International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:2, No:7, 2008

Effects of Photovoltaic System Introduction in Detached Houses with All-Electrified Residential Equipment in Japan

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***Abstract*—**In this paper, in order to investigate the effects of photovoltaic system introduction to detached houses in Japan, two kinds of works were done. Firstly, the hourly generation amount of a 4.2kW photovoltaic system were simulated in 46 cities to investigate the potential of the system in different regions in Japan using a simulation model of photovoltaic system. Secondly, based on the simulated electricity generation amount, the energy saving, the environmental and the economic effect of the photovoltaic system were examined from hourly to annual timescales, based upon calculations of typical electricity, heating, cooling and hot water supply load profiles for Japanese dwellings. The above analysis was carried out using a standard year's hourly weather data for the different city provided by the Expanded AMeDAS Weather Data issued by AIJ (Architectural Institute of Japan).

***Keywords*—**Photovoltaic system, Energy saving, Environmental effect, Japanese dwelling, Detached house.

I. Introduction

In spite of the fourth place country of energy consumption in the world, Japan imports almost of primary energy resources from oversea and declared to reduce 6% of its greenhouse gas emission at the1990 level during 2008 to 2012. Renewable energy application is very important for Japan to reduce the fossil energy consumption and the greenhouse gas emission. As inexhaustible and environmental friendly energy, solar energy utilization is an effective option for Japan to reduce greenhouse gas emission and fossil energy consumption. Among the utilization method of solar energy, photovoltaic system is an important and effective system, and has advantages, e.g., efficient integration to a building, high reliability and long lifetime, low maintenance cost and low environmental load.

Japanese energy consumption in residential sector is increasing, although those in other sectors are slightly decreasing or keeping up at the same level in recently years. Energy consumption of 2006 in residential sector increased 27.2% compared with 1990 according to the statistics data of Fiscal 2006 Annual Energy Report issued by Agency for Natural Resources and Energy [1]. As the CO_2 emissions from the residential sector in FY2005 were 174 million tons, that increases 36.7% to the base year FY1990 [2]. Based on above mentioned background, energy conservation and new energy introduction in residential sector are very important to achieve the target of greenhouse gas reduction for Japan. The target of photovoltaic system introduction in residential buildings is 3.9 million kW 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 photovoltaic system in residential house.

The number of detached houses in Japan is about 26.5 million according to the statistic data from 2003 Housing and Land Survey of Japan issued by Statistics Bureau of MIC (Ministry of Internal Affairs and Communication of Japan) [5], The detached houses in Japan will be the enormous market of the photovoltaic system application. Also, all-electrified residential equipment is widely adopted recently to detached houses in Japan. The advantages of this system are low running cost, convenience and safety to use.

Based on above mentioned background, two kinds of works were done in this paper. Firstly, the hourly electricity generation amount of a 4.2kW size photovoltaic system were simulated in 46 cities (they are prefecture capitals) to investigate the introduction potential. Secondly, based on the simulated electricity generation amount, energy saving, environmental and economic effects of the photovoltaic system were examined from hourly to annual timescales, calculating typical electricity amount of a detached house for heating, cooling and hot water supply in 16 typical cities. The above analysis was carried out by using a standard year's hourly weather data for the different cities of the Expanded AMeDAS Weather Data issued by AIJ (Architectural Institute of Japan) including the solar radiation amount, outside air temperature and relative humidity and so on.

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International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:2, No:7, 2008

II. Investigation Method

A. Calculation Model of Photovoltaic System

The capacity of object photovoltaic system is 4.2kW (panel area is 31.1 m^2). The direction of PV systems are facing to the south but inclination angles are set for optimal angles to each city referring to the paper: Aptitude for Solar Energy Utilization in Japan [6], and the solar utilization map of different regions of Japan released in the website of MIKI [7]. Table 1 shows the optimal inclination angles of different cities. The cities of bold letters in Table 1 denote the cities to examine the introduction effect of photovoltaic system in all-electrified residential equipment. The electricity generation efficiency is assumed to be 13.48%. The power generation amount of the photovoltaic system can be calculated using the following expressions [8] considering cell temperature, temperature coefficient and inverter efficiency.

$$W = \eta \times K \times I \times A \times \eta_{IN}$$

$$K = 1 - 0.0037(T_c - 25)$$

$$T_c = T_a + (-6.036 + 0.274V + 0.071V^2) + I \times (45.63 - 5.91V + 0.333V^2)$$

$$E > 0.3kW \qquad \eta_{IN} = 5.99 \times \ln(E) + 90.1$$

$$E < 0.3kW \qquad \eta_{IN} = 20.5 \times \ln(E) + 105.2$$

Here, $E = \eta \times K \times I \times A$ is the amount of generation electricity as direct current.

Where,

W: Power generation amount, kWh;

η: Electricity generation efficiency, assumed as 13.48%;

K: Temperature coefficient;

A: Area of panel, m^2;

T_c: Temperature of cell, ;

T_a: Outside air temperature, ;

η_{IN}: Inverter efficiency, %;

V: Wind velocity, m/s;

B. Energy Consumption Load Estimate and Energy System

A model detached house is set to estimate the energy consumption in different cities. It is a typical Japanese detached house proposed by AIJ (Architectural Institute of Japan). The first and second floor plans are illustrated in Fig. 1. The family is assumed as 4 people, parents and 2 children (Businessman, Housewife, Junior high school student and elementary schoolchild). The envelope satisfies the reference values of solar shading coefficient and heat loss coefficient proposed by the Newest Energy Saving Regulation. The hourly air-conditioning load and electricity consumption are calculated by using two kinds of software. One is the multi-space air temperature and thermal load calculating software—Trp developed by Hayashi [9]. The other is the Life Schedule Operation Generator—SCHEDULE Ver2.0 proposed by SHASE (the Society of Heating Air-conditioning and Sanitary Engineers of Japan). The hot-water supply load is calculated by using the seasonal hot water demand and the temperature difference between the inlet and supply. The hot water demand and the supply temperature are decided by SCHEDULE Ver2.0.

In this research, the annual operation of the energy supply including photovoltaic system is simulated to supply the energy demand in the object detached house. The energy system is shown in Fig. 2. The photovoltaic system has the capacity of 4.2 kW and a heat pump hot water heater (COP assumed as 3.0) is used to supply the hot water. The heating and cooling loads are handled by air-conditioner (COP is assumed as 4.9). This system consists of all-electrified residential equipment which means all the energy demand is satisfied by the electricity from photovoltaic system or utility power even if the cooking. The surplus electricity of the photovoltaic system can be sold to the

TABLE I The optimal inclination angle of different city

Region	Prefecture	City	Optimal inclination angle (°)	Region	Prefecture	City	Optimal inclination angle (°)
Tohoku distract	Aomori	Aomori	20.6	Kinki distract	Mie	Tsu	27.8
	Iwate	**Morioka**	24.8		Shiga	Otsu	25.6
	Miyagi	**Sendai**	28.8		kyoto	Kyoto	26.6
	Akida	Akida	19.9		Osaka	**Osaka**	26.6
	Yamagata	Yamagata	22.5		Hyogo	Kobe	26.7
	Fukushima	Fukushima	27.8		Nara	Nara	24.8
					Wakayama	Wakayama	25.7
Kanto distract	Ibaragi	Mito	29.8				
	Tochigi	Utsuomiya	31	Chugoku district	Tottori	Tottori	21.7
	Gunnma	**Maebashi**	30.9		Shimani	**Matsue**	21.8
	Saitama	Saitama	29.7		Okayama	Okayama	26.9
	Chiba	Chiba	29.5		Hiroshima	**Hiroshima**	27
	Tokyo	Tokyo	29.7		Yamaguchi	Yamaguchi	25.6
	Kanagawa	**Yokohama**	28.9				
				Shikoku distract	Tokushima	Tokushima	26.8
Chubu distract	Niigata	**Niigata**	21.6		Kagawa	**Takamatsu**	25.9
	Toyama	**Toyama**	22		Ehime	Matsuyama	25.9
	Ishikawa	Kanazawa	21.8		Kochi	**Kochi**	28.7
	Fukui	Fukui	22.7				
	Yamanashi	Koufu	29.9	Kyushu distract	Fukuoka	**Fukuoka**	25.5
	Nagano	Nagano	24.8		Saga	Saga	26
	Gifu	Gifu	28.5		Nagasaki	Nagasaki	25
	Shizuoka	Shizuoka	29.6		Kumamoto	**Kumamoto**	25.9
	Aichi	**Nagoya**	28.7		Oita	Oita	26.5
					Miyazaki	Miyazaki	27.5
Okinawa	Okinawa	**Naha**	20.7		Kagoshima	**Kagoshima**	26.5

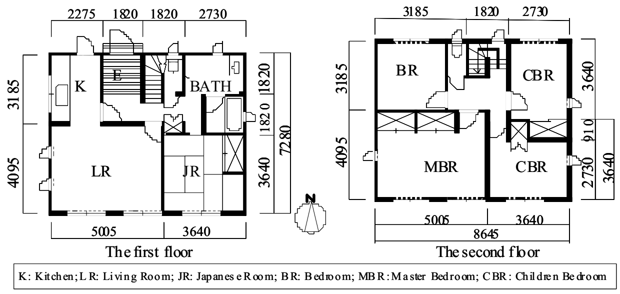

Fig. 1 The floor plan of the model detached house

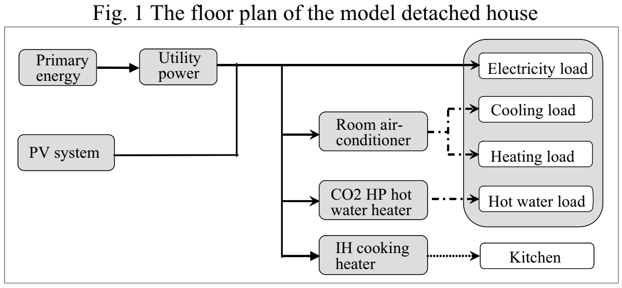

Fig. 2 the energy system with the photovoltaic system

TABLE II ANNUAL GLOBAL SOLAR RADIATION AMOUNT AND ANNUAL SLOPE SOLAR RADIATION AMOUNT

Region	City	Global solar radiation: Annual value (kWh/m² Year)	Global solar radiation: Region average (kWh/m² Year)	Slope solar radiation: Annual value (kWh/m² Year)	Slope solar radiation: Region average (kWh/m² Year)
Tohoku distract	Aomori	1213.67	1209.63	1314.78	1344.94
	Morioka	1200.68		1335.55	
	Sendai	1233.85		1403.86	
	Akida	1183.63		1279.06	
	Yamagata	1159.68		1316.40	
	Fukushima	1266.26		1420.00	
Kanto distract	Mito	1348.81	1283.24	1551.66	1470.12
	Utsuomiya	1234.26		1456.37	
	Maebashi	1328.75		1551.10	
	Saitama	1167.11		1313.39	
	Chiba	1327.69		1501.47	
	Tokyo	1240.16		1407.32	
	Yokohama	1335.87		1509.53	
Chubu distract	**Niigata**	1225.98	1314.74	1317.25	1461.80
	Toyama	1206.14		1304.42	
	Kanazawa	1218.77		1318.97	
	Fukui	1264.63		1368.30	
	Koufu	1428.75		1649.18	
	Nagano	1356.48		1512.27	
	Gifu	1375.36		1562.47	
	Shizuoka	1363.20		1558.22	
	Nagoya	1393.33		1565.13	
Okinawa	**Naha**	1427.83	1427.83	1487.14	1487.14

Region	City	Global solar radiation: Annual value (kWh/m² Year)	Global solar radiation: Region average (kWh/m² Year)	Slope solar radiation: Annual value (kWh/m² Year)	Slope solar radiation: Region average (kWh/m² Year)
Kinki distract	Tsu	1414. 77	1340.81	1584.77	1472.87
	Otsu	1239. 03		1355.26	
	Kyoto	1253. 29		1387.99	
	Osaka	1307. 34		1418.50	
	Kobe	1392. 09		1529.95	
	Nara	1366. 46		1493.15	
	Wakayama	1412. 71		1540.47	
Chugoku district	Tottori	1244. 57	1326.43	1336.05	1452.00
	Matsue	1226. 25		1317.68	
	Okayama	1382. 22		1531.25	
	Hiroshima	1421. 97		1575.39	
	Yamaguchi	1357. 17		1499.63	
Shikoku distract	Tokushima	1435. 46	1410.43	1605.93	1566.51
	Takamatsu	1394. 80		1525.62	
	Matsuyama	1417. 68		1553.29	
	Kochi	1393. 78		1581.19	
Kyushu distract	**Fukuoka**	1384. 08	1389.32	1496.82	1522.42
	Saga	1335. 71		1457.60	
	Nagasaki	1308. 18		1414.91	
	Kumamoto	1394. 78		1535.33	
	Oita	1423. 86		1570.79	
	Miyazaki	1468. 86		1629.67	
	Kagoshima	1409. 77		1551.80	

power company as the same price as the purchased. The shortage electricity is purchased from the power company.

III. ELECTRICITY GENERATION AMOUNT OF PHOTOVOLTAIC SYSTEM

A. Solar Radiation Amount

Each city's annual amounts of global solar radiation and slope solar radiation incident upon the panel are listed in Table 2. The monthly amounts of slope solar radiation of different regions are shown in Fig.3. The monthly averages of daily amount of slope solar radiation over the whole country are shown in Fig.4.

From Table 2, the annual amounts of solar radiation of the cities along the Pacific Ocean are larger than those along the Japan Sea. The reason is the Japan Sea side has less solar radiation in winter than the Pacific Ocean side. The cities in Kanto and Chubu distracts have little annual solar radiation. The maximum annual amount of regional average slope solar radiation occurs in Shikoku district as 1,566kWh/(m^2 Year). The annual average amount over whole country of slope solar radiation is 1,467 kWh/(m^2 Year).

From the profiles of Fig.3, in any region, the amounts of slope solar radiation in winter are the least among four seasons in any region. The rainy season in June and July also has little solar radiation. The whole country average amounts of monthly slope solar radiation in Nov., Dec., Jan. and Feb. are only about 96 kWh/(m^2 Month). As for the peak amount of slope solar radiation, it occurs in May in Tohoku and Kanto districts. However in Chubu, Kinki and Chugoku districts, the slope solar radiation amount is almost equal to those in May and

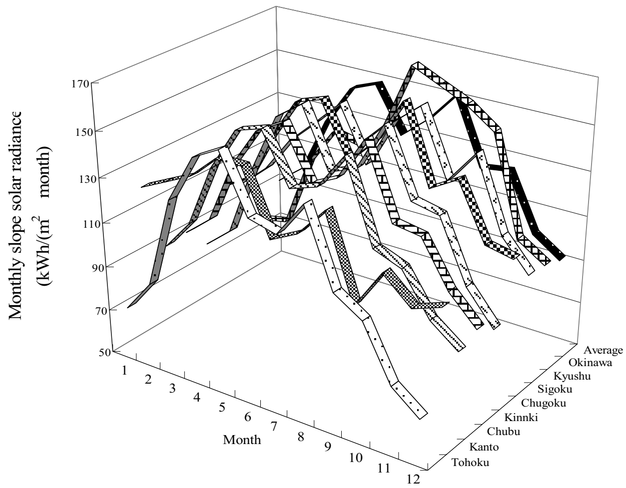

Fig. 3 Monthly slope solar radiation amount of different region

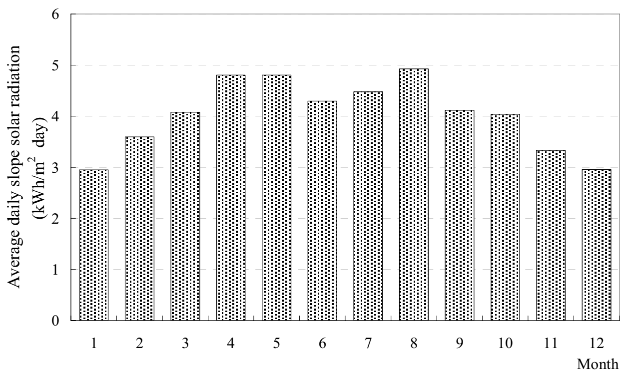

Fig. 4 Whole country average daily slope solar radiation amount

August. In Shikoku and Kyushu districts, the maximum slope solar radiation amount occur in August, and it is July in Okinawa distract. The whole country average slope solar radiation amount is 122 kWh/(m^2 month).

From Fig.4, the peak amount of whole country average daily slope solar radiation appears in April, May and August. The average daily slope solar radiation amount varies between 2.95 kWh/(m^2 day) and 4.93 kWh/(m^2 day).

B. Electricity Generation Amount

The annual electricity generation amount of each city is listed in Table 3. The regional average amount of monthly electricity generation is shown in Fig.5. Figure 6 shows the whole country average amount of daily electricity generation.

Most cities have more than 5,000 kWh electricity generation. Koufu located in Chubu district has the maximum annual electricity generation amount of 6,282kWh/Year. On the other hand, the minimum value of annual electricity generation is 4,916kWh/Year occurring in Akita. The Whole country average is 5,594kWh/Year.

TABLE III ANNUAL ELECTRICITY GENERATION AMOUNT OF EACH CITY

Region	City	Annual electricity generation amount		Region	City	Annual electricity generation amount	
		Annual Value (kWh/Year)	Region average (kWh/Year)			Annual Value (kWh/Year)	Region average (kWh/Year)
Tohoku distract	Aomori	5094.31	5206.15	Kinki distract	Tsu	6082.56	5603.15
	Morioka	5195.17			Otsu	5131.73	
	Sendai	5445.97			Kyoto	5270.37	
	Akida	4916.66			**Osaka**	5384.71	
	Yamagata	5140.58			Kobe	5834.43	
	Fukushima	5444.24			Nara	5648.83	
					Wakayama	5869.39	
Kanto distract	Mito	5966.94	5623.43				
	Utsuomiya	5586.84		Chugoku district	Tottori	5059.97	5506.21
	Maebashi	5962.16			**Matsue**	5013.76	
	Saitama	4965.86			Okayama	5806.28	
	Chiba	5743.36			**Hiroshima**	5961.42	
	Tokyo	5364.52			Yamaguchi	5689.63	
	Yokohama	5774.32					
				Shikoku distract	Tokushima	6139.58	5957.38
Chubu distract	**Niigata**	5035.62	5577.10		**Takamatsu**	5813.55	
	Toyama	4979.46			Matsuyama	5883.75	
	Kanazawa	4997.31			**Kochi**	5992.65	
	Fukui	5202.84					
	Koufu	6282.52		Kyushu distract	**Fukuoka**	5690.99	5772.38
	Nagano	5825.69			Saga	5517.99	
	Gifu	5949.52			Nagasaki	5352.65	
	Shizuoka	5930.44			**Kumamoto**	5804.79	
	Nagoya	5990.53			Oita	5991.50	
					Miyazaki	6184.17	
Okinawa	**Naha**	5565.18	5565.18		**Kagoshima**	5864.55	

From the profiles of Fig.5, the fluctuation of the monthly electricity generation is similar to that of monthly slope solar radiation amount. That is because the electricity generation is chiefly influenced by the solar radiation. The maximum amount is 615kWh/month in July in Okinawa, and the minimum amount 272kWh/month occurs in December in Tohoku. Among these 8 regions, the average amount of monthly electricity generation in Shikoku is the largest and 496kWh/month.

Different from the solar radiation, the maximum amount of electricity generation occurs in April as 18.45kWh/day (see Fig.6). The reason is that the electricity generation is influenced not only by solar radiation, but also by the outdoor temperature, wind velocity and other things. The average amount of daily electricity generation varies between 11.60kWh/day and 18.45kWh/day.

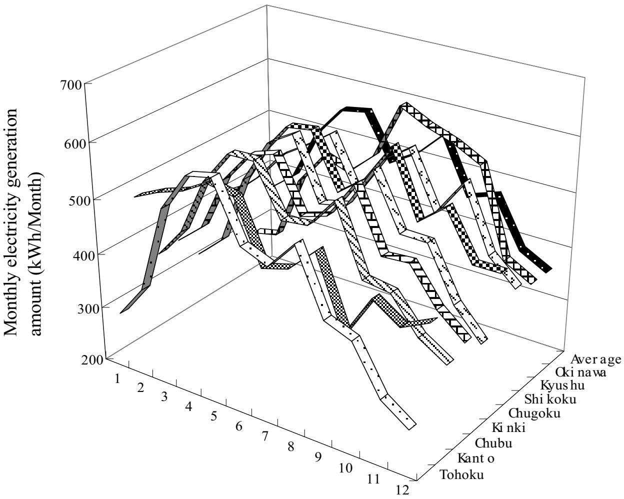

Fig. 5 Region average monthly electricity generation amount

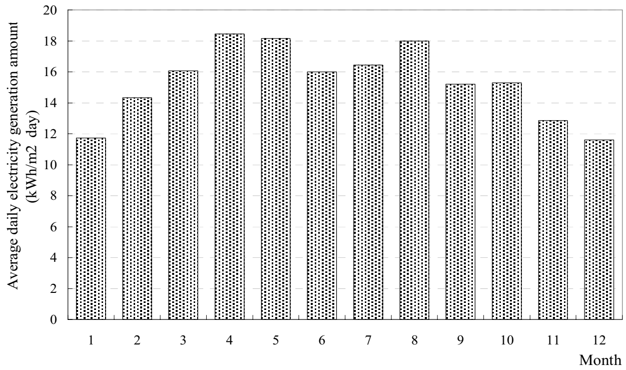

Fig. 6 Whole country average daily electricity generation amount

IV. EFFECT EVALUATION OF PHOTOVOLTAIC SYSTEM INTRODUCTION

Considering the weather, geography and other things, 16 cities are chosen as the objective cities to evaluate the introduction effect of photovoltaic system in a detached house with all-electrified residential equipment.

A. Electricity Generation Amount of 16 Cities

Fig.7 shows the annual electricity generation amount of these 16 cities. Although the cities in southern area in Japan have larger electricity generation, some cities in central part of Japan, e.g., Nagoya, Yokohama and Maebashi also have large amount. Matsue, Niigata and Toyama locating along the Japan Sea have little electricity generation because of little solar radiation in winter.

B. Energy Saving

Figure 8 shows the annual energy saving amounts caused by photovoltaic system in 16 cities. In primary energy calculation, the electricity generation efficiency of power companies is assumed as 40% in the demand side.

From Fig.7, except Matsue and Toyama along the Japan Sea and Maebashi, the annual energy saving amounts is more than 18,000MJ. Compared with other cities, the energy saving effect in Naha is large by the benefit of the large cooling load. In the same manner, large heating load in Niigata, Sendai, and Morioka promote the energy saving effect. From these results, the energy saving effect is not only related to the electricity generation amount, but also related to the energy consumption condition of dwellings. Among these 16 cities, the energy saving amount of 20,935MJ/year in Naha is the largest. On the other hand, the minimum energy saving amount occurs in Toyama as 17,342MJ/Year.

C. Environmental Effect

The annual CO_2 reduction amount of the detached house because introducing the photovoltaic system is evaluated considering the generated electricity, sold electricity and purchased electricity in whole year. The annual CO_2 reduction amount is shown in Fig.9. During evaluation, the CO_2 emission unit of photovoltaic system is 0.053kg-CO_2/kWh referring the research report of Central Research Institute of Electric Power Industry [10]. The CO_2 emission unit of utility electricity is 0.37kg-CO_2/kWh according to the Electricity Review Japan 2000-2001 issued by the Federation of Electric Power Companies of Japan [11].

In all of the 16 cities, the CO_2 reduction amount is more than 600kg/year. The maximum reduction amount is 735kg/year in Naha. However, although Morioka has larger level energy saving among these cities, its CO_2 reduction amount is the least with 600kg.

D. Economic Effect

Economic effect is evaluated by comparing the annual running cost between the systems introducing photovoltaic system and the none-photovoltaic system. Table 4 lists the residential electricity price for all-electrified users offered from a main electricity company in Japan. The selling electricity price is assumed as the same as the purchased one. Figure10 shows the amount of annual running cost reduction. Different from the energy saving and the environment effects, the reduction of running cost is uneven among the 16 cities. The cities in Tohoku district, Niigata, Sendai and Morioka, have less running cost reduction compared with other cities and the average value in these three cities is 10.36×10^4 Yen/year. The reason is that the electricity load is large in winter; that leads to the self-sufficiency rate of electricity from photovoltaic system is low and the purchased electricity increases in these cities. The number of cities which annual running cost reduction amount more than 15×10^4 Yen/year is 8 and accounting for the half of the evaluated cities. The largest reduction amount is 17.51×10^4 Yen occurring in Nagoya.

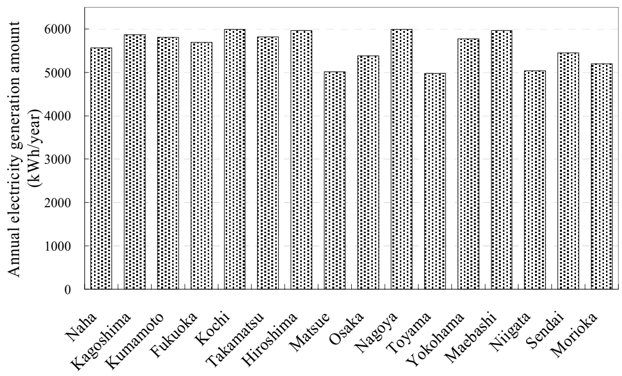

Fig.7 Annual electricity generation amount

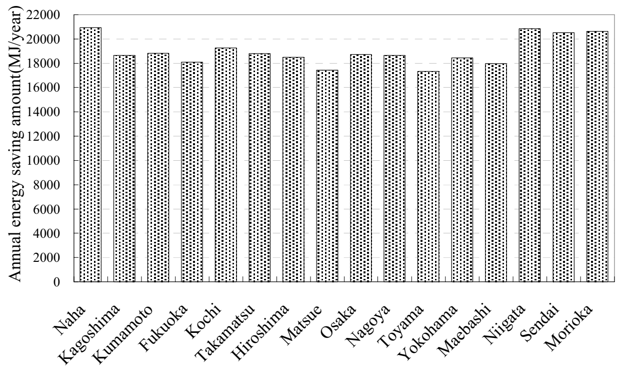

Fig. 8 Annual energy saving amount

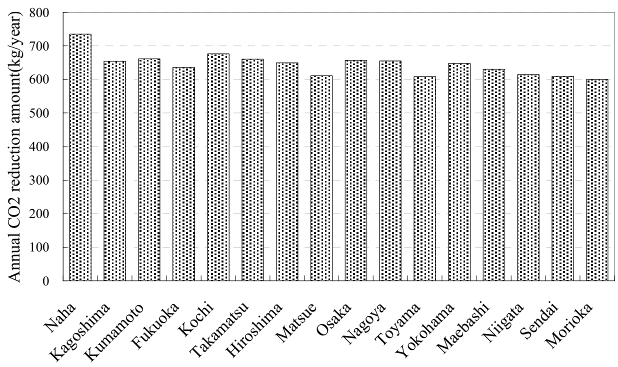

Fig .9 Annual CO_2 reduction amount

TABLE IV ELECTRICITY PRICE SERVED ALL-ELECTRIFIED USER

Period		Price (Yen/kWh)
22:00-8:00		7.19
8:00-10:00,17:00-22:00		20.13
10:00-17:00	Summer	32.01
	Other season	26.7
Initial fee (Yen/month)		1155

V. Conclusion

In this research, 46 cities in 8 regions except Hokkaido were chosen to investigate the electricity generation amount of a 4.2kW photovoltaic system. Sixteen cities in 8 regions were selected to evaluate the introduction effect of the photovoltaic system in a detached house with all-electrified residential equipment. The obtained results are summarized as follows:

(1) The cities along the Pacific Ocean have larger solar radiation amount than the cities along the Japan Sea. The maximum annual slope solar radiation occurs in Kofu as 1,649 kWh/(m^2Year). The whole country average annual slope solar radiation amount is 1,467kWh/(m^2Year).

(2) Most of the cities, the annual electricity generation amount of a 4.2kW photovoltaic system is more than 5,000 kWh. The whole country average value is 5,594 kWh. Among 8 regions, the annual and the monthly average amount of electricity generation in Shikoku is the largest, they are 5,957kWh/year and 496kWh/month.

(3) According to the evaluation results of the photovoltaic system in 16 cites for the model detached houses, they can gain excellent introduction effects. The annual energy saving amount is more than 18,000MJ in most of 16 cities. All of the evaluated 16 cities have more than 600kg/year CO_2 reduction amount. Although the running cost reduction is not even, the half of the cities obtains $15x10^4$ Yen/year of running cost reduction. The energy saving, the environmental and the economic effect of the photovoltaic system is influenced not only by electricity generation amount, but also by the energy consumption characteristics of the dwelling.

VI. Acknowledgment

The authors would like to thanks for the research support from the Japan Society for the Promotion of Science (JSPS) for this research.

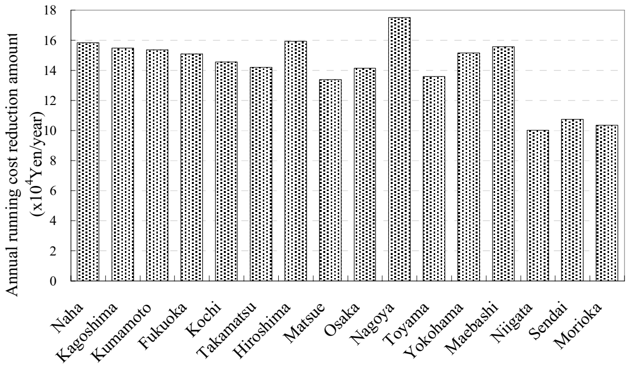

Fig.10 Annual running cost reduction amount

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