Study on Efficiency of Energy Demand and Supply System of Direct-current Power Supply System ~Applicability of Direct-current Power Supply System in Residential Building~

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ABSTRACT

This study aims to promote the widespread use of the direct current (DC) power supply system in residential buildings. In this study, the detached typical house for a single family in Japan is assumed as a model building, where photovoltaic panels are installed. When the DC power system was introduced, the energy consumption and running cost of the model building were estimated and analyzed with regard to energy savings and running cost reduction. The DC power system covered appliances with several different voltage ranges, such as low- and high-voltage appliances including the air-conditioning equipment and hot water equipment. The results indicate that the energy saving is greater than 13% when the DC power system supply power all possible appliances, and the running cost would be smallest.

KEYWORDS

DC power supply, energy saving, running cost, impact on power-grid

1. INTRODUCTION

Energy-saving technologies and the use of renewable energy are demanded for realizing the net-zero energy house (ZEH). The direct-current (DC) power supply system is an energy-saving technology, which is expected to contribute to this realization in near future. This system can mitigate energy consumption in a building. However, it is still under development (NEDO, 2011; Otosaka et al., 2014). Photovoltaic renewable energy is dramatically increasing in Japan, which is encouraged by the Feed-in-Tariff enforcement since 2012. Because of that photovoltaic panel could generate DC power, it is possible to apply electric power to the building appliances without converting DC to AC. This study aims to promote the widespread use of the DC power supply system into residential buildings. In particular, the detached typical house with photovoltaic panels, which is a common single-family residential building in Japan, is used as a model building in this study. We evaluate the energy performance, the PV effective utilization rate and the impact on the system power as well as running costs. Moreover, we examine the effect on the model building's running costs by falling down of electric power price produced from PV and the different power generation efficiency of the PV.

2. METHODOLOGY

2.1 MODEL HOUSE AND SYSTEM OVERVIEW

The model building is a 2-story residential building. The total floor area is 121.7 m^2, located in Tokyo. The building plan is illustrated in Figure 1. The capacity of solar panels is 3.5kW which covered 80% of the roof area (23.2 m^2) at the southern side of the building.

The family in the model building comprised two parents and two children. The household electric equipment assumed by referring to most frequently used (ECCJ, 2009). HVAC equipment and hot water equipment are assumed electric-driven equipment.

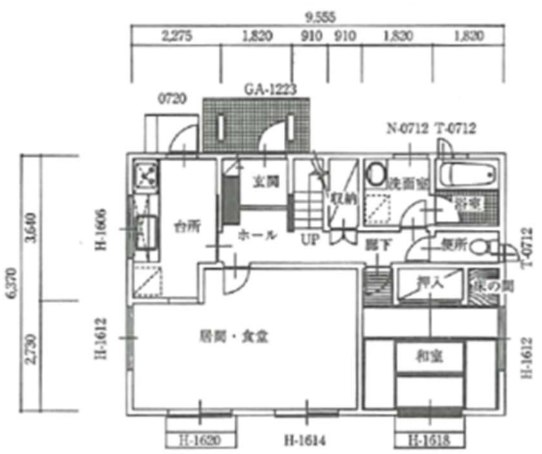

Figure.1 *The 1st floor plan of model house (IBEC, 2002)*

The annual electric power consumption was calculated in this study. The hourly electric power consumption for heating, cooling and hot water of the building were estimated by using the standardized value referred to the reference (JAPAN INDUSTRIAL PUBLISHING CO., LTD., 2005) on every month. For other electrical equipment, the electric power consumption was calculated based on the usage schedule of those, which were provided by the literature (SHASE, 2009). The annual primary energy consumption of the model building was estimated at 44.1 GJ/year (Figure 2). The largest proportion of annual primary energy consumption (38.4%) corresponded to lighting and others.

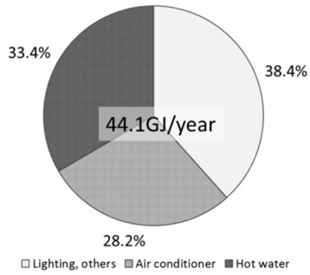

Figure2. *Breakdown of annual primary energy consumption*

A diagram of the conventional power supply system is presented in Figure 3. In conventional power supply system, the energy loss occurs by the AC/DC converter circuit. The DC power supply system is shown in Figure 4, and it does not require an AC/DC converter circuit. Therefore, the power generated from the PV can be directly supplied without conversion to AC in DC power supply system. Consequently, the energy loss could be reduced in the model building. To examine the effect of reducing the conversion loss, a case study was conducted wherein the DC power supply system which was connected to facilities with different range of service for DC power supply system in the model house.

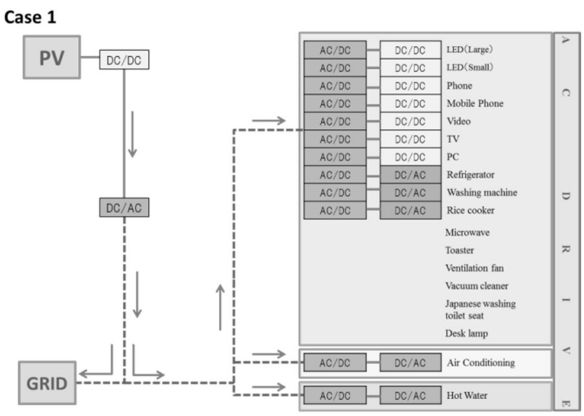

Figure3. *Conventional system*

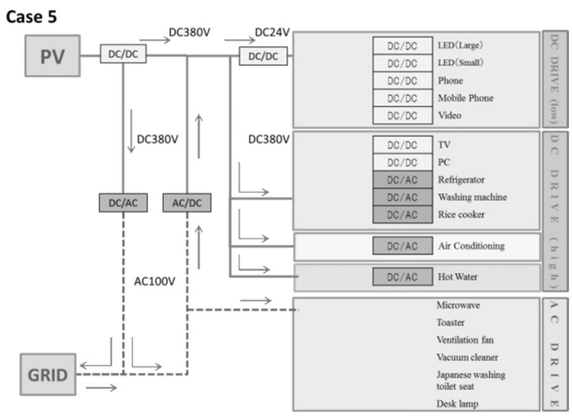

Figure4. *Direct-current power supply system*

2.2 CASE STUDY OVERVIEW

In this study, the PV power generation efficiency was assumed 0.15, which is a typical value presented by general manufactories, and 0.20 of which high-efficiency panel was employed (NEDO, 2014). For assessing the annual running cost, we assumed a reverse electric power price of 33 yen/kWh for 2015 and 31 yen/kWh for 2016, because the price of the reverse electric power produced by the PV was expected to be decreasing in order to mitigate the burden in purchase bids.

Table 1 shows the description of the case study discussed in this study. The facilities in the model building were classified into three categories according to the usage voltage of those equipment; Lighting and others, Air-conditioning and Hot water supply.

The electronic devices classified in lighting and others category were investigated regarding whether they could be connected to DC power directly; the electronic appliances having no affinity to DC power were set to apply AC power (NEDO, 2011). Moreover, the devices of lighting and others were classified into two kinds of equipment: low- and high- voltage equipment. Case 1 represented AC power supply system which is conventional system. In Cases 2 and 3, the DC power supply system services to the lighting and others equipment. In Case 4, the DC power supply system services to the air-conditioning systems as well. Finally, in Case 5, the DC power supply system provides DC power to all of the DC- friendly facilities in the model building.

Low-voltage DC power supply at 24V. Electronic devices with maximum power consumption less than 360 W were defined as low-voltage DC power supply equipment. Those with maximum power consumption over 360 W were defined as high-voltage DC power supply equipment supply at 380V. The conversion losses at the AC/DC converters and the inverter were set as shown in Table 2.

Table 1. *Case study description*

Case	Target devices for the DC power supply Lighting and others Low-voltage DC	Lighting and others High-voltage DC	Air conditioning	Hot water
Case 1	–	–	–	–
Case 2	●	–	–	–
Case 3	●	●	–	–
Case 4	●	●	●	–
Case 5	●	●	●	●

Table 2. *Conversion losses ratio in the conversion circuit*

	Onsite circuit		AC/DC circuit in appliances			
Converter	AC/DC	0.04	LED (large)	0.11	Mobile phone (for charge)	0.32
			LED (small)	0.32	Phone	0.32
	DC/DC	0.02	Washing machine	0.11	PC	0.11
			Rice cooker	0.11	Video	0.32
			Refrigerator	0.32	Air conditioner	0.11
Inverter DC/AC circuit	0.04					

3. USEFULNESS VERIFICATION OF DC POWER SUPPLY

3.1 ENERGY-SAVING PERFORMANCE

The energy-saving performance in each case is shown in Tables 3 and 4. Energy saving effect is defined as the reduction rate in annual electric power consumption in Case 2–5 and that in the conventional power system represented by Case 1. There are no significant differences in the energy-saving performance of the power supply system caused by variations in the power generation efficiency of the PV. However, the energy-saving effect increases with extending the kind of facilities supplied by DC power. This is because it is possible to consume more electric power provide by PV efficiently. In addition, the efficiency of the entire system is improved due to the reduction of the conversion loss achieved by the introduction of the DC power supply. The energy saving is confirmed in Case 5, 10.1% wherein which power generation efficiency corresponds to 0.15, and all high-affinity equipment with DC power supply were supplied with DC power.

3.2 EFFECTIVE UTILIZATION RATE OF PV

The PV effective utilization rate for each case is presented in Tables 3 and 4. It is defined as the percentage of PV-generated electric power used, and it includes the amount of electric power reversed to the power-grid. When the facilities driven by DC power supply increase, the PV effective utilization rate increases owing to the improvement of the energy efficiency of the electric power supply system. At the cases which power generation efficiency set by 0.15, the PV-generated power loss estimated by 437.9 kWh in Case 1, estimated by 227.4 kWh in Case 5. Therefore, the loss reduction by extending the facilities covered by the DC power supply system to all DC friendly equipment was calculated by approximately 48%.

3.3 IMPACT ON POWER-GRID

The impact on the power grid is estimated using the net grid[*1)] (net purchased amount of power) and evaluated using the standard deviation of the maximum ratio net purchased power $f_{grid,year}$ (REHVA, 2013). As the facilities supplied by DC power increase, the net grid amount becomes slightly larger; however, it was not significantly different (Tables 3 and 4). Furthermore, in the case that the power generation efficiency is improved, $f_{grid,year}$ is increased. In the power generation efficiency 0.15 of the Case 1, $f_{grid,year}$ was 34.4. And in the power generation efficiency 0.20 of the Case 1, $f_{grid,year}$ was 41.3, which was increased 20%. This is because the amount of electric power produced by PV is increased caused by improving the power generation efficiency of PV. Subsequently, the amount of reverse electric power to power grid has been increased.

3.4 IMPACT ON RUNNING COST

To calculate the running costs, the price system of the Tokyo Electric Power Company was adapted (Anonymity A http://www.tepco.co.jp/index-j.html, last accessed on July 20, 2016.). The price for the reverse electric power to power grid was set to 33 yen/kWh for the 2015 fiscal year and 31 yen/kWh for the 2016 fiscal year (Anonymity B http://www.enecho.-meti.go.jp/, last accessed on July 20, 2016.).

Table 3. *Effectiveness of introducing DC power supply (PV generation efficiency = 0.15)*

		Case 1	Case 2	Case 3	Case 4	Case 5
Energy saving effect		-	4.9%	5.5%	7.9%	10.1%
PV	PV Loss	437.9 kWh	341.4 kWh	329.4 kWh	273.0 kWh	227.4 kWh
	PV effective utilization rate	89.0%	91.4%	91.7%	93.2%	94.3%
GRID	Purchase electric power	3,701.4 kWh	3,556.1 kWh	3,539.2 kWh	3,472.3 kWh	3,356.7 kWh
	Reverse electric power	2,349.4 kWh	2,466.9 kWh	2,478.5 kWh	2,541.8 kWh	2,541.8 kWh
	Impact on power grid ($f_{grid,year}$)	34.4	34.9	34.9	35.4	36.5
COST	Running cost Sales price: 33 yen/kWh (2015)	¥7,891	¥426	-¥371	-¥4,059	-¥5,464
	Running cost Sales price: 31 yen/kWh (2016)	¥12,590	¥5,360	¥4,585	¥1,024	¥380

Table 4. *Effectiveness of introducing DC power supply (PV generation efficiency = 0.20)*

		Case 1	Case 2	Case 3	Case 4	Case 5
Energy saving effect		-	4.9%	5.4%	7.8%	10.0%
PV	PV Loss	524.3 kWh	424.3 kWh	411.9 kWh	353.1 kWh	305.6 kWh
	PV effective utilization rate	90.1%	92.0%	92.3%	93.4%	94.3%
GRID	Purchase electric power	3,648.0 kWh	3,506.1 kWh	3,489.3 kWh	3,422.4 kWh	3,306.6 kWh
	Reverse electric power	3,546.5 kWh	3,668.5 kWh	3,680.4 kWh	3,745.7 kWh	3,745.7 kWh
	Impact on power grid ($f_{grid,year}$)	41.3	41.9	41.9	42.6	44.1
COST	Running cost Sales price: 33 yen/kWh (2015)	-¥32,986	-¥40,501	-¥41,304	-¥45,059	-¥46,470
	Running cost Sales price: 31 yen/kWh (2016)	-¥25,893	-¥33,164	-¥33,943	-¥37,567	-¥38,979

As shown in Tables 3 and 4, when the power generation efficiency is 0.15 and the reverse electric power price is 33 yen/kWh, the sales of reverse electric power is greater than the bill for purchasing electric power from power grid in Cases 3–5, whereas the annual running cost is reduced. Therefore, under the reverse electric power price for 2015 (33 yen/kWh), the annual running cost is reduced by 2,427 yen (Cases 1–5) by supplying DC power to all DC power friendly facilities in the model building. This reduction is caused by the improvement in the efficiency of the entire system and the increase of the amount of reverse electric power. The annual running cost is reduced in all cases if the reverse electric power price was set by 31 yen/kWh.

4. CONCLUSION

In the present study, we confirmed the usefulness of the DC power supply system in residential building in terms of energy saving, PV effective utilization rate, the impact on the power grid and running costs.

The following findings were obtained:

• Energy-saving performance: As the kind of facilities driven by DC power supply system is expanded, the energy-saving effect is increased.

• PV effective rate: As the kind of facilities driven by DC power supply system is expanded, the PV effective utilization rate is increased. In addition, the PV effective utilization rate increases according to the PV power generation efficiency.

• Effect on the grid: The effect on the grid is increased by improving the power generation efficiency. Concerning the impact on the power grid, the use of electric storage (battery) would be useful.

• Impact on the running cost: When the reverse electric power price is 31 yen/kWh, the running cost is not reduced even by expanding the scope of DC power supply.

It should be noted that, although the conversion loss of the conversion circuit is constant, in a future study, it is necessary to take into account the variation of the conversion efficiency under the unsteady electric power usage.

ANNOTATIONS

*1) Net grid represents the grid net power considering backward flow. Calculate the monthly and hourly net purchase amount of power, and evaluate the influence of the grid power using the standard deviation of the maximum ratio net power purchase. $f_{grid,year}$ indicates that there is a large impact on larger as the system power.

$net\ \ grid = W_{grid\ \ out} - W_{grid\ \ reverse}$

$net\ \ grid$: Net purchase amount of power [kWh]
$W_{grid\ \ out}$: Grid output (purchase amount of power) [kWh]
$W_{grid\ \ reverse}$: Reverse power flow (selling amount of power) [kWh]

$$f_{grid,i} = \frac{net\ \ grid}{\max|net\ \ grid|} \cdot 100\ \ [\%] \qquad f_{grid,year} = STD(\ _{grid,i})$$

i : Time interval
$f_{grid,i}$: Maximum ratio net purchase power [kWh]
$f_{grid,year}$: The standard deviation of the maximum ratio net purchase power [kWh]

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