Analysis on the Cost Effectiveness of the Residential Distributed Energy System composed of Fuel Cell, Photovoltaics and Battery

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Summary

It is unclear how the feed-in tariff (FIT) and residential energy consumption structure impact the cost effectiveness of the residential distributed energy system composed of the fuel cell cogeneration system, photovoltaics and a battery, which are drawing more attention than ever after the Tohoku Earthquake in 2011. This study develops a simulation model for performance evaluation of the residential distributed energy system and analyzes the impact of the number of household members, FIT, and system specifications on the cost effectiveness. In addition, a future direction for technology development is proposed based on a quantitative analysis on cost effectiveness improvement by system performance upgrade.

According to the analysis results, in the case where only hot water demand is included in the thermal demand, the payout time ranges from 36 years (5-person household) to 43 years (single-person household) if the FIT is reduced to a level equivalent to the residential average electricity rate (21JPY/kWh) from the 11^{th} year. If the FIT continues to be 34JPY/kWh, the payout time is shortened to from 26 years (4-person household) to 29 years (single person household).

If the FIT is kept higher than a certain level, revenue from feed-in photovoltaic electricity combined with the photovoltaic power "push-up" effect of the battery overshadows the positive correlation between energy demand and cost effectiveness generally observed in cogeneration systems and diminishes the impact of the number of family members on the cost effectiveness, though a 4-to-5 person household delivers the highest cost effectiveness, due to a preferable balance between the feed-in photovoltaic electricity and operation rate of fuel cell.

In order to raise the cost effectiveness of the system by means of improvement in the performance of system components, there are three possible measures: improvement in the contribution rate of heat recovery, battery charging and discharging efficiency gain, and fuel cell power generation efficiency gain, of which the fuel cell power generation efficiency gain is the most effective. A 1% gain of fuel cell power generation gain reduces annual running costs by 3,000JPY/year and the payout time can be shortened by 0.4 years.

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Introduction

The residential distributed energy system (hereinafter referred to as "RDES") composed of a fuel cell co-generation system (FC-CGS), a photovoltaic system (PV) and a battery aims to raise the energy self-sufficient rate in houses along with realizing energy saving and reduction in CO2 emission. Since the Tohoku Earthquake in 2011, the RDES has been drawing much more attention than ever and is expected to be widely introduced. Although the RDES equipped with HEMS (Home Energy Management System), as a Smart House, has been launched on the market, the initial cost is still high.

The operation configuration of the system is significantly complicated due to buy-back of photovoltaic surplus electricity based on the feed-in-tariff (FIT) system along with interaction among power generation, heat supply, electricity charge and discharge. A variety of research on performance evaluation of a single residential co-generation system (CGS) and a CGS-PV hybrid system was carried out based on the field test data [1]-[6]. Researches on performance evaluation of the RDES composed of FC-CGS, PV and a battery for a single category of family number were also conducted [7] and [8]. However, how the FIT of PV surplus electricity and the energy demand structure in a household affect the cost effectiveness of the system is not yet revealed.

This study analyzes the impact of the number of family members, FIT, and the system specifications on the cost effectiveness of the RDES by developing a simulation model for performance evaluation of the system.

1. Energy Consumption and Photovoltaic Power Generation in a Detached Household in Japan

Though FC-CGS and the PV system can be introduced into apartments, there still currently remain barriers deriving from the physical structure of apartments. This study supposes the introduction of the RDES only into detached houses. This chapter develops datasets of energy consumption and PV power generation in a household, which is required for simulation input.

1-1 Annual Energy Consumption

As it is highly likely that the performance of the RDES is affected by energy consumption, data on energy consumption by number of family members are prepared (Table. 1-1). A single-person household consumes 33GJ annually, a 3-person household 58GJ, a 6-or-more person household 81GJ, and, on average, 54GJ. In general, energy consumption is categorized into electric demand and thermal demand to evaluate the CGS performance. In this study, electricity consumption for heating is categorized in electric demand. As for cooking use, electricity consumption for cooking is categorized in electric demand and the other energy consumption for cooking is put outside the scope of the study. The electricity consumption for cooling is classified in electric demand (Table. 1-2).

Table. 1-1 Annual Energy Consumption per Household (Detached House)

Number of family members	(GJ/household) Electricity	Energy for hot water (including electricity)	Energy for space heating (except for electricity)	Energy for cooling (electricity)	Energy for cooking (except for electricity)	Total	(million) Number of households
1p	16.1	5.7	8.8	0.8	2.0	33.4	4.1
2p	20.4	10.9	11.2	1.1	2.4	45.9	8.5
3p	24.6	13.9	15.4	1.6	2.5	58.0	6.0
4p	26.5	15.9	15.7	1.8	2.4	62.2	5.0
5p	29.4	17.3	17.7	1.8	2.6	68.7	2.3
6~p	34.9	18.6	23.4	1.9	2.6	81.4	1.6
Avg.	23.4	12.6	13.8	1.4	2.4	53.6	27.5

Source: Estimated by the Institute of Energy Economics, Japan

Table. 1-2 Category of Energy Use

Demand	Energy use	Simulation
Electric	Electricity consumption (lighting & miscellaneous, space heating, cooking)	Input to simulator
	Electricity consumption for space cooling	
Thermal	Water heating (energy except for electricity)	
	Space heating (energy except for electricity)	
Other	Cooking (energy except for electricity)	outside scope

1-2 Hourly Energy Consumption

The hourly energy consumption data required for input to the simulation is created from the hourly electric demand, space cooling demand, space heating demand and water heating demand by month of "Manual for Co-generation" (Advanced Cogeneration and Energy Utilization Center JAPAN). The hourly energy consumption is adjusted so that the integrated value of the hourly energy consumption equals the annual energy consumption shown in Table.1-1.

Though the hourly energy consumption profile must differ by the number of family members, this study assumes a single-shape profile for all households, due to the low availability of data. Fig.1-1 shows an example of the hourly energy consumption profile of a 3-person household.

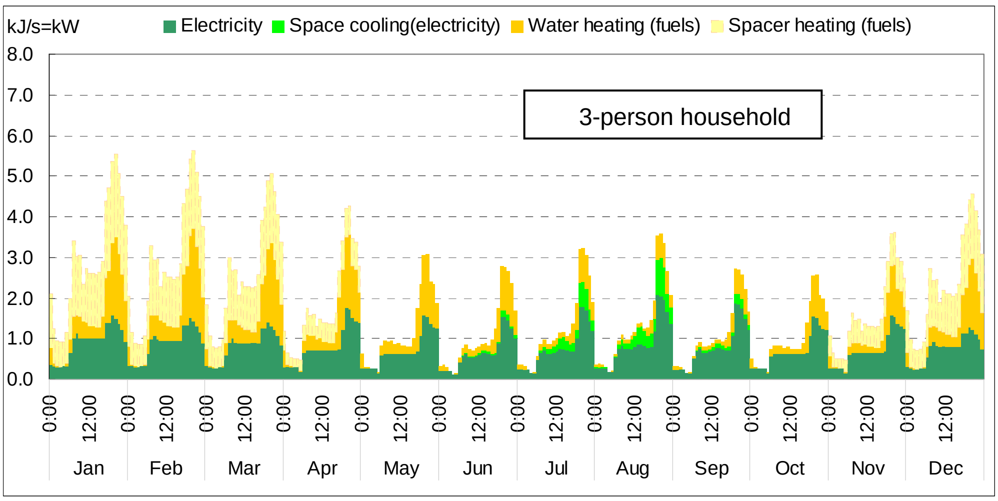


Fig. 1-1 Hourly Energy Consumption (detached house, 3-person household)

1-3 Photovoltaic Power Generation

The hourly PV power generation is based on the "Solar Radiation Database of NEDO" (New Energy and Industrial Technology Development Organization). Tokyo is chosen as a representative location. The hourly power generation per unit rating power generation capacity (kWh/h/kW) is calculated by the hourly global solar radiation per square meter averaged for the past decade multiplied by the power generation efficiency (13%) and divided by the panel area per unit rating power generation capacity (7m^2/kW) (See Fig.1-2). The calculated load factor of PV power generation is 12.8%, which roughly equals the 12% commonly observed in Japan.

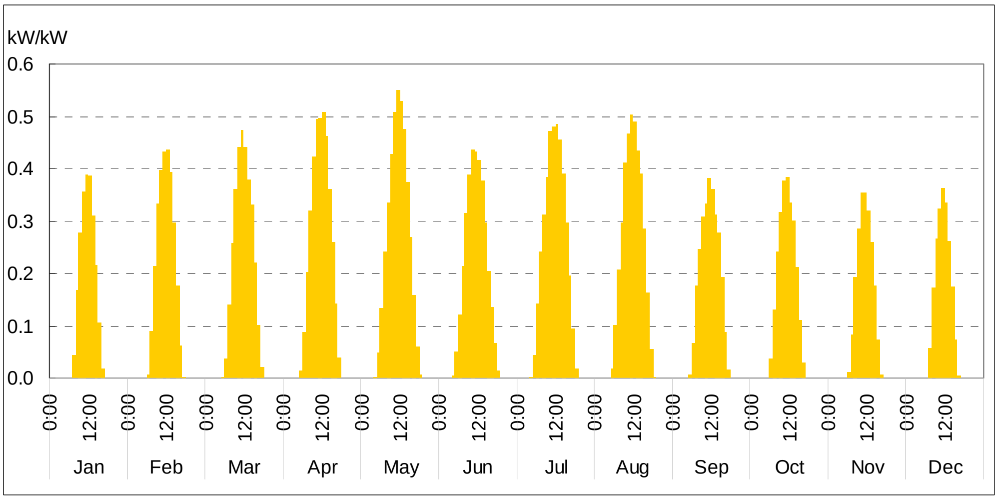


Fig. 1-2 Hourly PV Power Generation per unit Capacity

2. Development of Simulation Model

2-1 System Components and Specifications

The definition of the RDES is not clear and the system equipped with HEMS (Home Energy Management System) and an electric vehicle as components is occasionally called a Smart House. For the sake of simplicity, this study ignores these components and hourly energy demand is given as constant. There are various configurations for the energy supply system, like a single FC-CGS, a single PV, hybrid of the FC and PV, and also batteries can be added. In reality, the system configuration and capacity are chosen according to the number of family members. It is unrealistic that the system is introduced to a single-person family, especially to an aged single-person. Since one of the major objectives of this study is to analyze how the energy consumption impacts the cost effectiveness of the system, a unique energy supply system composed of a FC, a PV and a battery is supposed to be introduced into all households. The reference system used for performance evaluation of the RDES purchases electricity from the grid to meet the whole electricity demand and uses a boiler to which purchased city gas is input to meet the whole thermal demand (Fig.2-1). The fuel used for the both systems is assumed to be city gas.

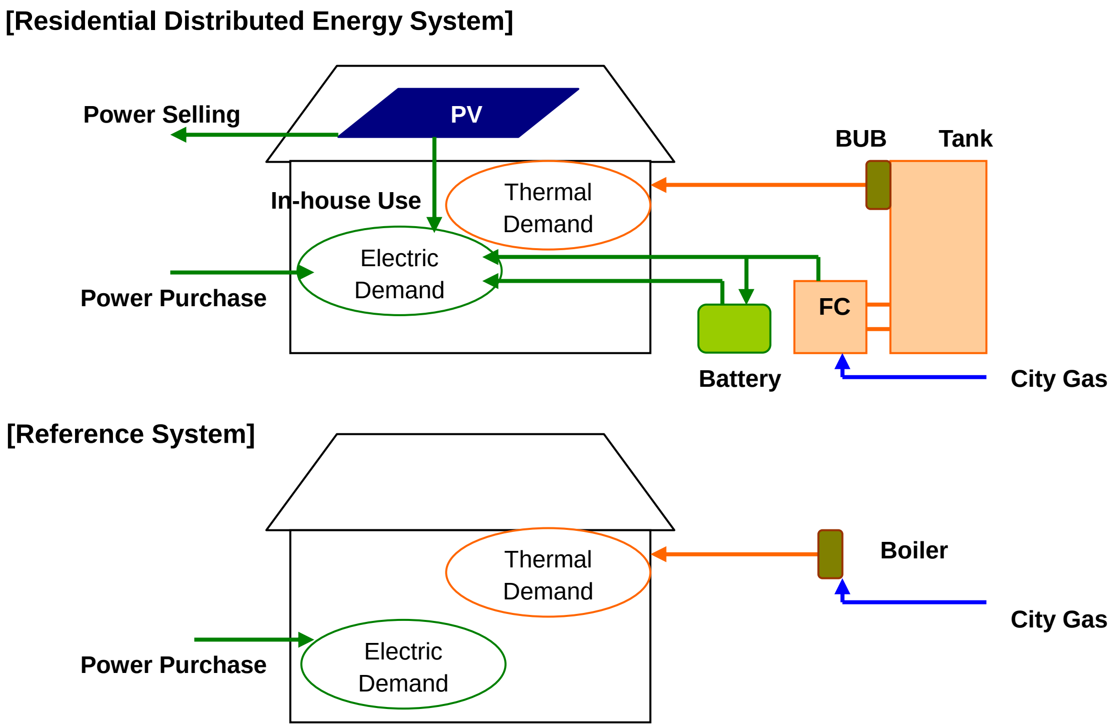


Fig. 2-1 Configuration of Residential Distributed Energy System

Note: PV means Photovoltaic system, FC is fuel cell, BUB is back-up boiler.

The system specifications are shown in Table.2-1. The average PV power generation capacity cumulatively installed in Japan from 1994 to December 2010 is 3.74kW. However, as the larger capacity has been introduced in the last few years (average capacity in a single year 2009 is 3.82kW and 4.05kW in 2010 [9]), the PV power generation capacity is assumed to be 4kW. The PEFC (Polymer Electrolyte Fuel Cell) type CGS, with the name "Ene-Farm," has already been launched on the Japanese market in 2009. The SOFC (Solid Oxide Fuel Cell) type CGS has also been commercialized in March 2012. Since the SOFC is operated at elevated temperature, load-following capability has been a disadvantage. However, field tests have revealed high capability of SOFC in load following. In addition, the power generation efficiency of SOFC is higher than PEFC. For these reasons, this study uses SOFC for CGS and the power generation capacity is assumed to be 0.7kW [10]. The battery capacity is assumed to be 2kWh.

The system cost, energy price and FIT are shown in Table.2-2 and Table.2-3. The RDES system with FC-CGS, 4kW of PV and 2kWh of battery costs 4.15 million JPY if the subsidy to the FC-CGS is included. On the other hand, the reference system costs 0.3 million JPY deriving only from a boiler. The subsidy for PV is not taken into consideration, due to the fact that the FIT scheme was introduced from July 2012.

The RDES is a so-called "Double Power Generation System," to which 34 JPY/kWh of FIT is applied for 10 years. Since the framework of the FIT scheme from the 11th year has not yet been discussed, this study assumes continuation of the FIT scheme and analyzes three cases of FIT: 34JPY/kWh, 21JPY/kWh (equivalent to the average residential electricity rate) and 10JPY/kWh.

Table. 2-1 Specifications of the System Components

Type	Component/system	Specification	
RDES	Photovoltaic System	Rated Power Generation Capacity	4.0kW
	Fuel Cell Co-generation System (SOFC) (1)	Rated Power Generation Capacity	0.7kW
		Rated Power Generation Efficiency (2)	42.0% (HHV) 46.5% (LHV)
		Rated Heat Recovery Efficiency (2)	39.2% (HHV) 43.5% (LHV)
		Tank Volume	90L
		Storage Temperature	70ºC
		Supply Water Temperature	15ºC
		Thermally-full coefficient of tank (3)	0.8
		Buck-up Boiler Efficiency	80%
	Battery	Battery Capacity	2kWh
		Charging Efficiency	95%
		Discharging Efficiency	95%
Reference		Boiler Efficiency	80%

Note (1) See website of Osaka Gas: http://www.osakagas.co.jp/company/press/pr_2012/1196121_5712.html, meanwhile, back-up boiler efficiency is assumed.

Note (2) Since combustion does not take place in the FC reaction process, HHV based efficiency is used.

Note (3) In general, the residential co-generation system provides hot water from the top of the tank and the same quantity of water is fed into the bottom of the tank. The exhaust heat is provided into the top of the tank and the low temperature water at the bottom of the tank is circulated to the engine/FC. The temperature of the whole of water in the tank rarely reaches the storage temperature and the full level is assumed to be 80% of the tank volume, which means the maximum heat storage is (70ºC-15ºC)*90L*4.18605kJ/kg/ºC*0.8=16.6MJ.

Table. 2-2 Cost of System Components

Type	Component/system	Price	Subsidy	Price-Subsidy	Unit
RDES	Photovoltaic System	450,000	0	450,000	JPY/kW
	Fuel Cell Co-generation System	2,751,000	1,000,000	1,751,000	JPY/unit
	Battery	300,000	0	300,000	JPY/kWh
Reference	Boiler	300,000	0	300,000	JPY/unit

Table. 2-3 Energy Price and FIT

	Price
FIT of PV for Double Power Generation System	34JPY/kWh (for 10 years), 34, 21 and 10JPY/kWh (from the 11th year)
Electricity rate for residential use (1)	21.4JPY/kWh (24.9JPY/1000kcal)
City gas rate for residential use (1)	12.5JPY/kWh (14.5JPY/1000kcal)

Source (1) "Handbook of Energy & Economic Statistics in Japan," The Institute of Energy Economics, Japan

2-2 Operation Pattern and Simulation

There are a variety of RDES operation patterns depending on what is to be optimized. Because of the fact that one of the major objectives of the RDES is to raise energy self-sufficiency and that consumers focuses on cost effectiveness, the operation patterns are set as below:

[Operation Pattern]

- The basic concept is that electricity from PV fed into the grid is to be maximized and a combination of FC power generation and battery operation minimizes the purchase of electricity.
- FC generates power following the electric demand of household in the daytime (6:00~18:00). During other times, FC operates at the rated power generation capacity and surplus power is charged to the battery. If the battery is full, the power generation from FC is reduced.
- Electricity is discharged when the electric demand exceeds the FC rated power generation capacity, and if still insufficient, electricity from PV is used followed by electricity purchase from the grid.
- Thermal storage from FC heat recovery to the tank is completely dependent on FC power generation operation and is not controlled. When the tank is thermally full, the recovered heat is discharged to the atmosphere.
- If the heat provided from the tank is not sufficient to meet the thermal demand, the back-up boiler is turned on.

Based on the operation pattern, the hourly FC power generation, heat recovery, electricity charged, electricity discharged, electric storage, thermal storage, heat supply from the tank, FC gas consumption, back-up boiler gas consumption, PV power in-house use, surplus power from PV, and power purchased are calculated from hourly electric demand, thermal demand and PV power generation.

With respect to the tank, heat loss and internal temperature should be calculated using the differential equation (A) shown below. This study, however, with a view to simplification, assumes that a certain percentage of thermal storage is lost regardless of the internal temperature of the tank (see equation (B-1) and (B-2)).

$$Mc_p \frac{dTR(t)}{dt} = -UA\left(TR(t) - TA(t)\right) + HR(t) - PH(t) \tag{A}$$

where M: mass of tank water (kg), c_p: specific heat of water (4.18605kJ/kg/ºC), U: heat transfer coefficient of tank surface (W/m^2/ºC), A: tank surface area (m^2), TR: internal temperature of tank (ºC), TA: ambient temperature (ºC), HR: heat recovery (kJ/s), PH: heat provided to the demand (kJ/s).

$$\frac{dTST(t)}{dt} = -HL(t) + HR(t) - PH(t) \tag{B-1}$$

$$HL(t) = aTST(t) \tag{B-2}$$

where TST: heat quantity in tank, HL: heat loss from tank, a: heat loss ratio (assumed to be 10%).

3. Analysis Results of Cost Effectiveness

In general, the thermal demand includes water heating and space heating. A house to which CGS is installed necessarily uses the recovered heat for water heating, but not always for space heating demand that is quite often met by air conditioners or fuel heaters. The simulation is run for two cases, one of which is that thermal demand includes only water heating and the other is that the thermal demand includes water heating and space heating. The impact of changes in system specification on the cost effectiveness is also analyzed.

3-1 Payout Time by Number of Family Member

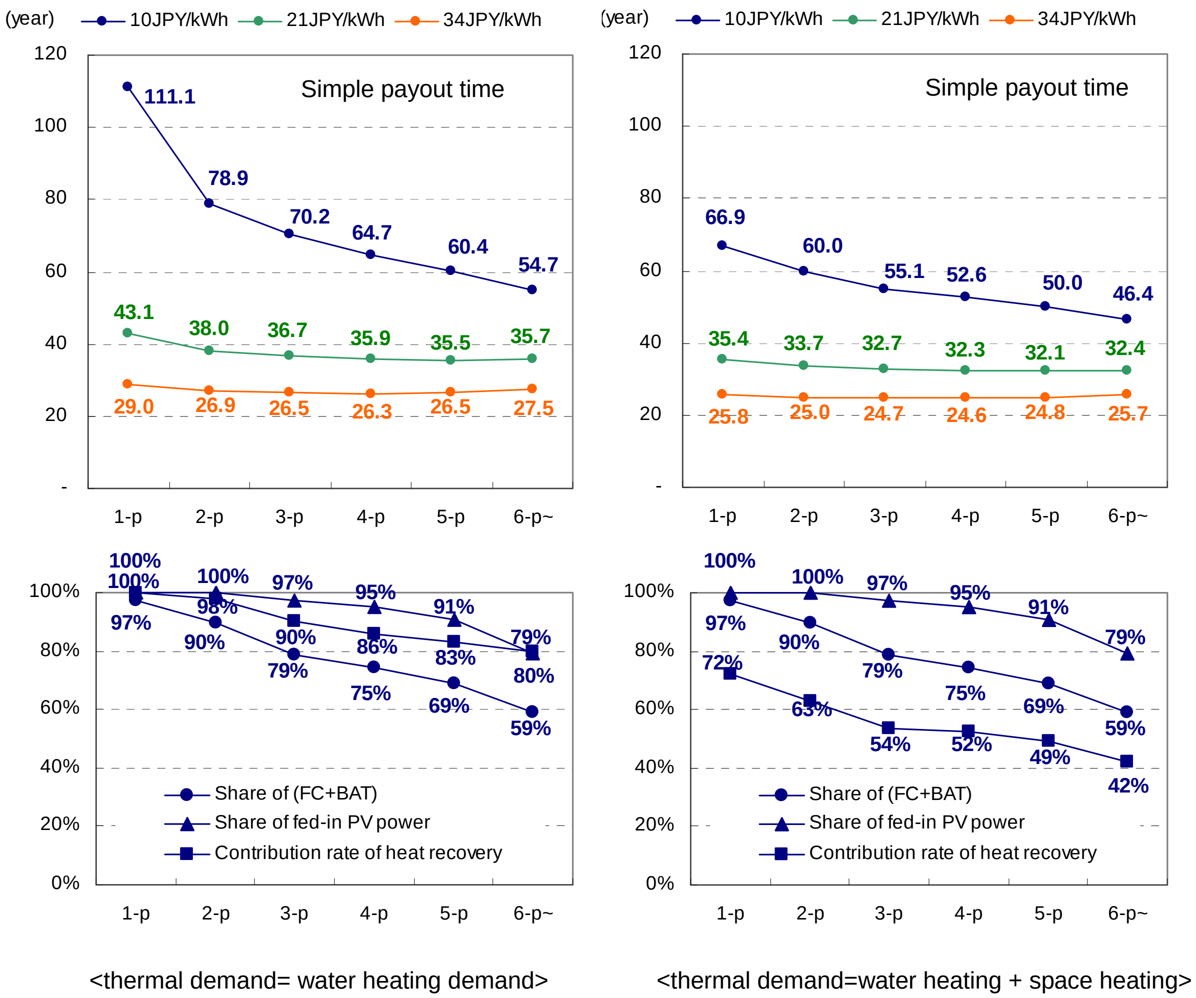
Fig.3-1 presents simulation results; simple payout time by RDES, share of electricity from FC (including via battery) in the electric demand, share of fed-in electricity in PV power generation and share of recovered heat in the thermal demand (contribution rate of recovered heat). The details of the simulation results are shown in Table.3-1, Table.3-2 and Fig.3-2.

In the case where the thermal demand includes only water heating, (left side of Fig.3-1 and Table.3-1), when FIT continues to be 34JPY/kWh from the 11th year, a large difference in payout time among the number of family members is not observed, ranging from 26 years for a 4-person family to 29 years for a single-person family. In a single–person household having small electric and thermal demand, the share of fed-in electricity in PV power generation and heat recovery share in the thermal demand are both 100%. Meanwhile, much gas is consumed, as FC share in the electric demand is large, which leads to smaller benefit. A larger number of family members decreases the contribution rate of recovered heat (percentage of recovered heat in the thermal demand) and the percentage of fed-in electricity in PV power generation, but simultaneously decreases the percentage of FC power generation in the electric demand, and then the payout time decreases until a 4-person family. However, a household with 5 persons or more that demands much more electricity runs out of the electricity charged in the battery in the morning, reducing the “push-up” effect of PV power along with the share of fed-in electricity, which results in less cost effectiveness. If the FIT from the 11th year is 21JPY/kWh, the payout time becomes longer (ranging from 36 years to 43 years). The relation among the number of family members is similar to the case of 34JPY/kWh. If the FIT is reduced up to 10 JPY/kWh, the impact of PV power buy-back diminishes and the feature indigenous to CGS, which is that larger energy demand results in higher cost effectiveness, becomes remarkable, though the payout time even for a household with 6 persons or more is as long as 55 years.

If space heating is added to the thermal demand (right side of Fig.3-1 and Table.3-2), the payout time is shortened by a few years, though it is still 46 years for a household with 6 persons or more in the case of 10JPY/kWh of FIT from the 11th year.

In summary, if the FIT is higher than a certain level, a positive correlation between energy demand and cost effectiveness observed in CGS is weakened and differences in the number of family members diminishes, though the 4- to 5-person household is the most economically efficient, due to preferable balance between the fed-in electricity from PV and the operation rate of FC.

The primary energy saving ratio is 18% to 24% in the case of “thermal demand = water heating” and 17% to 26% in the case of “thermal demand = water heating + space heating,” if PV power production is not taken into consideration.



(FC=0.7kW & 90L, PV=4kW, battery=2kWh)

Fig. 3-1 Payout time and Performance Indices

Note: Calculated for cases; FIT from the 11th year are 10JPY/kWh, 21 JPY/kWh and 34 JPY/kWh.

Note: Share of (FC+BAT) is percentage of electricity from FC (including electricity via battery) in the electric demand. Share of fed-in PV power is percentage of fed-in electricity in electricity generated from PV. Contribution rate of heat recovery is percentage of heat supplied from FC in the thermal demand.

Table.3-1 Simulation Results by Number of Family Members (1)

(Thermal demand=water heating, FC=0.7kW & 90L, PV=4kW, battery=2kWh)

			Unit	1-p	2-p	3-p	4-p	5-p	6-p ~
Distributed system	Energy Balance	Electric demand	kWh/a	4,701	5,951	7,284	7,845	8,664	10,216
		FC power generation	kWh/a	4,625	5,421	5,803	5,920	6,017	6,096
		Electricity charged	kWh/a	465	681	694	693	683	628
		Electricity discharged	kWh/a	489	717	730	729	718	661
		PV power generation	kWh/a	4,499	4,499	4,499	4,499	4,499	4,499
		In-house consumed PV power	kWh/a	0	0	116	223	423	944
		Fed-in PV power	kWh/a	4,499	4,499	4,383	4,276	4,076	3,555
		Electricity purchase	kWh/a	127	603	1,440	1,777	2,297	3,244
		Thermal Demand	kWh/a	1,257	2,421	3,090	3,524	3,834	4,125
		Useful FC recovered heat	kWh/a	1,257	2,367	2,791	3,019	3,175	3,292
		BU heat	kWh/a	0	53	299	504	659	833
		FC gas consumption	kWh/a	11,011	12,907	13,817	14,095	14,327	14,513
		BU gas consumption	kWh/a	0	66	373	631	823	1,042
		Total gas consumption	kWh/a	11,011	12,973	14,190	14,726	15,151	15,555
	Running Cost	Fed-in electricity	10^3JPY/a	-153	-153	-149	-145	-139	-121
		Electricity purchase	10^3JPY/a	3.0	13	31	38	49	69
		Gas purchase	10^3JPY/a	137	162	177	184	189	194
		Total	10^3JPY/a	-13	22	59	77	100	143
	System Cost		10^3JPY	4,150	4,150	4,150	4,150	4,150	4,150
Reference system	Energy Balance	Electricity purchase	kWh/ a	4,701	5,951	7,284	7,845	8,664	10,216
		Gas purchase	kWh/ a	1,571	3,026	3,862	4,405	4,792	5,157
	Running Cost	Electricity purchase	10^3JPY/a	101	127	156	168	185	219
		Gas purchase	10^3JPY/a	20	38	48	55	60	64
		Total	10^3JPY/a	120	165	204	223	245	283
	System Cost		10^3JPY	200	300	300	300	300	300
Comparison	Difference in running cost		10^3JPY/a	-133	-143	-145	-146	-145	-140
	Difference in system cost		10^3JPY	3,850	3,850	3,850	3,850	3,850	3,850
	Simple payout time (10JPY/kWh) (1)		Year	111.08	78.85	70.23	64.70	60.38	54.69
	Simple payout time (21JPY/kWh) (1)		Year	43.10	38.02	36.74	35.86	35.50	35.71
	Simple payout time (34JPY/kWh) (1)		Year	28.97	26.91	26.55	26.33	26.49	27.48
	Primary energy saving (2)		GJ/a	10.7	16.4	18.7	19.9	20.7	21.4
	Primary energy saving ratio (2)		%	21%	24%	22%	22%	20%	18%

Note (1): FIT from the 11th year.
Note (2): Excludes fed-in PV power.
Note: For the sake of comparison, gas consumption and heat are expressed in kWh.
Note: Negative running cost value means revenue.
Note: The cost of RDES includes subsidy to FC.
Note: Primary energy convertor of electricity is 9.76MJ/kWh.
Note: Primary energy savings = [Purchased electricity converted to primary energy + gas consumption in the reference system] – [Purchased electricity converted to primary energy + gas consumption + in-house consumed PV electricity converted to primary energy in the RDES]. Primary energy saving ratio = Primary energy savings/primary energy consumption in the reference system

Table.3-2 Simulation Results by Number of Family Members (2)

(Thermal demand=water heating + space heating, FC=0.7kW & 90L, PV=4kW, battery=2kWh)

			Unit	1-p	2-p	3-p	4-p	5-p	6-p ~
Distributed system	Energy Balance	Electric demand	kWh/a	4,701	5,951	7,284	7,845	8,664	10,216
		FC power generation	kWh/a	4,625	5,421	5,803	5,920	6,017	6,096
		Electricity charged	kWh/a	465	681	694	693	683	628
		Electricity discharged	kWh/a	489	717	730	729	718	661
		PV power generation	kWh/a	4,499	4,499	4,499	4,499	4,499	4,499
		In-house consumed PV power	kWh/a	0	0	116	223	423	944
		Fed-in PV power	kWh/a	4,499	4,499	4,383	4,276	4,076	3,555
		Electricity purchase	kWh/a	127	603	1,440	1,777	2,297	3,244
		Thermal Demand	kWh/a	3,216	4,910	6,520	7,003	7,770	9,330
		Useful FC recovered heat	kWh/a	2,312	3,077	3,492	3,665	3,809	3,921
		BU heat	kWh/a	903	1,833	3,028	3,338	3,961	5,409
		FC gas consumption	kWh/a	11,011	12,907	13,817	14,095	14,327	14,513
		BU gas consumption	kWh/a	1,129	2,292	3,785	4,172	4,951	6,761
		Total gas consumption	kWh/a	12,140	15,198	17,602	18,267	19,278	21,274
	Running Cost	Fed-in electricity	10^3JPY/a	-153	-153	-149	-145	-139	-121
		Electricity purchase	10^3JPY/a	3.0	13	31	38	49	69
		Gas purchase	10^3JPY/a	152	190	220	228	241	266
		Total	10^3JPY/a	1.0	50	102	121	151	214
	System cost		10^3JPY	4,150	4,150	4,150	4,150	4,150	4,150
Reference system	Energy Balance	Electricity purchase	kWh/a	4,701	5,951	7,284	7,845	8,664	10,216
		Gas purchase	kWh/a	4,020	6,138	8,150	8,753	9,712	11,662
	Running Cost	Electricity purchase	10^3JPY/a	101	127	156	168	185	219
		Gas purchase	10^3JPY/a	50	77	102	109	121	146
		Total	10^3JPY/a	151	204	258	277	307	364
	System cost		10^3JPY	300	300	300	300	300	300
Comparison	Difference in running cost		10^3JPY/a	-149	-155	-156	-156	-155	-150
	Difference in system cost		10^3JPY/a	3,850	3,850	3,850	3,850	3,850	3,850
	Simple payout time (10JPY/kWh) (1)		Year	66.90	59.96	55.10	52.56	49.98	46.38
	Simple payout time (21JPY/kWh) (1)		Year	35.44	33.69	32.75	32.33	32.12	32.37
	Simple payout time (34JPY/kWh) (1)		Year	25.78	24.98	24.69	24.63	24.80	25.68
	Primary energy saving (2)		GJ/a	15.4	19.6	21.9	22.8	23.6	24.2
	Primary energy saving ratio (2)		%	26%	24%	22%	21%	20%	17%

Note (1): FIT from the 11^{th} year.

Note (2): Excludes fed-in PV power.

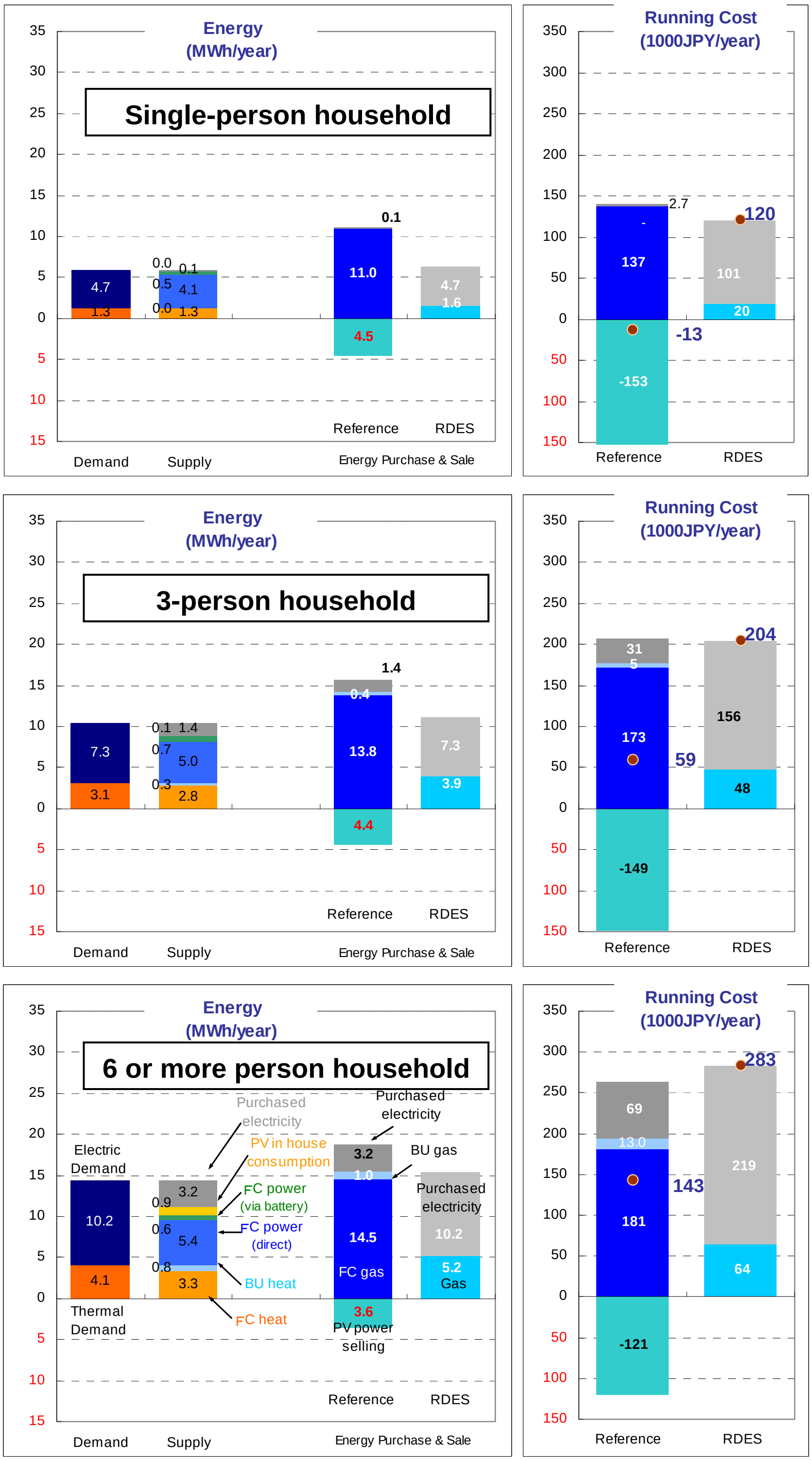
Note: For the sake of comparison, gas consumption and heat are expressed in kWh.

Note: Negative running cost value means revenue.

Note: The cost of RDES includes subsidy to FC.

Note: Primary energy convertor of electricity is 9.76MJ/kWh.

Note: Primary energy savings = [Purchased electricity converted to primary energy + gas consumption in the reference system] – [Purchased electricity converted to primary energy + gas consumption + in-house consumed PV electricity converted to primary energy in the RDES]. Primary energy saving ratio = Primary energy savings/primary energy consumption in the reference system



(Thermal demand=water heating, FC=0.7kW & 90L, PV=4kW, battery=2kWh)

Fig.3-2 Energy Balance and Running Cost

Note: [FC power generation] = [FC power directly supplied] + [Electricity charged] / [Charging efficiency]

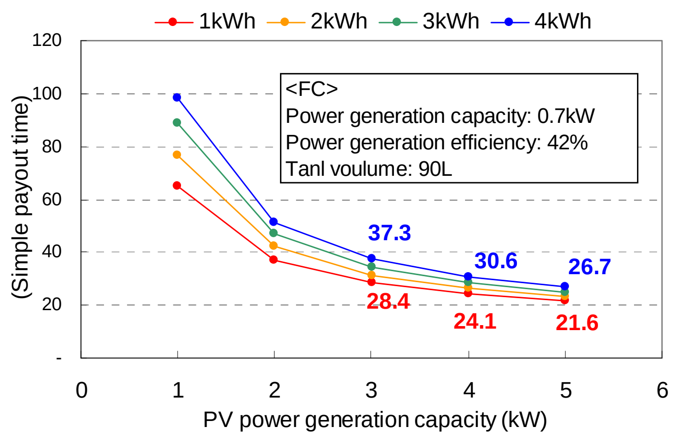
Note: For the sake of comparison, gas consumption and heat are expressed in kWh.

3-2 Impact of System Specification on Cost Effectiveness

Choosing a 4-person household that delivers relatively high cost effectiveness and accounts for larger market share (5 million households and 18% of the detached houses; See Table.1-1), the impact of PV power generation capacity and battery capacity on the cost effectiveness is analyzed hereafter. It is assumed that the thermal demand includes only water heating.

Fig.3-3 shows the results of simulation run for the combination of 1 to 5 kW of PV power generation capacity and 1 to 4 kWh of battery capacity, fixing the FC power generation capacity. For the sake of ease of interpretation in analysis results, the FIT after 10 years is assumed to be 34 JPY/kWh. The larger PV power generation capacity increases fed-in power and shortens the payout time. For example, in the case of 2kWh of battery capacity (Table.3-3) and 2kW of PV, annual fed-in electricity and revenue is 2,050kWh and 70 thousand JPY, respectively. 4kW of PV nearly doubles to 4,276kWh and 150 thousand JPY. However, since electricity purchase and gas purchase are almost identical between these two cases, the running cost of the latter case is lower than the former case by the difference in revenue from PV fed-in electricity, which is 80 thousand JPY. If compared to the reference system, running cost reduction of the RDES is 70 thousand JPY and 150 thousand JPY for 2kW and 4kW of PV, respectively. However, since the investment cost of 4kW of PV is only 1.3-fold that of 2kW of PV (3.85/2.85 million JPY), the payout time is reduced compared to 2kW of PV.

On the other hand, the smaller capacity of the battery raises the cost effectiveness. Taking 4kW of PV as an example (Table.3-3), although 1 kWh of battery yields smaller benefit from revenue of fed-in electricity than 3kWh of battery due to reduction in the “push-up” effect on PV power by battery discharge, decrease in FC power generation for charging reduces gas consumption of FC, which leads to net reduction in running costs, though the gas consumption of the back-up boiler and electricity purchase increase. In addition, smaller investment cost in battery is the other positive impact on cost effectiveness. If the battery capacity exceeds 3kWh, 0.7kW of FC power generation capacity is not able to reach full charging level, resulting in unnecessary investment and degrading the cost effectiveness.



(4-person household, thermal demand=water heating, FIT=34 JPY/kWh)

Fig. 3-3 Impact of PV and Battery Capacity on Payout Time

Table.3-3 Cost Effectiveness by Battery Capacity and by PV Capacity

(4-person household, thermal demand=water heating, FC=0.7kW & 90L,)

			Unit	Battery=2kWh					PV=4kW			
				PV capacity					Battery capacity			
				1kW	2kW	3kW	4kW	5kW	1kWh	2kWh	3kWh	4kWh
Distributed system	Energy balance	Electric demand	kWh/a	7,845	7,845	7,845	7,845	7,845	7,845	7,845	7,845	7,845
		FC power generation	kWh/a	5,920	5,920	5,920	5,920	5,920	5,537	5,920	6,072	6,072
		Electricity charged	kWh/a	729	729	729	729	729	347	729	874	830
		Electricity discharged	kWh/a	729	729	729	729	729	365	729	874	874
		PV power generation	kWh/a	1,125	2,249	3,374	4,499	5,624	4,499	4,499	4,499	4,499
		In-house consumed PV power	kWh/a	139	199	216	223	228	405	223	184	184
		Fed-in PV power	kWh/a	986	2,050	3,158	4,276	5,395	4,094	4,276	4,315	4,315
		Electricity purchase	kWh/a	1,861	1,801	1,784	1,777	1,772	1,941	1,777	1,678	1,678
		Thermal Demand	kWh/a	3,524	3,524	3,524	3,524	3,524	3,524	3,524	3,524	3,524
		Useful FC recovered heat	kWh/a	3,019	3,019	3,019	3,019	3,019	2,985	3,019	3,028	3,028
		BU heat	kWh/a	504	504	504	504	504	539	504	496	496
		FC gas consumption	kWh/a	14,095	14,095	14,095	14,095	14,095	13,182	14,095	14,458	14,458
		BU gas consumption	kWh/a	631	631	631	631	631	673	631	620	620
		Total gas consumption	kWh/a	14,726	14,726	14,726	14,726	14,726	13,856	14,726	15,078	15,078
	Running cost	Fed-in electricity	10^3JPY/a	-34	-70	-107	-145	-183	-139	-145	-147	-147
		Electricity purchase	10^3JPY/a	40	39	38	38	38	42	38	36	36
		Gas purchase	10^3JPY/a	184	184	184	184	184	173	184	188	188
		Total	10^3JPY/a	190	153	115	77	38	75	77	77	77
	System cost		10^3JPY	2,800	3,250	3,700	4,150	4,600	3,550	3,850	4,150	4,450
Reference system	Energy balance	Electricity purchase	kWh/a	7,845	7,845	7,845	7,845	7,845	7,845	7,845	7,845	7,845
		Gas purchase	kWh/a	4,405	4,405	4,405	4,405	4,405	4,405	4,405	4,405	4,405
	Running Cost	Electricity purchase	10^3JPY/a	168	168	168	168	168	168	168	168	168
		Gas purchase	10^3JPY/a	55	55	55	55	55	55	55	55	55
		Total	10^3JPY/a	223	223	223	223	223	223	223	223	223
	System cost		10^3JPY	300	300	300	300	300	300	300	300	300
Comparison	Difference in running cost		10^3JPY/a	-3.3	-7.0	-10.8	-14.6	-18.4	-14.7	-14.6	-14.5	-14.5
	Difference in system cost		10^3JPY	250	295	340	385	430	355	385	415	445
	Simple payout time (10JPY/kWh) (1)		Year	252.7	117.7	81.7	64.7	54.7	52.2	64.7	74.6	81.8
	Simple payout time (21JPY/kWh) (1)		Year	117.7	60.9	44.0	35.9	31.1	31.7	35.9	39.7	43.0
	Simple payout time (34JPY/kWh) (1)		Year	76. 7	42.1	31.5	26.3	23.3	24.1	26.3	28.6	30.6
	Primary energy saving (2)		GJ/a	19.9	19.9	19.9	19.9	19.9	19.6	19.9	20.0	20.0
	Primary energy saving ratio (2)		%	22%	22%	22%	22%	22%	21%	22%	22%	22%

Note (1): FIT from the 11th year.

Note (2): Excludes fed-in PV power.

Note: For the sake of comparison, gas consumption and heat are expressed in kWh.

Note: Negative running cost value means revenue.

Note: The cost of RDES includes subsidy to FC.

Note: Primary energy convertor of electricity is 9.76MJ/kWh.

Note: Primary energy savings = [Purchased electricity converted to primary energy + gas consumption in the reference system] – [Purchased electricity converted to primary energy + gas consumption + in-house consumed PV electricity converted to primary energy in the RDES]. Primary energy saving ratio = Primary energy savings/primary energy consumption in the reference system

3-3 Proposal for Improvement in Cost Effectiveness

According to the simulation results presented above, if the FIT is as high as a certain level, the cost effectiveness in a 4- to 5-person household is the highest in the case of introduction of the unique RDES, though there is not a remarkable difference among households. Besides, the analysis for a 4-person household revealed that installation of batteries does not yield any benefit, as the larger battery capacity does not bring about a decrease in the running costs but causes an increase in investment costs. This is due partly to the fact that batteries are not power generation equipment but only have a function to shift power supply time, and partly to loss in charge and discharge. Nevertheless, battery introduction has a "push up" effect of PV power.

Hereinafter, the relationship between the performance of system components and cost effectiveness is analyzed from comparison of running costs between the RDES and the reference system and measures of technology improvement are proposed aiming at further cost effectiveness.

The difference in running costs between the RDES and the reference system is expressed by formula (1) below, the larger the difference, the more cost effective the RDES.

Difference in Running Cost = Running Cost of the RDES - Running Cost of the reference system
= Benefit in Running Cost

$$\underbrace{\left(P_{GS}\frac{s_{HR}}{\eta_B}\right)HD}_{\text{Benefit from heat recovery}} - \underbrace{\left(\frac{P_{GS}}{\eta_{FCP}} - P_{EL} + P_{EL}\beta(1-\eta_C\eta_{DC})\right)FCP}_{\text{Effect of FC power self-sufficiency}} + \underbrace{((1-c)FIT + cP_{EL})PVP}_{\text{Benefit from feed-in of PV power}} \qquad (1)$$

where, HD: thermal demand, η_B: boiler efficiency, P_{EL}: grid-electricity rate, P_{GS}: gas rate, PVP: PV power generation, c: percentage of in-house use in the electricity supplied by PV, β: percentage of electricity via battery in the electricity supplied by FC, η_C: charging efficiency, η_{DC}: discharging efficiency, FCP: FC power generation, η_{FCP}; FC power generation efficiency, s_{HR}: percentage of recovered heat in the thermal demand (contribution rate of recovered heat), FIT: feed in tariff.

The first term of formula (1) represents reduction in running costs from a decrease in gas consumption of the back-up boiler by recovery of exhaust heat from FC; the larger the s_{HR} (contribution rate of recovered heat) is, the larger the benefit. The second term represents the difference between the real price of FC power generation taking into account power generation efficiency and the grid electricity price, and also the loss in electricity provided via battery. The larger η_{FCP}, η_C and η_{DC} bring larger benefit. The third term represents benefit from revenue of PV fed-in electricity and reduction in electricity purchase; the smaller c (percentage of in-house use in the electricity supplied by PV) brings larger benefit.

The city gas rate (P_{GS}) is 12.5JPY/kWh, the grid-electricity rate (P_{EL}) 21.4JPY/kWh, the FC power generation efficiency (η_{FCP}) 42%, the charging efficiency (η_C) 95% and the discharging efficiency (η_{DC}) 95%. The second term is always negative due to the fact that the real rate of electricity from FC (P_{GS}/η_{FCP}) is 12.5/42%=29.7JPY/kWh, higher than the grid-electricity rate, and including 10%(=1-95%*95%) of the charging and discharging overall loss. The first and third terms are always positive. The larger battery capacity allows FC to generate more electricity (though *FCP* reaches a ceiling, as the rated power generation capacity is fixed), which leads to a higher contribution rate of recovered heat (s_{HR}), that is, increase in the first term. However, the absolute value of the second term increases due to a larger *FCP* and larger β (percentage of electricity via battery in the electricity supplied by FC). Meanwhile, the larger battery capacity increases the push-up effect on PV power generation and *c* (percentage of in-house use in the electricity supplied by PV) decreases, which leads to increase in the third term.

Table.3-4 shows a breakdown of benefit in running costs by battery capacity, in the case of 4kW of PV capacity. The larger battery capacity increases the benefit from heat recovery and from feed-in of PV power generation, while the negative effect of FC power self-sufficiency is larger, which leads to a slight decrease in the total benefit.

Table.3-4 Breakdown of Benefit in Running Cost of RDES

(4-person household, thermal demand=water heating, PV=4kW, FIT after 10 years=34JPY/kWh)

(unit: 10^3 JPY/year)

	Battery capacity	1kWh	2kWh	3kWh	4kWh
1st term	Benefit from heat recovery	46.6	47.1	47.3	47.3
2nd term	Effect of FC power self-sufficiency	-47.0	-51.0	-52.6	-52.6
3rd term	Benefit from feed-in of PV power	147.9	150.1	150.6	150.6
Total		147.5	146.2	145.3	145.3

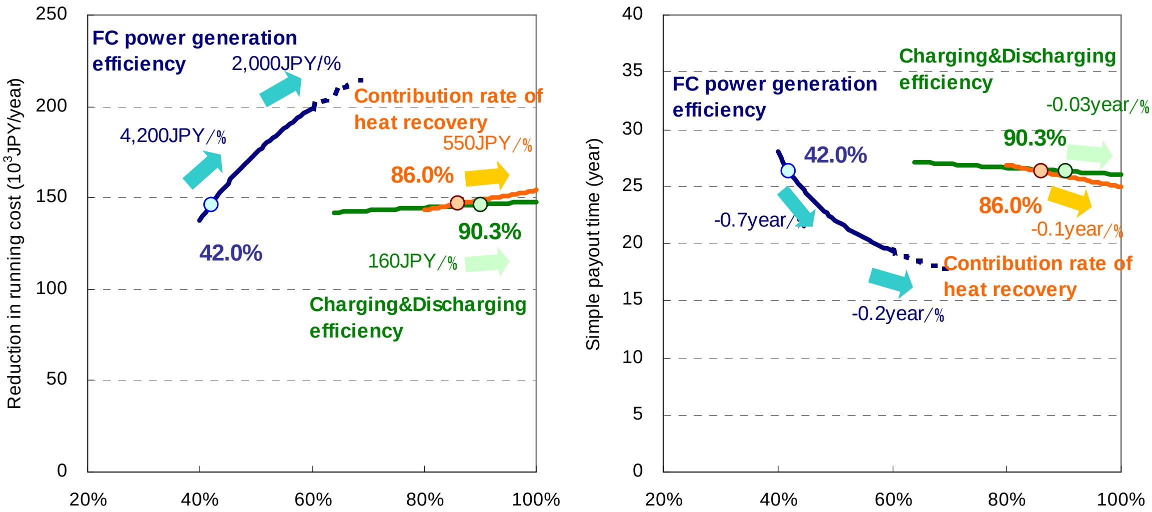
Note: Positive value means decrease in running cost of RDES compared to the reference system

It was revealed that batteries bring no benefit. However, if incorporating a battery that plays a role to strengthen energy security in a house when a disaster occurs is sine qua non, the performance of the whole RDES should be upgraded in order to improve the cost effectiveness, except for the measures to directly reduce investment costs. It is required that the first and third terms in formula (1) be increased and that the absolute value of the second term be decreased. When the FC power generation capacity, PV power generation capacity and battery capacity are fixed, the third term highly depends on the FIT for which uncertainty remains (and the percentage of in-house use in the electricity supplied by PV (*c*) is already controlled below 10% under the operation mode assumed in this study). Therefore, there remain three possible measures; improvement in s_{HR} (contribution rate of recovered heat) in the first term, upgrade of charging and discharging efficiency ($\eta_C*\eta_{DC}$) in the second term and upgrade of FC power generation efficiency (η_{FCP}) in the second term.

Fig.3-4 shows the impacts of these three measures on the cost effectiveness. A 1% of gain in overall charging and discharging efficiency is able to reduce annual running costs only by 160 JPY/year and the payout time is shortened by no more than 0.03 year. In addition, as the efficiency of charging and discharging is set as high as 95%, further improvement in cost effectiveness can hardly be expected. A 1% of improvement in the contribution rate of recovered heat is able to reduce annual running costs by 550JPY/year and the payout time is shortened by

0.1 year. However, it might be technologically difficult to further improve the contribution rate except for by increasing the tank volume, as the contribution rate is already high based on the fact that the heat storage level is constantly sufficiently high due to the smaller tank volume (90L) and to the electric demand following operation mode. On the other hand, a 1% of gain in FC power generation efficiency is able to reduce annual running costs by 2,000 to 4,000JPY/year and the payout time is shortened by 0.2 to 0.7 year.

Supposing 20-year operation of the RDES system, the system cost increment should be kept within 3,200JPY per 1% gain of charging and discharging efficiency and 11,000JPY per 1% gain of s_{HR} (contribution rate of recovered heat) in order to improve the cost effectiveness of the RDES. Meanwhile, if a 1% gain of FC power generation efficiency could be achieved within a 60,000JPY increment cost, the cost effectiveness is improved.



(4-person household, thermal demand=water heating, PV=4kW, battery=2kWh, difference in system cost=3.85million JPY)

Fig.3-4 Relation between Performance of System Components and Cost Effectiveness

Note: Dots mean current situations

4. Concluding Remarks

Developing a simulation model, the cost effectiveness of the residential distributed energy system (RDES) composed of a FC, a PV and a battery was analyzed. In general, the co-generation system has a characteristic of delivering more economically efficient performance if introduced in a house with larger energy demand. According to the simulation results, if the FIT is kept high at a certain level, revenue from feed-in PV electricity combined with the PV power “push-up” effect by the battery overshadows the co-generation characteristic and weakens the impact of the number of family members on the cost effectiveness, though the cost effectiveness of a 4- to 5-person household is highest.

Introduction of batteries does not yield any economic benefit. Though reduction in the investment cost is the most effective to improve the cost effectiveness of the RDES, there are three measures which are focused on performance improvement of system components: gain in contribution rate of heat recovery, improvement in charging and discharging efficiency and improvement in FC power generation efficiency, of which the first and the second measures do not have a remarkable impact, and the third measure is the most effective one. However, since improvement in the FC power generation efficiency might cause a decrease in heat recovery efficiency, striking a balance between the two efficiencies might be important.

This study assumed the unique operation mode of the RDES, which is electric demand following pattern. However, there may be a variety of operation modes like when the thermal demand following mode is chosen, when Time-of-Use electricity tariff system is applied and so on. Combination of system components may affect the cost effectiveness of the RDES. Hence, cost effectiveness evaluation for various system configurations and operation modes is a study to be tackled. In addition, energy saving ratio, CO2 reduction and peak cut effect that were not analyzed in this study will be addressed on another occasion.

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Appendix

A-1 Simulation Flow

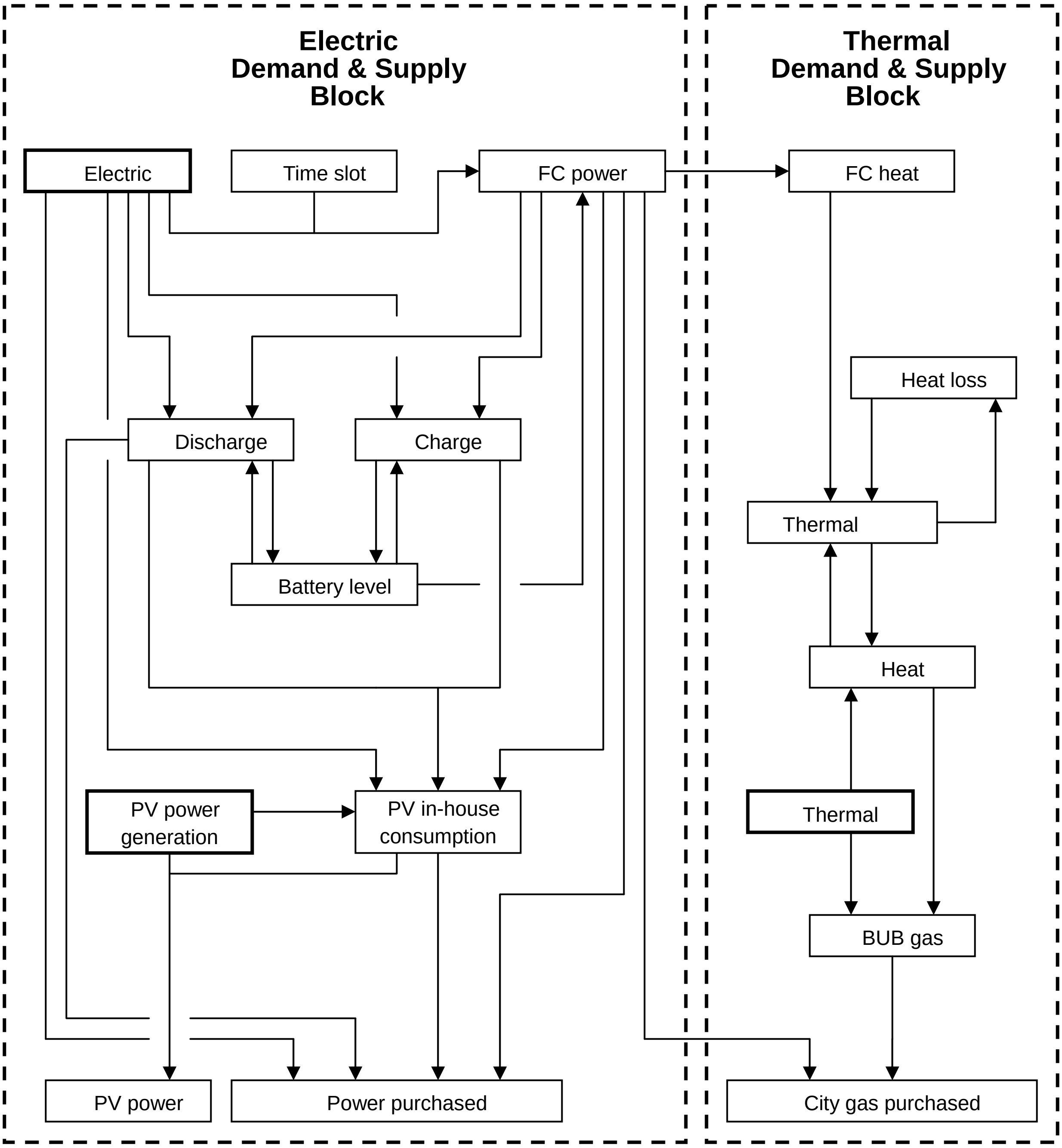
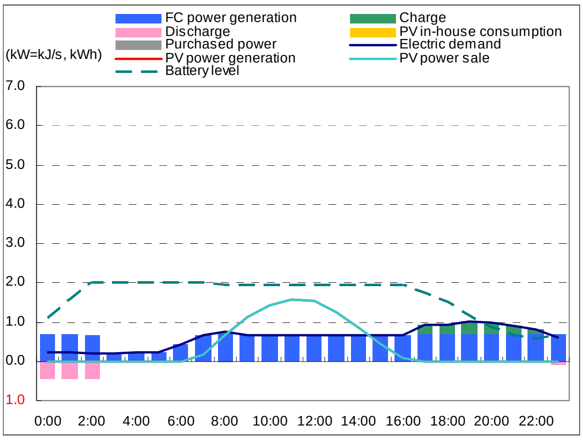


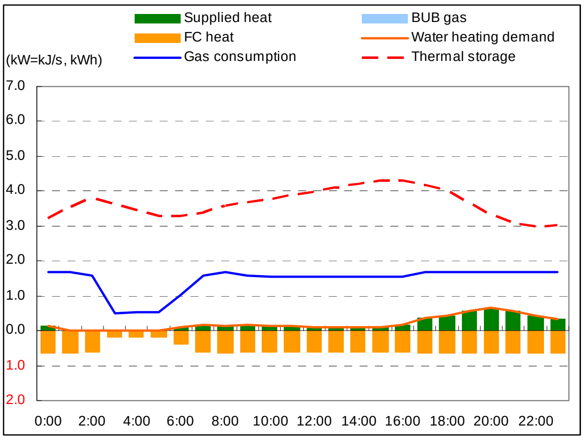
Fig.A-1 Simulation Flow

A-2 Examples of Simulation Results

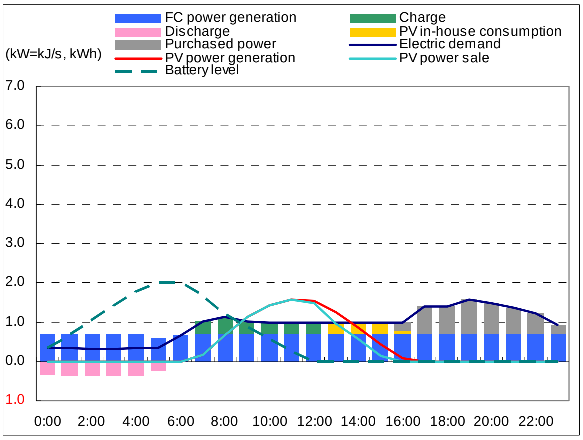
- January

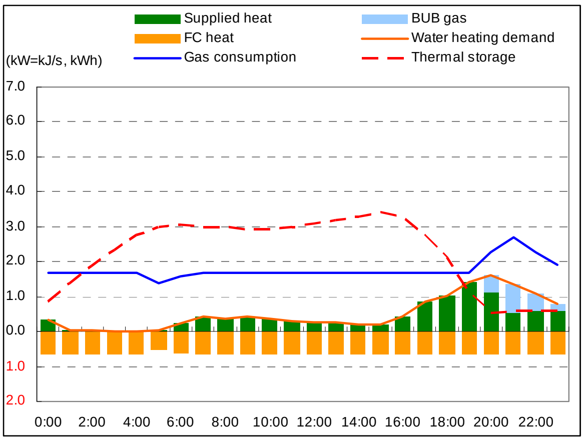
<Single-person household>



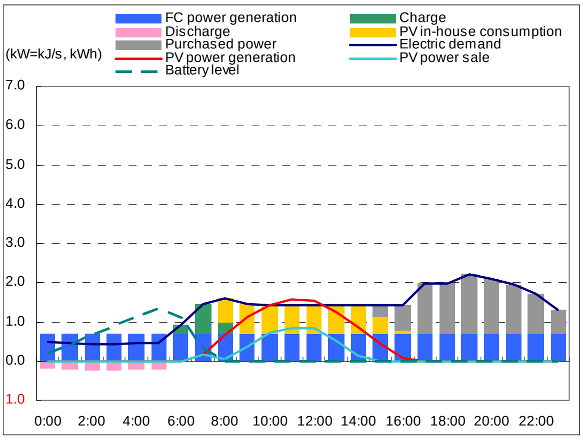


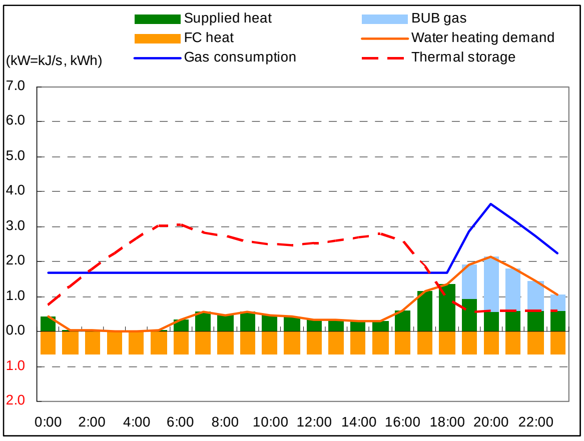
<3-person household>





<6-person or more household>



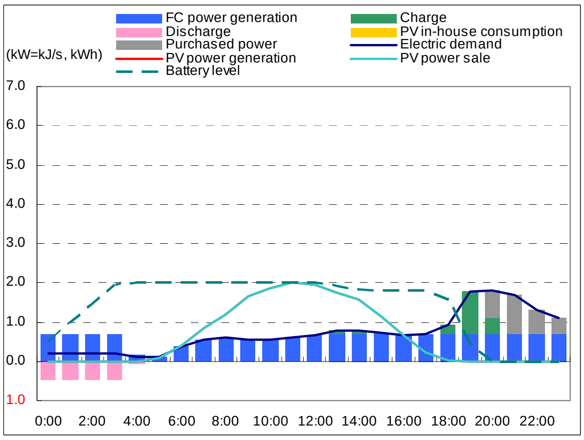


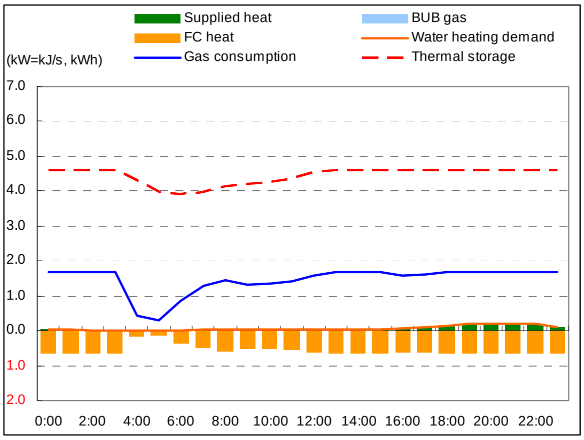
(FC=0.7kW/90L, PV=4kW, battery=2kWh)

Fig. A-2 Simulation Results (January)

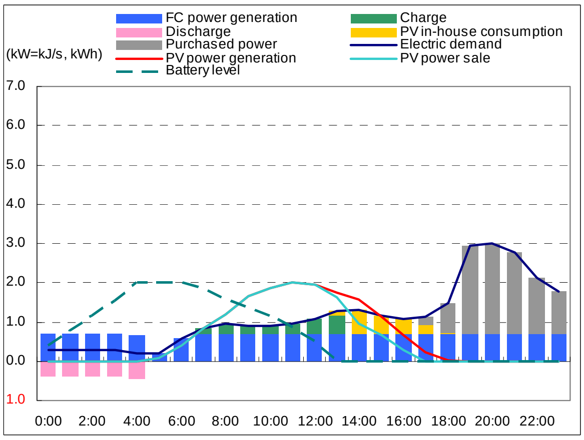
- August

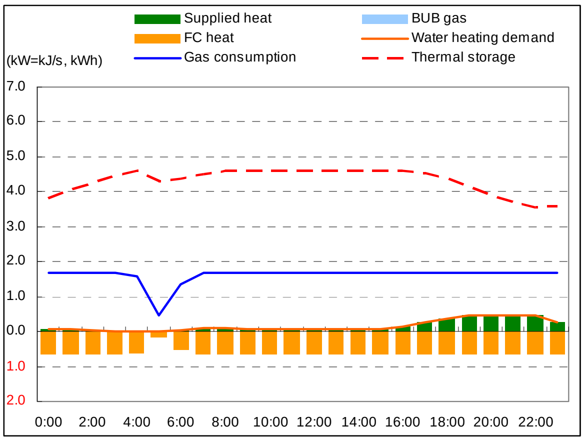
<Single-person household>



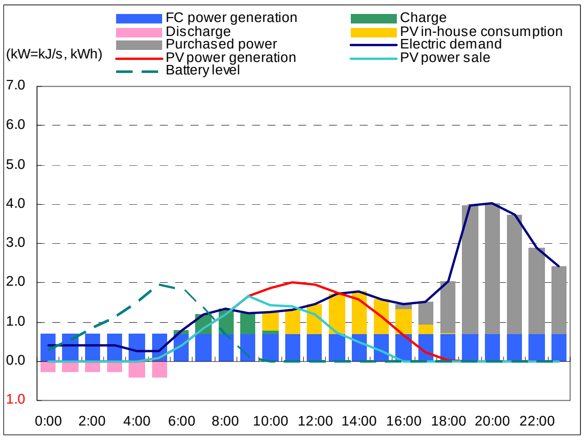


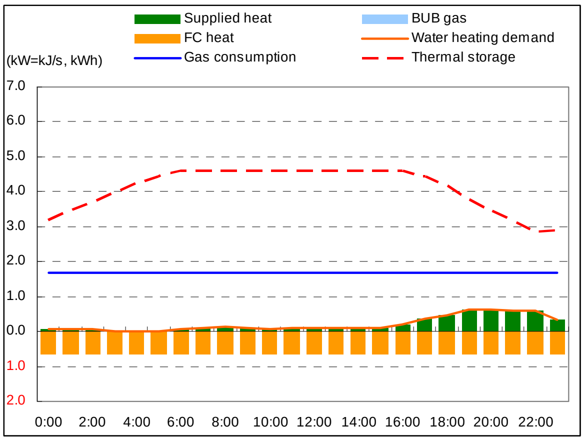
<3-person household>





<6-person or more household>





(FC=0.7kW/90L, PV=4kW, battery=2kWh)

Fig. A-3 Simulation Results (August)

Contact: report@tky.ieej.or.jp