E3S Web of Conferences **111**, 04010 (2019) https://doi.org/10.1051/e3sconf/201911104010
CLIMA 2019

Energy Efficiency and Cost Performance of Direct-Current Power Supply Systems in Residential Buildings by 2030s and 2050s

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Abstract. In an effort to clarify the potential use and effectiveness of direct current (DC) power supply systems and further promote their usage, this study investigates the energy saving and cost performance characteristics of such a system for a detached house equipped with roof-mounted solar photovoltaic (PV) panels. Our evaluation considered different DC-powered appliances under different energy price conditions and made projections based on present, 2030s, and 2050s scenarios. Initial cost reductions were also considered based on assumed near-future technological developments. Our case study results show that the simple payback period is likely to be shortest in cases where DC power is only used for low-voltage appliances under present price conditions, when supplying DC power to cover interior space heating under the 2030s energy price scenario, and when covering all DC-powered appliances (including water heating) under the 2050s scenario. Taken together, these results indicate that it is desirable to set the introductory targets while projecting future energy price fluctuations and anticipating the cost reductions that will result from ongoing technological developments.

1 Introduction

Because the promotion of energy conservation in private dwellings has emerged as one of the more important methods for reducing greenhouse gas emissions, the net zero-energy-house (ZEH) concept has drawn significant attention in recent years. As envisioned, a ZEH would achieve fundamental energy conservation targets, including a zero-energy balance, by extensive use of renewable energy. To date, various technologies have been proposed to facilitate energy conservation in houses, including passive measures to suppress heat loads and active measures to improve energy utilization efficiency.

Additionally, as a means to promote renewable energy utilization, the spread of solar photovoltaic (PV) power generation has been significantly expanded in Japan due to the implementation of the feed-in-tariff (FIT) scheme. According to the PV power roadmap developed by the New Energy and Industrial Technology Development Organization (NEDO), further diffusion of such power supplies is expected to occur in near the future and targets call for 5 to 10% of Japan's domestic primary energy demand to be met with PV power generation by the 2050s [1].

Since current PV panels generate direct current (DC) electric power, such systems can supply electricity to DC appliances without the need for conversion from alternating current (AC) power. Therefore, it is thought that the usefulness of such systems will increase further as PV power generation systems spread, even though DC power supply systems are still under development.

A previous study [2] examined the practicality of DC supply systems in private houses and found that as the energy-saving effects of such systems increase, their introduction into private homes increases as well. However, there is still room for consideration of factors such as the purchase price of electricity, which can be expected to experience significant fluctuations in the future.

This study aims to clarify the effect of introducing DC power supply systems for detached houses under introduction scenarios for the present, the 2030s, and the 2050s, in order to promote increased use of such DC power supply systems.

In this paper, based on the consideration that PV-generated DC power can be applied to detached houses in various ways, we evaluate various scenarios based on the range of the DC-powered devices and electric energy flow, as well as the primary energy consumption, initial costs, running costs, and the simple payback periods for each scenario. Additionally, electricity price fluctuations and changes in the initial cost of the DC power supply system are considered.

2 Research outlines

2.1 DC power supply system

Figure 1-(a) shows a diagram of a conventional electric power supply system. Here, DC power from a PV panel is

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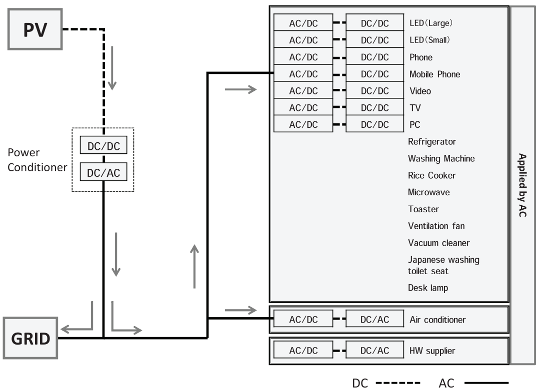
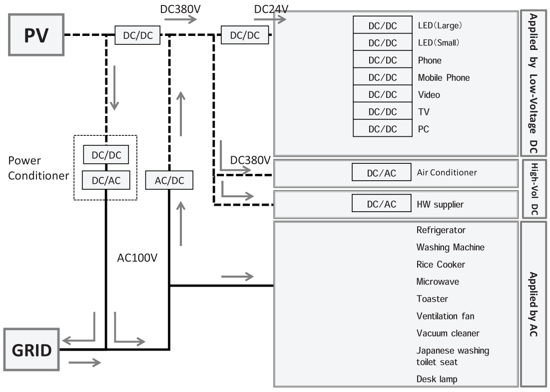


(a) Conventional electric power supply system



(b) DC power supply system

Fig. 1. Schematic of conventional electric power supply system (upper) and DC power supply system in case of supplying DC power to all DC-powered appliances including water heater (bottom).

supplied to a power conditioner (consisting of a converter and a regulator) where it is transformed into AC power and then supplied to the household appliances. After use, it is re-converted to DC power by a power transfer circuit embedded in the appliances.

Figure 1-(b) shows a simplified DC power supply system. In this case, DC power from the PV panel is supplied directly to the household appliances without conversion. It should be noted that using such systems to supply PV-generated power directly to DC-oriented appliances such as lighting equipment, air conditioners, and heat pump type water heaters would eliminate the conversion losses that normally occur inside power transfer circuits.

2.2 Different scope of appliances supplied by DC power systems and energy price scenarios

The diagram in Figure 2 shows different scopes for supplying DC power to appliances along with the energy price scenarios used in this study. Here, it can be seen that DC power supply systems can achieve higher energy saving effectiveness as the range of DC-power supplied appliances broadens. However, as the range of supplied appliances expands, introductory costs and energy prices must also be considered.

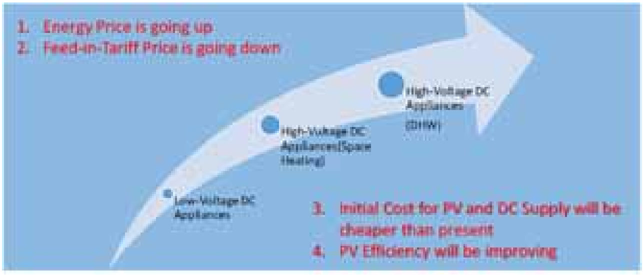


Fig. 2. Different ranges of DC-powered appliances and energy price scenarios.

For example, it is expected that the electric power price offsets provided by the FIT will decline simultaneously with a rapid increase in the actual price of electricity.

In addition, the need to replace appliances and increases in electric power consumption are expected to proceed apace along with changes to electrification policies and strategies for maximizing energy efficiency.

Considering these issues, we will next estimate the cost-effectiveness and contribution to the promotion of DC power supply that results for each case.

2.3 Model detached house and appliances

The building model used in this study is a two-story wooden detached house with a total floor area of 121.7 m^2 that is located in Tokyo [3]. The occupants are four family members: two adults and two children (high school student, junior high school student). The house is equipped with 23.2 m^2 of installed PV panels that cover 80% of the south side of the roof. The rated power capacity is 3.5 kW and the power generation efficiency is rated at 0.15.

The household electric appliances were selected from among the general household appliances according to higher ownership levels and use frequency [4]. Light-emitting diode (LED) lighting was adopted for illumination and an electricity-driven air source heat pump was selected to provide cooling. Both interior space heating and the hot water supply were initially presumed to be provided by conventional natural gas-fueled devices, but in the advanced electrification scenario, it was assumed that the natural gas fuel equipment was replaced by an electricity-driven air source heat pump.

Next, the household appliances in the model building were classified into DC- or AC-powered devices based on their affinity with a DC power supply, cost feasibility, and equipment characteristics. The DC-powered devices were further subdivided into high- and low-voltage use according to their operating voltage levels. Lighting and other devices categorized as low-voltage DC equipment were assumed to require 24 V power, whereas the electricity-driven air source heat pump, which was categorized as a high-voltage DC device, was supplied at 380 V.

3 Case study

Table 1 shows the case examinations in this study. The range for the four cases was set based on the DC-supplied appliances corresponding to the three major energy consumption categories of lighting, interior space heating/cooling, and hot water supply.

The daily energy consumption levels for each month in this study were estimated using hourly electricity and heat demand load patterns based on energy consumption units referred to in the literature [5,6], whereas PV power generation amounts were calculated using solar radiation levels measured in Tokyo [7] and the electric power generation efficiency.

The electric power purchase amounts, power transfer losses (see Appendix I), and annual energy consumption were evaluated for each case.

4 Results and discussion

4.1 Electric power energy flow and annual electric power consumption

Figure 3 shows the electric power flow in Case 1. Here it can be seen that the annual electric power generated from PV is 3,987.7 kWh and the purchased grid power is 924.9 kWh, while the annual electric power sold is 3,226.4 kWh. The power transfer losses are 121.8 kWh inside each appliance and 263.1 kWh at the power conditioner. The proportion of these losses to the electric power consumption for appliances, which are 9.2% and 17.8% respectively, could be mitigated by supplying DC power without the power conversion step.

Table 3 shows a breakdown of the electric power consumption for each case. In Case 2, it can be seen that the power transfer losses are considerably reduced compared to those for Case 1. This is because AC/DC conversion circuits in the DC-oriented appliances have been eliminated.

For Cases 3 and 4, the transfer losses are increased compared to Cases 1 and 2, because these cases cover interior space heating and hot water supply appliances as DC-powered devices. However, it can also be seen that there are reductions in the proportion of transfer losses to the total amount of electric power consumed.

4.2 Primary consumption for each case

Figure 4 shows the annual primary energy consumption estimation results for each case. Here, it can be seen that the primary energy consumption decreases as the DC power supply range expands.

This is because the conversion losses are suppressed by expanding the use of DC power supply. The primary energy consumption for Case 2, 3 and 4 were reduced by 1.8%, 2.2% and 11.1% respectively comparing with that of Case 1. Here, the decrease rate for Case 4 is larger than the others because of the energy efficiency improvements results from adapting an electricity-driven appliance for hot water supply instead of using natural gas-fueled devices.

4.3 Running cost evaluations

The natural gas fraction of the total calculated running cost was estimated using the metered and basic fees in the general contract fee schedule of the Tokyo Gas Co., Ltd.

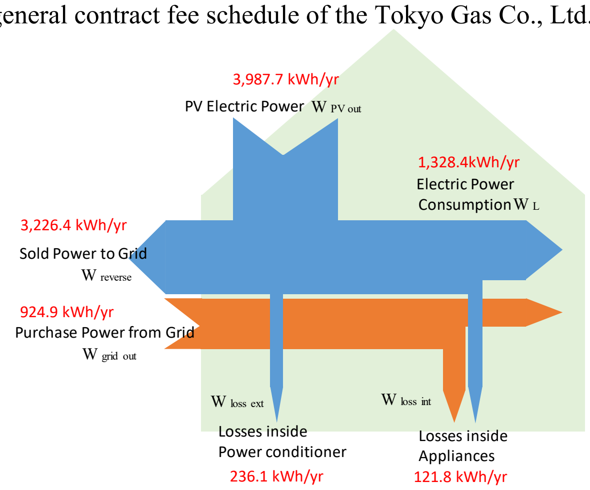


Fig. 3. Electric power flow in Case 1

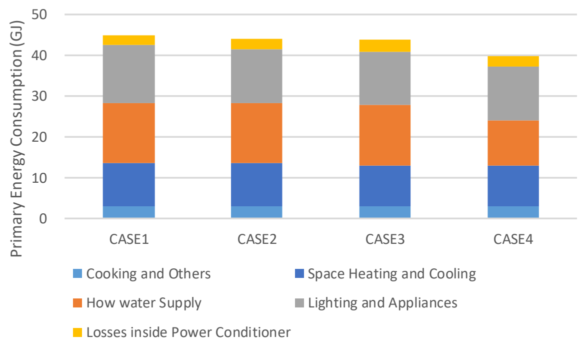


Fig. 4. Primary energy consumption for each case

Table 1. Case study settings

	Scope of Appliances DC power Supplied		
	(1)	(2)	(3)
DC power Supplied Appliances	LED(Large), LED(Small) Phone, Mobile Phone Video, TV, PC	Air Conditioner (Space Heating)	Domestic How Water Supplier
Case1	-	-	-
Case2	●	-	-
Case3	●	●	-
Case4	●	●	●

(1) Low Voltage DC Power Oriented Appliances
(2) High Voltage DC Power Equipment (Space Heating)
(3) High Voltage DC Power Equipment (DHW)

Table 2. Electric power costs at present, in the 2030s, and in the 2050s for each scenario

		2017	2030s	2050s
Basic fee (yen)		1,123 (case1) 1,404 (case2,3,4)		
Raw material cost adjustment (yen/kWh)		-3.10		
Renewable energy levy (yen/kWh)		2.64		
Metered fee	0-120kWh	19.52	22.00	25.00
	120-300kWh	26.00	29.30	33.30
	300kWh over	30.02	33.83	38.45

homepage [8]. The metered fees used in the 2030s and 2050s calculations were estimated by referring to the predicted prices of natural gas [9], and the basic fee is fixed with the present value.

The Tokyo Electric Power Company (TEPCO) metered electric light B fee schedule [10] was adopted to calculate the purchase budget. These electricity fee calculations use a three-tier fee system that contains a disparity in the unit price that depends on the amount of electricity used. For the 2030 and 2050 scenarios, the metered fees were estimated from past price trends.

Regarding the electricity FIT price offsets, we adopted 28 yen/kWh for the present price by referring to the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry (METI), and 11 yen/kWh and 9 yen/kWh for the 2030s and 2050s, respectively.

Table 4 shows the running cost calculation results. The running cost was evaluated using the annual utility fee excluding FIT offsets. This table shows that by introducing a DC power supply system in Cases 2 to 4 in the 2030 and 2050 scenarios, running costs decreased in comparison to Case 1 for the conventional power supply system, and that the amount of decrease became larger as the supply range expanded.

Regarding predictions that energy costs are expected to increase significantly in the future, since FIT offsets are scheduled to decline, energy cost reductions will most likely be achieved by minimizing energy consumption in the house, and FIT offsets should not be expected to reduce running costs.

4.4 Initial costs and simple payback period

The initial costs take into consideration expenses related to purchasing devices such as adapters and receptacles necessary for DC power supply systems, but do not consider construction costs. The initial expenditures are estimated at about ¥0.24 million, ¥1.25 million, and ¥1.55 million for Cases 2, 3, and 4, respectively.

Table 5 shows the simple payback period for each case. Under the present situation, the simple payback period is shortest for Case 4, however it is as long as 57 years. Therefore, it can be concluded that DC power supply system under the current situation is an exorbitant solution if there are no subsidies or political advantages to using it.

Under the 2030s scenario, the simple payback period for Case 4 is to be most short as like the present situation. And, it is still longer period than 20 years. The shortest payback period is 21 years at the Case 4 under the 2050s scenario. So, R&D of DC supply system and cost reduction are strongly desired to promote the system in the future.

If the initial costs of DC power supply systems will be reduced due to technological developments and energy conservation policies, the simple payback period could be expected to be shortened. Table 6 shows the simple payback period under anticipated initial cost reductions for Cases 3 and 4.

Table 3. Electric power and others for each case (kWh)

case	Electric power consumption (w/o Losses inside appliances)	Sold power to GRID	Purchased from GRID	Losses inside power conditioner	Losses inside appliances
1	1,328.4	3,226.4	924.9	236.1	121.8
2	1,328.4	3,257.3	875.5	262.8	14.8
3	2,345.0	2,908.9	1,598.0	296.2	35.6
4	3,477.4	1,828.7	1,652.3	275.6	58.7

Table 4. Energy Bills and Running Cost for each case (kWh)

	case	Sold power	Energy Bills			Annual Utility Fee
			Electric Power	City Gas	Total Amount	
2017	1	90,339	31,107	82,083	113,190	22,851
	2	91,204	30,165	82,083	112,248	21,044
	3	81,636	46,345	54,261	100,606	18,970
	4	51,780	47,501	0	47,501	-4,279
2030	1	35,490	33,400	84,113	117,513	82,023
	2	35,830	32,336	84,113	116,449	80,619
	3	32,071	50,613	55,389	106,002	73,931
	4	20,342	51,918	0	51,918	31,576
2050	1	29,038	36,175	107,018	143,193	114,156
	2	29,316	34,963	107,018	141,981	112,665
	3	26,240	55,776	69,114	124,890	98,650
	4	16,643	57,262	0	57,262	40,618

Table 5. Simple payback period for each case

	Case-2	Case-3	Case-4
2017	133	322	57
2030s	171	154	31
2050s	161	81	21

Table 6. Simple payback period under the initial cost reduction

Cost reduction		Case-3	Case-4
2030s	50%	77	15
	70%	46	9
2050s	50%	40	11
	70%	24	6

In Case 3, under the 2030s scenario, it can be seen that the simple payback period for Case 3 can be shortened to about 77 years if the current cost is reduced by 50% and about 46 years under the 70% cost reduction. Even though under the 2050s scenario, the simple payback period would be 40 years under the 50% cost reduction, 24 years under the 70% cost reduction.

In Case 4, all of simple payback period are under the 20 years and the shortest period is 6 years under the 70% cost reduction.

5 Conclusions

An energy saving and cost performance analysis of the effects of the introduction of DC power supply systems to a detached house equipped with roof-mounted solar PV panels was conducted for a range of DC power-supplied appliance cases and in different energy price conditions under present day, 2030s, and 2050s scenarios. In addition, the initial cost reductions that can be expected due to near-future technological developments were considered.

https://doi.org/10.1051/e3sconf/201911104010

Based on the estimation results, we found that DC power supply system under the current situation is an exorbitant solution if there are no subsidies or political advantages to using it.

It is expected that the simple payback period could be shortened while the initial costs of DC power supply systems is reduced due to R&D and energy conservation policies. In Case 4 which is introducing DC power to low voltage DC equipment and all high voltage DC equipment including how water supplier as well, it could be expected to be shorted less than 10 years. However, the simple payback period is longer than 20 years even though the cost reduction is considered, while it is introducing DC power to low voltage DC equipment and partial high voltage DC equipment as like Case 3.

It is necessary to set the promotion timetable while tracing the energy price fluctuation in the future and the cost reductions of the system. Also, it is desirable to maximize the improvement of equipment efficiency by electrification and DC supply to high voltage DC equipment as many as possible.

Although no batteries were used in this study, it can be expected that the DC power supply introduction effect can be increased by their use. Accordingly, as future work, the energy conservation and cost performance effectiveness of DC power supply systems equipped with battery storage subsystems should be considered.

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Appendix I. Power transfer circuit losses [11]

	Transfer circuit	Transfer losses
AC/DC Converter	Power conditioner	0.04
	LED (large)	0.11
	LED (small)	0.32
	Mobile phone	0.32
	Phone	0.32
DC/DC Converter	Washing machine	0.11
	Rice cooker	0.11
	Refrigerator	0.31
	PC	0.11
	Video deck	0.32
	Air conditioner	0.11
DC/AC Inverter		0.04