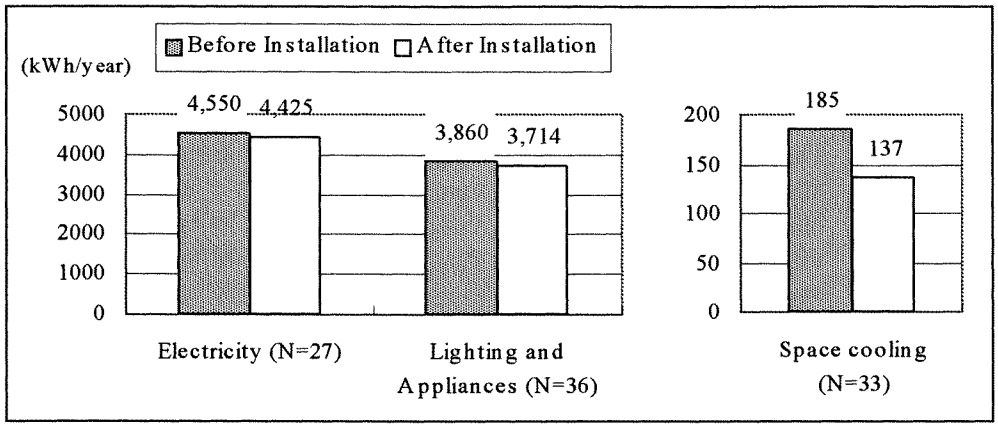

Figure 8. Electricity consumption of monitored households before and after installation of PV systems

Potential electricity generation of PV systems in residential homes

To be compared with existing electric power stations PV systems require larger land space. Because land cost in Japan is quite high, it is not feasible for the electric power companies to construct land fixed PV power stations on the ground. Therefore, it is more reasonable for PV systems to be set on the roofs of residential houses, public facilities and commercial buildings in Japan.

An assessment study (PVTEC 1998), regarding of solar gain conditions and scale of the housing spaces, estimated the percentages of the houses which can potentially install PV systems are 30% for single family dwellings and 12.5% for multi family dwellings. And, the generation capacity of PV systems for each type of houses would be 3 kWp and 14 kWp, respectively. The estimation also indicates the potential capacity of PV systems to be 26.6 GWp as a whole in Japan, which is over 400 times as much as installed capacity shown in **Table 1**, and 3.6 GWp specifically in Tokyo/Kanagawa area. Based on the average year's radiation data for a surface oriented to the south and titled by 30 degrees, the study estimates the potential electricity output of PV systems to be as total of 28.9 TWh/year in Japan, and 3.8 TWh/year in Tokyo/Kanagawa area.

On the other hand, according to the estimation based on TEPCO/CO-OP monitoring program, which calculated by the average actual PV electric output (adjusted by average year's radiation), the potential PV electric output is to be 3.5 TWh/year in Tokyo/Kanagawa area, which is 8% smaller than the estimation by the government study above. Also, the potential electricity output of PV systems is estimated to be total of 25.8 TWh/year in Japan, about 14% of the residential electricity consumption in 1998. This difference could be due to actual installed conditions, such as array azimuth cannot be always optimal.

Conclusion

The private-sector Seikatsu Club Consumers' Cooperative and the Tokyo Electric Power Company (TEPCO) granted about $4,500/ kWp to home owners who were planning to install PV system in the Tokyo area. Out of 376 applicants, 132 households were selected through careful consideration, and grid-connected systems (total 412kWp, mean 3.1 kWp) have been installed on the rooftops of their houses. The status of operation of PV system from October 1998 to September 1999 indicated that the pay back period is 42 years (30-65 years), with consideration of subsidization; the pay back period is 23 years (12-37 years). On the assumption that the duration of PV system is 20 years, the cost of installation is required to be reduced at 1/3 (less than $3,000/ kWp). Therefore, price reduction of PV module and inverter shall be needed as well as the cost reduction of installation. The PV electric output was 34% of total capacity when the peak demand for TEPCO was occurred. And electricity consumption for cooling was reduced 26% compared that of before installation. This might be brought by reduction of cooling load by PV arrays blocking roof sunlight, and also by the households' control of the air conditioner. From the result of measurement and estimated potential installation capacity mentioned on existing report, the potential electricity output of PV system is up to 25.8 TWh/year in Japan. This is equivalent to 14% of the total residential electricity consumption in 1998.

Acknowledgements

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