THE EFFECTIVENES OF INTRODUCING EFFECTIVE ENERGY SAVINGS MEASURES FOR HOUSEHOLDS IN JAPAN'S RESIDENTIAL SECTOR

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ABSTRACT

A simulation model was developed for energy consumption in Japan's residential sector. This model classifies households into 912 categories by household type, building type, and house insulation level. The total energy consumption in the Japanese residential sector was evaluated along with the effect of introducing various energy saving systems, including introducing new-generation water heaters such as heat pumps, cogeneration, and other systems.
Except for photovoltaic generation, these systems are competitive. So most effective systems are selected in each household and the effect of these various systems was evaluated at a nationwide level.

INTRODUCTION

In Japan, energy consumption of the residential sector has increased steadily in response to improvements in the standard of living and increase in the number of households, particularly of single households. Compared to 1973, energy consumption per household in 2004 increased 1.5 times while the number of households has increased 1.6 times.

Consequently, energy consumption in the residential sector more than doubled in the last 30 years while the total population has increased only 1.1 times (Agency for Natural Resource and Energy, 2006).

"The New Climate Change Policy Program", adopted by the Japanese government in March 2002, sought to maintain CO_2 emissions attributed to energy usage at 1990 levels. In April 2005, the "Kyoto Protocol Target Achievement Plan" was adopted. The intention was to reduce CO_2 emissions from the residential sector to levels only 6% higher than they were in 1990, by improving the energy efficiency of buildings and appliances. To achieve this goal and reduce the CO_2 emission further, distributed power generation and highly efficient water heater systems were developed. These systems are mainly for reduction of electricity (energy) consumption of hot water, which is at a high rate in Japan's residential area.
Systems considered in our model are the micro gas engine (MGE), polymer electrolyte fuel cell (PEFC) , and solid oxide fuel cell (SOFC) cogeneration systems, as well as a condensing gas water heater that recovers latent waste heat (LHB), CO_2 heat pump water heater (CO2HP), solar thermal water heater (SOLAR), and photovoltaic generation (PV).
These systems are competitive because only one system is introduced per household. In addition, the effect of introducing these systems is that they vary greatly among household types. For these reasons, the best systems for primary energy savings, CO_2 emission reduction, and cost are selected by each household and the nationwide effect of introducing these systems are evaluated. Viewing past studies, there are studies of the effect of introducing each system only, for example, CO2HP only (Yokoyama et al, 2005) or cogeneration system only (Shimizu et al, 2007). Comparing these studies, this paper's special feature is simulating the effects of introducing each system estimated by these system's detailed operation model on each different 912 households.

SIMULATION MODEL

Structure of the simulation model

The authors developed an original bottom-up model to simulate the nationwide energy consumption in the residential sector. Figure 1 shows a simulation model flow chart. In this simulation, the annual energy consumption of one household is calculated iteratively for 19 household categories, as well as 12 building categories— six of which were classified as detached houses and the other six as apartments; each group of six was also classified by floor area. In addition, four different building insulation levels, no insulation , at the 1980 level standard ,the 1992 level standard and the 1999 level standard,were considered. (912 types is multiplication of this 19 households, 12 buildings and 4 insulation level.) In the appliance energy use model, the energy use of each appliance was simulated separately and is based on occupant behavior. For the heating and cooling model, dynamic heat load simulations were conducted using both building data and weather data. Ventilation and heat conduction between rooms was considered using a thermal circuit network method. Heating and cooling loads were simulated relative to the internal heat gain, which is calculated using the appliance energy use model and occupant behavior. The time step of the heat-load calculation and energy-use simulation was five minutes. The use of distributed power generation and highly efficient water heater system models are also based on these calculations.

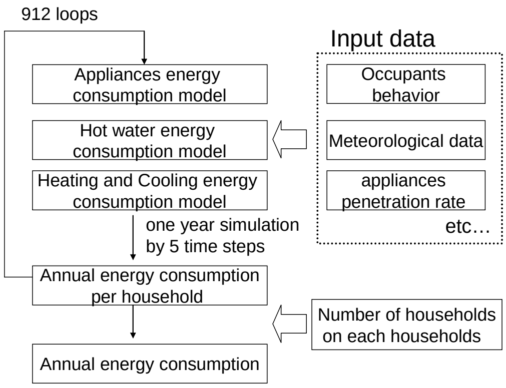

Figure 1 Simulation model flow chart

Total energy consumption in the residential sector was evaluated by acumulations of calculations of the sector, separated into 17 regions. The energy consumption for each region was estimated by multiplying the simulated energy consumption by the number of households in each category and then summing them.

The authors previously developed a *'Stock mode'l* (Shimoda Y., 2007), which is used here to estimate the average energy efficiency of appliances and the distribution of building insulation levels in each region.

Simulation results for present conditions and model verification

Figure 2 compares the simulated annual primary energy consumption and energy consumption data based on energy supply statistics for the residential sector in Japan, 2005. (Agency for Natural Resource and Energy, 2005)

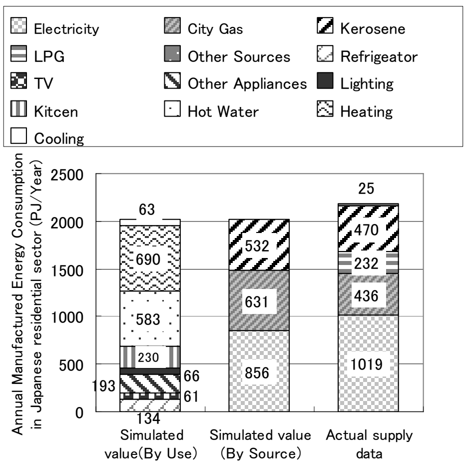

Figure 2 Simulated annual primary energy consumption and actual energy supply in Japan for 2005

Compared to the actual data, the simulation errors were 19% for electricity, 5% for gas (there is no distinction between city gas and Liquefied Petroleum Gas(LPG) in the simulation) and 13% for kerosene. The main reason for the error in estimating electricity use is because only major appliances generally used in households were considered in our model—other miscellaneous electrical appliances were not adequately considered.

DISTRIBUTED POWER GENERATIONS AND HIGHLY EFFICIENT WATER HEATER SYSTEMS

The systems evaluated are as follows:

- Micro gas engine cogeneration system (MGE)
- Polymer electrolyte fuel cell cogeneration system (PEFC)
- Solid oxide fuel cell cogeneration system (SOFC)
- Condensing gas water heater recovering latent waste heat (LHB)
- Heat pump water heater (CO2HP)
- Solar thermal water heater (SOLAR)
- Photovoltaic generation (PV)

Energy consumption of households using conventional gas water heaters

In this section, the energy saving mechanism of each system is compared to the conventional gas water heaters. The thermal efficiency of the conventional gas water heater is set at 78%, and the energy consumption was evaluated for Osaka city (2005). Our model uses 912 household types, but only 36 of them (six types of family members and six floor areas of detached houses, with the building insulation set at 1980 levels) are shown in this section. Figure 3 shows the annual primary energy consumption using conventional gas water heaters and figure 4 shows the hot water demand.

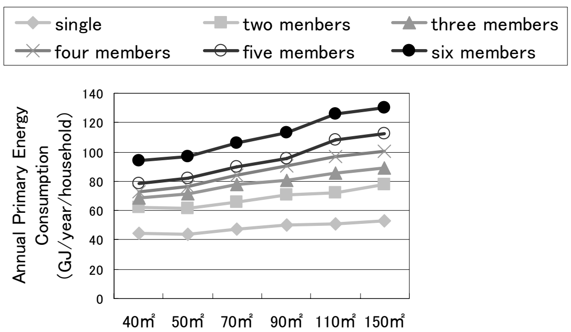

Figure 3 Annual primary energy consumption

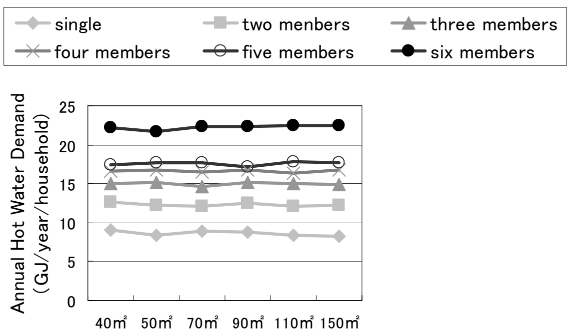

Figure 4 Annual hot water demand

As the number of family members increased and the houses became larger, the total primary energy consumption also increased. Electric demand follows the same trend. Hot water demand also increased with an increase in the number of family members; however, no relationship was found to the house size. Annual primary energy consumption was found to be 44.7~130.0 [GJ/Year/household] and hot water demand was 8.4~22.5 [GJ/Year/household].

MGE cogeneration system

MGE consists of a micro gas engine electric generation unit and a water heating unit that utilizes waste heat. MGE supplies electric power and hot water from city gas, which accumulates in the tank. If the electric power generation is greater than the electrical demand of the house, it is utilized for water heating using an electric heater system. As the part-load generation efficiency of MGE is low, the MGE is controlled at rated capacity. MGE operation depends on the hot water demand of the household, and when the demand is greater than its available supply, an auxiliary gas water heater makes up the difference. The power generation capacity is selected from 0.5〜1.5 kW, depending on the electrical and hot water demand.

Table 1 shows MGE specifications (1 kW) and figure 5 shows the annual primary energy savings from introducing MGE. The annual primary energy savings of MGE are 1.6~7.8 [GJ/Year/household].

Table 1 MGE specification (1 kW)

capacity of electiricity generation	1kW
output of waste heat	3.25kW
gas consumption	5.54kW
hot water supply capacity	42kW(MGE)
	35kW(auxiliary)

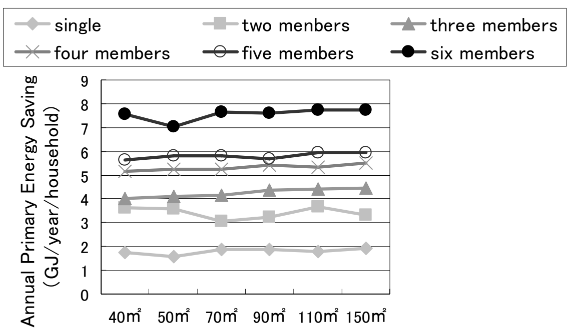

Figure 5 MGE annual primary energy savings

PEFC cogeneration system

PEFC consists of reformer, which transforms city gas into hydrogen, and a fuel cell, which generates electrical power from hydrogen. To extend the reformer lifetime, the PEFC is operated in a daily start and stop mode, and operates at four output steps, 25, 50, 75, and 100% of capacity, depending on the electrical demand. Similar to MGE, generated electricity above the electrical demand is utilized for water heating. If the heat demand is larger than the PEFC heat supply, an auxiliary gas water heater makes up the difference. The PEFC can generate 0.5~1.5 kW and optimum capacity is defined for each household category by preliminary simulation. Table 2 shows the PEFC specification and figure 6 shows the PEFC partial load characteristics. (HHV is higher heating value, gross calorific value)

Table 2 PEFC specification

capacity of electricity generation	1kW
power generation efficiency(100%)	31%(HHV)
waste gas efficiency(100%)	38%(HHV)
hot water supply capacity	42kW (FC)
	35kW (auxiliary)

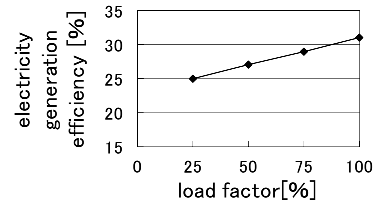

Figure 6 PEFC partial load characteristics

Figure 7 shows a one day simulation result for PEFC, and figure 8 shows the annual primary energy savings from introducing PEFC. The annual primary energy savings of PEFC are 0.1~10.4 [GJ/Year/household].

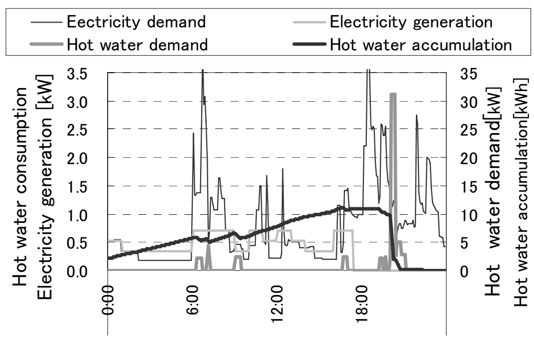

Figure 7 PEFC one day simulation result

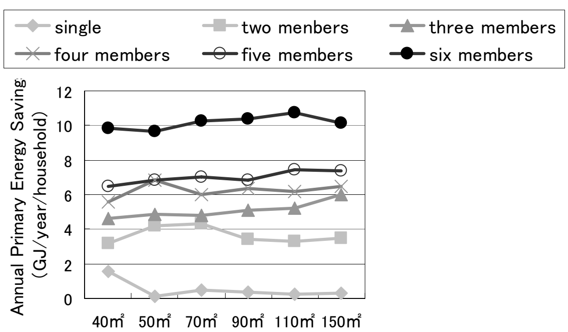

Figure 8 PEFC annual primary energy savings

SOFC cogeneration system
Similar to PEFC, SOFC consists of a reformer and fuel cell, and it supplies electric power and hot water from city gas. On the other hand, SOFC has a higher electrical generation efficiency and smaller waste heat recovery efficiency. It can operate depending strictly on the electrical demand, since waste heat recovery does not usually exceed the hot water demand Capacity of electricity generation was 0.5~1.5 kW and optimum capacity for each household category was determined by preliminary simulation. Table 3 shows the SOFC specifications, figure 9 shows the SOFC partial load characteristics, and figure 10 shows the annual primary energy savings from introducing SOFC— 4.2~16.8 [GJ/Year/household]. (LHV is lower heating value, net calorific value)

Table 3 SOFC specification

capacity of electricity generation	700W
power generation efficiency(100%)	45%(LHV)
waste gas efficiency(100%)	36%(LHV)
hot water supply capacity	42kW(FC) 35kW(auxiliary)

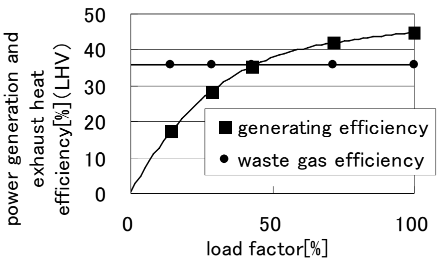

Figure 9 SOFC partial load characteristics

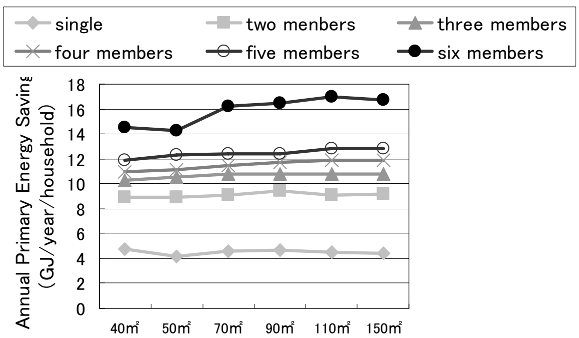

Figure 10 SOFC Annual primary energy savings

Condensing gas water heater recovering latent waste heat (LHB)
LHB has secondary heat exchanger that recovers latent heat from exhaust gas that is usually emitted into the atmosphere. Its thermal efficiency is 95% in higher heating value and considerably higher than the 78% efficiency of conventional gas water heaters. Figure 11 shows LHB annual primary energy savings—1.7~4.8 [GJ/Year/household].

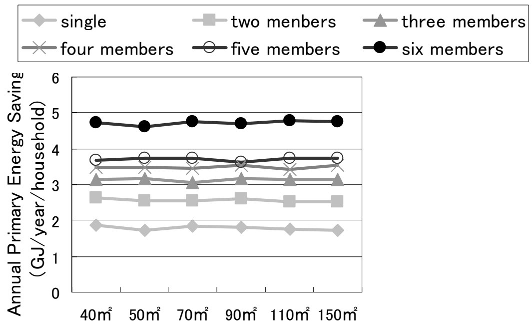

Figure11 LHB annual primary energy savings

CO2 heat pump water heater
The CO2HP heats water using electrical power. CO2HP consists of a heat pump cycle, which uses the outdoor air as the heat source and CO_2 as refrigerant. CO2HP generates and accumulates hot water in the tank at midnight, and supplies it when demanded. When the hot water accumulation falls below a certain amount, the CO2HP generates hot water, even in the daytime.
Table 4 shows the CO2HP specifications and figure 12 shows the relationships between CO2HP COP and outdoor air temperature.

Table 4 CO2HP specification

tank capacity	200～460ℓ
water temperature	90～65℃
rated capacity	3.6～4.5kW

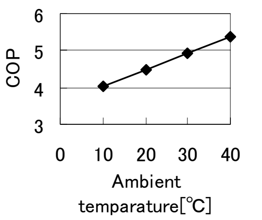

Figure 12 CO2HP COP

Figure 13 shows CO2HP the results of simulation for one day and figure 14 shows the annual primary energy savings of 3.2~10.6 [GJ/Year/household].

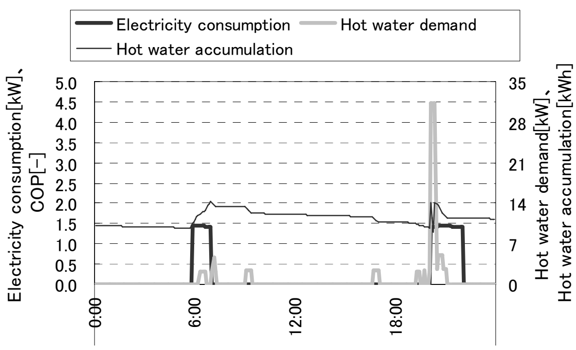

Figure 13 CO2HP one day simulation result

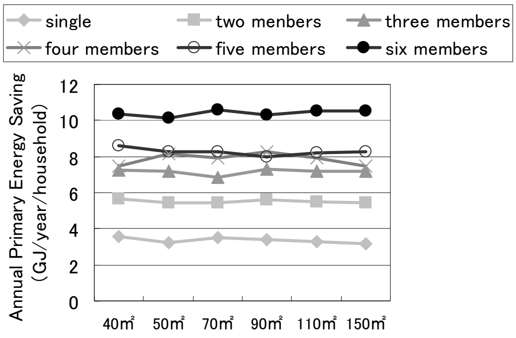

Figure 14 CO2HP annual primary energy savings

Solar thermal water heater

The SOLAR system consists of solar heat collection panels and a hot water tank. SOLAR is introduced only for detached houses and not for cold areas.

Solar panels are generally set on south-facing roofs, at an angle of 30° —they have an area of 3m^2 for all households.

Figure 15 shows SOLAR annual primary energy savings—4.9~9.1[GJ/Year/household].

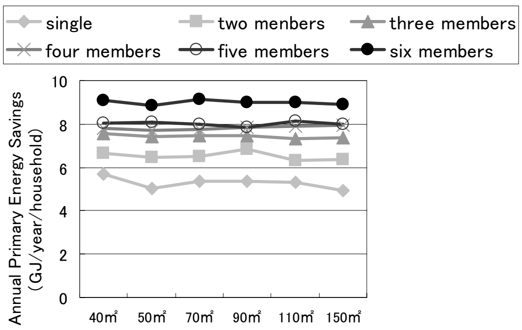

Figure 15 SOLAR annual primary energy savings

PV generation

PV system consists of solar cells and a power conditioner. PV systems are installed only for detached houses. The electrical power generated is calculated based on meteorological data every 5 minutes. If excess electrical power is generated, it is sold to the grid power system.

Table 5 shows the PV generating capacity for each floor area, estimated by the relationships between total floor area and roof area. Figure 16 shows PV annual primary energy savings (does not depend on the number of family members). PV primary energy savings are 9.1~27.2 [GJ/Year/household].

Table 5 PV generating capacity

unit:[kW]

～40㎡	1.0
40～60㎡	1.5
60～80㎡	2.0
80～100㎡	2.5
100～120㎡	3.0
120㎡～	3.0

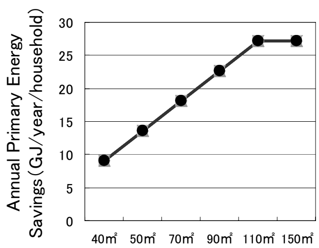

Figure 16 PV annual primary energy savings

COMPARING THE EFFECTS OF INTRODUCING EACH SYSTEM

In this section, the effect of introducing these systems, primary energy savings, CO_2 emission reduction and cost, are compared and the best system are selected in each 912 households.

Comparison of primary energy savings

Figure 17 compares the energy savings of a detached house for each system in case of a single woman household (left) and one with six family members—grand parents, parents, and two children (right). Except for PV, the effect of introducing each system depends on the number of family members and not on floor area. (PV has the opposite trend) In terms of primary energy savings, PV is the best system, but SOFC is better for several households where there are many family members and a small floor area.

The PV energy savings are 10~28 [GJ/Year/house-holds]; the energy savings of the other systems for a single household are 0~6 [GJ/Year/households], and differences among the systems are small. However, for six family members, these energy savings effects are 5~16 [GJ/Year/households]. The energy savings of MGE, PEFC, SOFC, and CO2HP vary greatly, depending on the number of family members, mainly for hot water demand. However, there is a small difference between LHB and SOLAR energy savings.

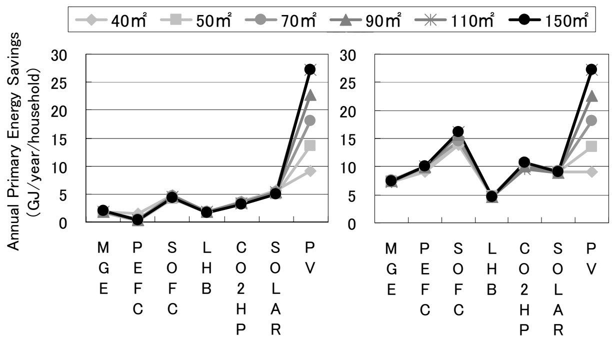

Figure 17 The comparison of primary energy saving effects (left: single, right: six family members)

Table 6 shows the 19 categories of family sizes and figure 18 shows the best system for primary energy savings for 228 households, with thermal insulation level only at the 1980 standard level. (Thermal insulation level makes little difference for the selection of the best system.)

PV is the best system for primary energy savings in case of a detached house and SOFC is found to be the best for apartment houses. The effects of introducing PV and SOFC systems are more significant for energy saving than the other systems.

Comparison of CO_2 emission reduction

Figure 19 shows the best system for CO_2 emission reduction. The CO_2 emission rate is set at 0.358 [kg-CO_2/kWh] for electricity, 52.5 [kg-CO_2/kJ] for city gas, and 67.9 [kg-CO_2/kJ] for kerosene. Because of the small rate of CO_2 emission for electrical power, CO2HP is the best system in terms of CO_2 emission reduction for all apartment and small-detached households.

Table 6 19 family member's type abbreviation

1-a	single man
1-b	single woman
1-c	single aged man
1-d	single aged woman
2-a	working couple
2-b	couple
2-c	aged couple
2-d	working mother and child
2-e	mother and child
3-a	working parents and child
3-b	parents and child
3-c	working mother and two children
3-d	mother and two children
4-a	working parents and two children
4-b	parents and two children
5-a	working parents and three children
5-b	parents and three children
6-a	grand parents,working parents and two children
6-b	grand parents, parents and two children

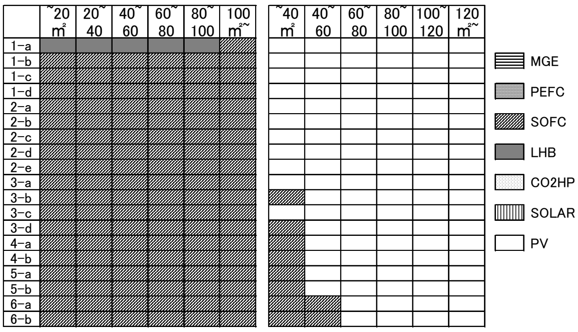

Figure 18 System comparisons for primary energy savings

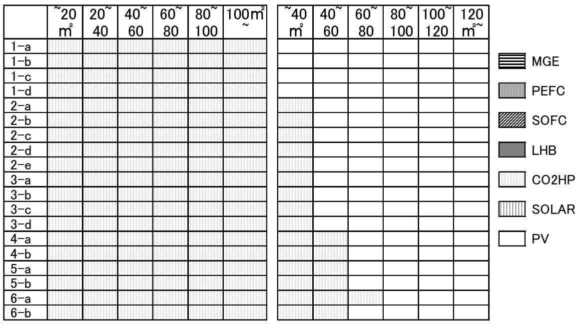

Figure 19 System comparisons for CO_2 emission reduction

Cost comparison

Table 7 shows each system's initial cost. PEFC is not been commercialized as yet, but in this paper we assumed a PEFC initial cost; SOFC, which is under investigation, is omitted in this evaluation. Each system's cost is defined 10 year deficit on each household, calculated by taking the savings from operating costs over 10 years (ten times of one year savings) into account.

Operating cost includes electricity fee, gas fee and kerosene cost that are saved from cutting energy consumption. And these fees are based on each region fee structure

Table 7 initial cost

MGE	800,000 [¥]
PEFC	1,000,000 [¥]
LHB	350,000 [¥]
CO2HP	700,000 [¥]
SOLAR	250,000 [¥]
PV	700,000 [¥/kW]

Figure 20 shows the best system in terms of cost. The best system is LHB for apartment households and SOLAR for detached houses. Over the 10 year span, except for SOLAR, energy cost savings did not exceed the initial cost; thus, the best system in terms of cost is the system with the lowest initial cost.

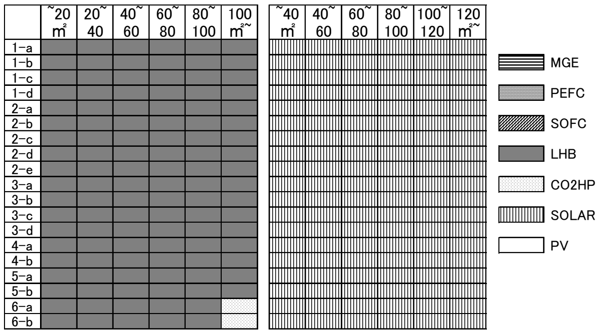

Figure 20 Comparing systems based on cost

NATIONAL EFFECT OF INTRODUCING THE BEST SYSTEMS

Our model separated Japan into 17 areas from north to south and calculated energy consumption based on meteorological data, number of households, appliance penetration rate, and so on.

This section selects the best systems for households in each area and shows the nationwide effects of introducing these systems. This evaluation omits PV and SOFC because PV is very expensive and SOFC is still being investigated. Table 8 shows the generating efficiency of electricity for calculating the primary energy consumption and CO_2 emission rate in each area. The CO_2 emission rate for kerosene is 67.9 [kg-CO_2/kJ] in all areas.

Table 8 Setting figure for each area

area No	representative city	generating efficiency	CO2 emission rate	
			electricity [kg-CO_2/kWh]	gas [kg-CO_2/kJ]
1	Asahikawa	0.376	139.4	55.7
2	Sapporo	0.376	139.4	55.7
3	Morioka	0.385	141.7	55.7
4	Sendai	0.385	141.7	55.7
5	Utunomiya	0.406	102.2	53.4
6	Nigata	0.385	141.7	52.9
7	Otu	0.376	108.8	52.8
8	Nagano	0.397	125.6	53.4
9	Urawa	0.406	102.2	53.4
10	Tokyo	0.405	103.8	53.5
11	Nagoya	0.397	125.6	54.3
12	Kyoto	0.384	99.4	52.5
13	Osaka	0.384	99.4	52.5
14	Hiroshima	0.373	151.7	56.3
15	Fukuoka	0.391	112.0	55.5
16	Kagoshima	0.393	101.4	55.4
17	Okinawa	0.341	261.1	58.2

Figure 21 shows the contribution of each system, in each area from the viewpoint of primary energy savings, CO_2 emission, and cost.

The best system trend is about the same for all areas with two exceptions. One is area 1, 2, and 3, where SOLAR was not introduced, and the other is area 17. In area 17, where the generating efficiency is low and the CO_2 emission rate for electricity is high, hence the trend is for gas systems to be superior to electrical systems.

Figure 22 and Table 9 show the nationwide effects of introducing the best systems for each household type (AH: Apartment House, DH: Detached House). ENE represents the best system in terms of primary energy savings and CO2, COST indicates the best system for CO_2 emission reduction and cost, respectively. +PV indicates that PV was introduced to all detached houses, in addition to the ENE case.

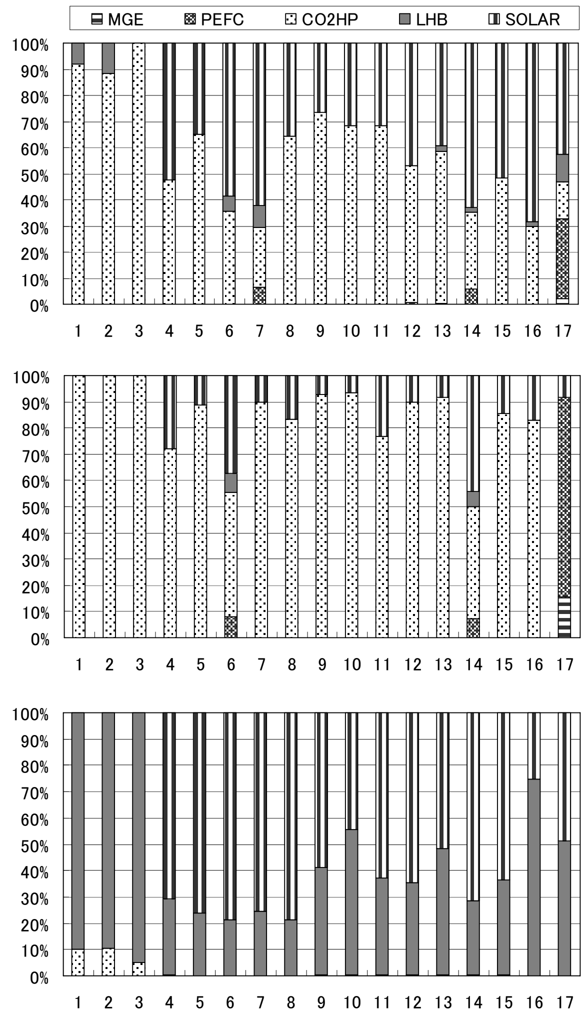

Figure 21 The best system's share in each area (upper: primary energy savings, middle: CO_2 emission reduction, lower: cost)

Table 9 The effect of introducing the best systems

	ENE (PJ/Year)	Sell-ENE(PJ/	CO2(10^5t /Year)	COST(10^{10}¥ /10Year)
Base	3349.5	0.0	1697.4	
ENE	3001.3	14.5	1479.1	1820.0
CO2	3009.3	16.5	1467.3	2506.0
COST	2956.6	0.0	1459.9	1163.1
+PV	2323.9	369.7	1003.3	4993.5

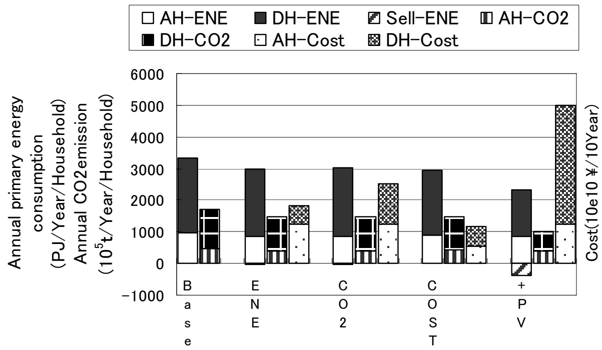

Figure 22 The effect of introducing the best systems (Left: Primary Energy Consumption, middle: CO_2 consumption, right: Cost)

Among ENE, CO2, and COST, there are slight differences in their primary energy savings and CO_2 emission. However, the cost in the CO2 case is 1.3~2.2 times greater than other cases because of the higher cost of CO2HP.

The percentage of savings from introducing these best systems is about 11% for primary energy, 12% for CO_2 emission, and for + PV, 42% for primary energy and 41% for CO_2 emission. Considering +PV case cost increases about 2.7 times from the ENE case, cost by introducing PV is the highest, but the primary energy saving in introducing PV is the highest— 30 % energy savings of total energy consumption.

CONCLUSION

Introducing PV and SOFC systems can provide significant energy savings. In particular, the primary energy savings on PV is high, about 30% energy savings of the total energy consumption. However, PV is expensive and the economic burden is great for households. The key to great energy savings and CO_2 emission reduction is spreading PV over many households. SOFC is still under investigation; however, it is expected to be commercialized in the near future. The effect of introducing CO2HP on CO_2 emission reduction is significant, because of the small CO_2 emission rate of electricity. The best systems in terms of cost are SOLAR and LHB. Over a 10 year span, except for SOLAR, savings from energy costs did not exceed the initial cost and the best system in terms of cost is the one with the lowest initial cost.

There are small differences about the best system among the 17 areas. However, in area 1, 2 and 3(cold area), SOLAR was not introduced, and in 17, gas systems are superior to the electric system because of the high electrical CO_2 emission rate.

Among three cases, ENE, CO2, and COST, there are small differences in primary energy consumption and CO_2 emission—about 11 % primary energy savings and 12% CO_2 emission reduction result from the baseline. Cost for the COST case is the least, the cost for ENE is 1.6 times that of the COST case, while the cost for the CO2 case is 2.2 times that of the COST case. For the + PV case, the primary energy savings rate is 42% and the CO_2 emission reduction rate is 41%—about 3.7 times that of the ENE case. +PV case cost 2.7 times the ENE case.

When introducing only these two systems, the best system and PV—it cuts about 40% of the total energy consumption and CO_2 emissions. It is revealed that the effect of introducing distributed power generations and highly efficient water heaters systems in Japan's residential sector are great. In addition, these effects are widely different depending on households so these energy savings effect in residential sector depends on which system is introduced into which household. Therefore, development of institutions, which lead each household to introduce most appropriate system, is extremely important.

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