EVALUATION OF THE IMPACT OF NEW RESIDENTIAL WATER HEATER DISSEMINATION BY A RESIDENTIAL ENERGY END-USE MODEL

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ABSTRACT

The purpose of the present paper is to evaluate the potential of CO_2 emission reductions and mitigation costs when installing various types of high-efficiency hot water supply systems on a prefectural scale. The residential energy end-use model, which is a bottom-up type simulation model developed by our research group, calculates the hot water and electricity demands at five-minute intervals and evaluates the energy consumption for each hot water supply system in detail for various household categories. In addition, the impact of the amount of hot water use on the CO_2 emission reduction effect is evaluated.

INTRODUCTION

The energy consumption of domestic water heaters accounts for approximately one-third of total residential energy consumption in Japan. In recent years, various types of high-efficiency hot water supply systems, such as heat pump water heaters, condensing gas water heaters, gas engine cogeneration systems, solid oxide fuel cell (SOFC) cogeneration systems, and polymer electrolyte fuel cell (PEFC) cogeneration systems, are becoming more widespread.

Increased use of these systems is anticipated, but since only one system is installed in a household the systems are in competition with each other. In addition, the energy reduction effect of each system is influenced by the hot water and electricity use profile of the family, which is affected by the number and behavior of the family members, as well as other factors. Therefore, the effects of installing each system in various households that have different energy demand profiles should be quantified. This would enable the optimum water heater to be selected based on the CO_2 emission reduction effect or the mitigation cost. The potential CO_2 emission reduction and mitigation costs obtained by installing an optimum system on a city or prefectural scale should be evaluated from the viewpoint of policy making.

Our research group developed the residential energy end-use model in order to carry out such an evaluation. The developed model is a bottom-up type simulation model that estimates city or prefectural scale energy consumption in the residential sector. The energy consumption of households differs depending on family composition, climate conditions, building type, number and energy efficiency of the appliances, as well as other factors. In order to consider these various factors, the developed model prepares different household categories classified according to family composition, building type, and floor area, and it simulates the energy consumption of each household category. Based on the occupant behavior schedules, the model simulates the hot water and electricity demands of the household at five-minute intervals.

These two features make it possible to simulate the realistic performance of hot water supply systems, such as heat pump water heaters and cogeneration systems. Therefore, it is possible to compare the CO_2 emission reduction and mitigation costs among different household categories and systems using this model. This leads to the selection of a CO_2-optimum or cost-optimum system for each household and to the evaluation of potential CO_2 emission reductions on the prefectural scale.

In the present paper, the effects of the installation of a hot water system in each household category are evaluated. The optimum system for each household category is selected based on the CO_2 emission reduction and the mitigation cost. The total CO_2 emission reduction in Osaka Prefecture achieved by the installation of the optimum system for each household category is estimated. In addition, the sensitivity of the CO_2 emission reduction effect to hot water use is examined.

SIMULATION MODEL

Structure of the simulation model

The authors developed the residential energy end-use model, which is an original bottom-up type simulation model to simulate city or prefectural scale energy consumption in the residential sector (Shimoda et al., 2007). Figure 1 shows a flow chart of the model. In the simulation, the diversity of family and building types is considered. The model estimates the total energy consumption of the target region in the following three steps. 1) The households in the target region are classified into 228 categories (19 categories of family members [shown in Table1] and 12 building categories, including six categories for detached houses and six categories for apartment houses are decided based on floor area) based on the National Population Census (National Statistics Bureau, 2010).

In addition, four levels of building insulation (Ministry of Economy, Trade and Industry 2013) are considered, and a total of 912 categories are prepared. 2) Representative households are determined for the 912 categories. The energy consumption of the representative households is iteratively simulated. 3) The total residential energy consumption in the target region is estimated by multiplying the simulated energy consumption of the representative households by the number of households in each category and summing the multiplication products. The number of households in each category is obtained in the first step.

The model consists of three parts: the database, the data preparation model, and the energy-use model. The database includes census data and other statistics that are loaded into the energy-use model. The database also includes the data estimated in the data preparation model. The data preparation model consists of the following components: the occupant behavior schedule model, the stock model, the hot water demand model, and the household category model. The occupant behavior schedule model (Yamaguchi et al., 2014) and the stock model (Shimoda et al., 2007) were described previously. In the hot water demand model, we assume that heat demands for hot water occur when occupants bathe, fill a bathtub, wash their faces, cook, and wash dishes. The amount of hot water use for each behavior is set as shown in Table 2 and is estimated from the measured data for gas, water, and electricity consumption of approximately 200 households in Osaka Prefecture (Ukawa et al., 2014). In the present paper, the average amount of approximately 200 households is extrapolated to all categories. We assumed that the set temperature of hot water is 40°C. The temperature of city water is calculated based on the outdoor air temperature (Nabeshima 1998). The frequency of bathing (with or without bathtub filling) is set as shown in table 3, based on a questionnaire survey.

Energy consumption is simulated at five-minute intervals using the energy-use model based on the occupant behavior schedule, which is generated by the occupant behavior schedule model. The hot water demand model simulates the heat demand for hot water based on the occupant behavior. This model is linked with the hot water energy use model and the heat demand is converted to energy consumption. The hot water energy use model has sub-models for each hot water supply system, such as a heat pump water heater, a condensing gas water heater, and a cogeneration system. The sub-models simulate the energy consumption of these systems based on the hot water and electricity demand profile. As mentioned above, linking these models enables accurate estimation of energy consumption, and detailed analysis such as the sensitivity of the hot water demand profile to energy use.

The target area of the present study is Osaka Prefecture (population: 8.87 million; number of

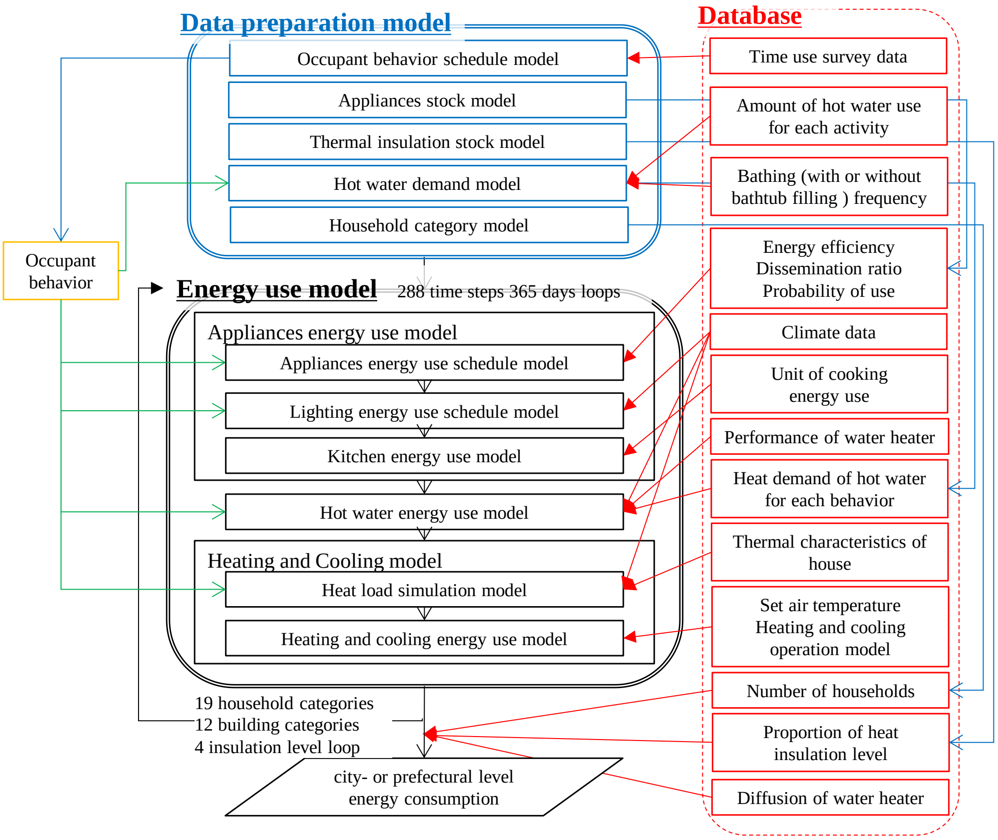


Figure 1 Structure of the simulation model

households: 3.81 million), and the target year is 2012. In the baseline, all of the households of Osaka Prefecture are assumed to have conventional instant gas (CIG) water heaters, conventional instant oil (CIO) water heaters, or electric resistance (ER) water heaters combined with storage tanks.

CIG water heaters and CIO water heaters are tank-less water heaters and use hot water energy at the same time that heat demand for hot water occurs. In the hot water demand model, the heat demand for hot water is calculated at five-minute intervals. That does not influence the estimation of the hot water energy use, because the efficiency of tank-less water heaters varies very little with partial load ratio. The heat loss from house supply pipes is assumed to be 7%.

Electric resistance generates hot water to be stored in tanks during the hours from midnight to early morning, during which time the electricity rate is the lowest. Using the heat demand for hot water at five-minute intervals, the total heat demand for the day is calculated considering the heat loss from storage tanks (16%) and house supply pipes (7%). Then, the number of hours of operation needed in order to generate the total heat demand is calculated. The hot water corresponding to the rated heating capacity (4,500 W) is generated during the hours of operation.

The efficiency of the CIG water heater is set to be 78% for higher heating values (HHV), that of the CIO water heater is set to be 80%, and that of the ER water heater is set to be 90%. Figure 2 shows the baseline diffusion ratio of water heaters, which is estimated from the share of the energy sources for hot water demand calculated based on the efficiency of water heaters and the energy consumption for each energy source estimated from Japanese Family Income and Expenditure Survey (Ministry of Internal Affairs and Communications, 2010).

Table 1 Family member category abbreviations

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 a child
2-e	Mother and a child
3-a	Working parents and a child
3-b	Parents and a 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
6-b	Grand parents, parents and two children

Table 2 Quantity of hot water use for each behavior and season

[ℓ/min]	Dec.-Mar.	June-Sep.	Other
Bathing	3.25	3.83	3.54
Bathtub Filling	9.43	9.22	9.52
Face Washing	2.17	2.68	2.29
Cooking and Dish Washing	1.85	2.12	1.97

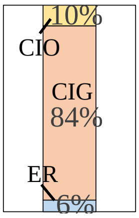


Figure 2 Baseline diffusion of water heaters

Table 3 Frequency of bathing (with or without bathtub filling) for each member and season

[number of times /week]	Bathing(with bathtub filling)			Bathing(without bathtub filling)		
	Dec.-Mar.	June-Sep.	Other	Dec.-Mar.	June-Sep.	Other
One members	4.50	3.82	4.31	1.93	4.64	2.59
Two members	5.21	4.91	5.05	1.32	3.69	1.67
Three members	5.86	5.28	5.59	1.11	3.37	1.67
Fore members	6.08	5.46	5.81	1.32	3.68	1.88
Five members	5.86	5.31	5.53	0.73	3.36	1.19
Six members	6.05	5.98	5.52	1.33	4.19	1.86

Validation of simulated residential energy consumption in Osaka Prefecture

In order to verify the accuracy of the model, the simulated total end-use residential energy in 2012 in Osaka Prefecture is compared with the estimated energy consumption from two sources: the Energy Balance Statistics Table (Agency for Natural Resource and Energy, 2013), which is generated annually based on national statistics related to energy supply and demand, and the Osaka Statistics Year Book (Osaka Prefectural Government, 2013), which shows the electricity and gas consumption for residential sector in Osaka Prefecture based on supply data from electric and gas utilities.

Figure 3 compares the simulated annual end-use energy and the energy supply statistics for the Osaka Prefecture residential sector in 2012. The simulated total end-use energy is close to the statistics. However, the simulated electricity consumption obtained using the developed model is lower than the statistics by 13% or 16%, and the simulated gas consumption is higher than the statistics by 7% or 9%.

Figure 4 shows the simulated monthly gas consumption and the gas supply statistics (Osaka Prefectural Government, 2013). On the whole, the seasonal variation is close to the statistics, but our simulation results are higher than the statistics. One possible reason for these differences is that dissemination of high-efficiency hot water supply systems, such as heat pump water heaters and condensing gas water heaters, has not be considered in the baseline. Another reason is that our assumption of the share of gas heaters used for heating may be higher than the actual value.

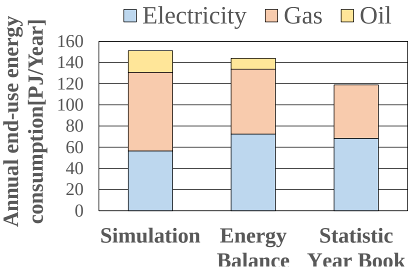


Figure 3 Annual end-use energy consumption in Osaka Prefecture

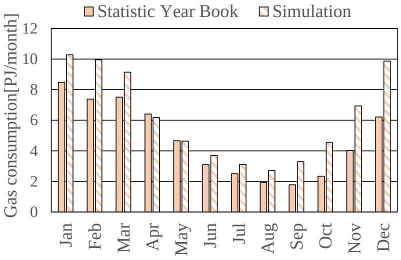


Figure 4 Monthly gas consumption in Osaka Prefecture

COMPARISON OF THE EFFECTS OF INSTALLING HIGH-EFFICIENCY HOT WATER SUPPLY SYSTEMS

In this section, CO_2 emission reductions and mitigation costs are evaluated for three cases: 1) each household installs the same type of system, 2) each household installs an optimum system for CO_2 emission reduction, and 3) each household installs an optimum system for replacement cost.

The following five systems are evaluated in the present study. The efficiencies and partial load characteristics are modeled based on manufacturer catalogs and interviews with energy companies.

Condensing gas (LHB) water heater

The LHB water heater can be simulated in the same manner as the CIG water heater by simply changing the thermal efficiency. The thermal efficiency of the LHB water heater is 95% (HHV), which is considerably higher than the 78% efficiency of conventional gas water heaters.

Heat pump (CO_2HP) water heater

The CO_2HP water heater generates hot water and stores it in tanks during the hours from midnight to early morning, during which time the electricity rate is the lowest. The boiling-up temperature is chosen depending on the amount of heat demand for the day. When the hot water in the storage tank falls below a certain amount, the CO_2HP generates hot water again even in the daytime at a higher electricity rate.

Table 4 shows the CO_2HP specifications, and Figure 5 shows the relationship between the coefficient of performance (COP) of the heat pump and the outdoor air temperature. Figure 6 shows the simulation results for CO_2HP for one day.

Table 4 CO_2HP specifications

Tank capacity	370ℓ
Boiling-up temperature	65, 70, 75, 85℃
Rated heating capacity	4.53kW

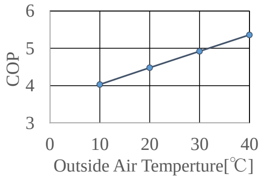


Figure 5 Relationship between COP and outside air temperature of CO_2HP

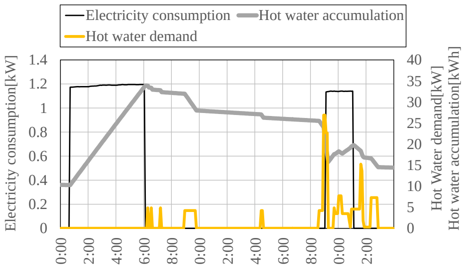


Figure 6 Example simulation of daily CO_2HP system operation

Micro gas engine (MGE) cogeneration system

The MGE cogeneration system consists of a micro gas engine electric generation unit, a water heating unit that uses waste heat, an auxiliary LHB water heater, and an electric resistance heater. The MGE supplies electric power and hot water from gas. The generated hot water is stored in a tank. The MGE operating hours are decided depending on the hot water demand of the household. When the demand is greater than the available supply, an auxiliary LHB water heater makes up the difference. Since the partial load efficiency is low, the MGE is programmed to operate at the rated capacity. If the electric power generation is greater than the electricity demand of the household, the electric power is used to heat water through an electric resistance heater. Table 5 shows the specifications of the MGE. Figure 7 shows the simulation results for the MGE for one day.

Table 5 MGE specifications

Capacity of electricity generation	1.0kW
Electricity generation efficiency	23.7% (HHV)
Waste heat recovery efficiency	59.3% (HHV)

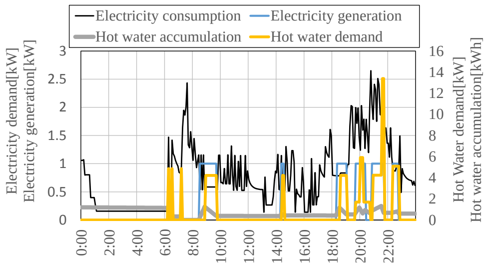


Figure 7 Example simulation of daily MGE system operation

Polymer electrolyte fuel cell (PEFC) cogeneration system

The PEFC cogeneration system consists of a reformer that transforms gas into hydrogen, a fuel cell that generates electrical power from hydrogen, an auxiliary LHB, and an electric resistance heater. The PEFC cogeneration system is operated in a daily start and stop mode, and operates at four partial load steps, 25%, 50%, 75%, and 100% of the rated power generation capacity, depending on the electricity demand. The operation schedule of the auxiliary LHB and the electric resistance heater is the same as for the MGE. Table 6 shows the specifications of the PEFC. The partial load characteristic are modeled using a cubic function. Figure 8 shows the simulation results for the PEFC for one day.

Table 6 PEFC specifications

Capacity of electricity generation	0.7kW
Electricity generation efficiency	35.2% (HHV)
Waste heat recovery efficiency	50.6% (HHV)

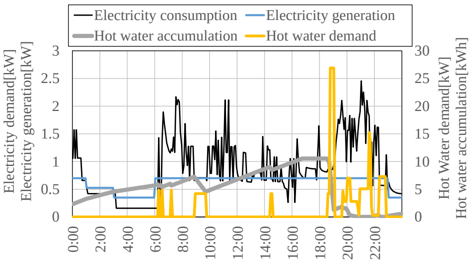


Figure 8 Example simulation of daily PEFC system operation

Solid oxide fuel cell (SOFC) cogeneration system

The SOFC cogeneration system consists of a reformer, a fuel cell, and an auxiliary LHB. The electricity generation efficiency of an SOFC cogeneration system is higher than that of a PEFC cogeneration system. On the other hand, the heat recovery efficiency of an SOFC is lower than that of a PEFC. Since the SOFC is operated depending strictly on the electricity demand, the amount of heat recovery does not usually exceed the hot water demand. Table 7 shows the SOFC specifications. The partial load characteristic are modeled using a cubic function. Figure 9 shows the simulation results for one day.

Table 7 SOFC specifications

Capacity of electricity generation	0.7kW
Electricity generation efficiency	42.0% (HHV)
Waste heat recovery efficiency	39.2% (HHV)

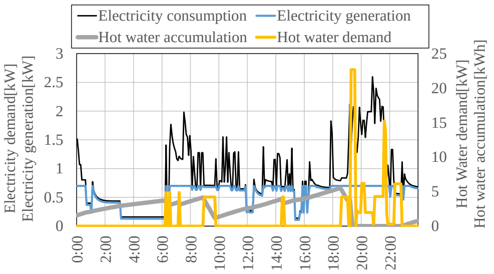


Figure 9 Example simulation of daily SOFC system operation

Evaluation indicator

The present study takes into account an indicator called the replacement cost (Rc), which refers to the total expenditure for installing high-efficiency hot water supply systems. The replacement cost is calculated as follows:

$$Rc = P_i - P_r \times 10 \qquad (1)$$

where P_i is the initial cost of water heating system (yen), P_r is the annual running cost reduction from the baseline (yen/year). The product lifetime of hot water systems is assumed to be 10 years. Electricity, gas and oil rates, which are required for calculating utility costs, are based on the rates of energy supply companies of Osaka.

Table 8 shows the initial cost of each system used in the present study. These costs are set based on manufacturer catalogs.

The CO_2 emission factor is set to be 0.516 kg-CO_2/kWh for electricity, 50.9 kg-CO_2/kJ for gas, and 67.8 kg-CO_2/kJ for oil.

Table 8 Initial cost

LHB	360,000 yen
CO_2HP	800,000 yen
MGE	820,000 yen
PEFC	1,830,000 yen
SOFC	2,180,000 yen

Case in which the same system was installed for every household categories

In this subsection, the case in which the same system is installed for every household category is evaluated. For the baseline, a conventional water heater, i.e., a CIG, CIO, or ER water heater, is installed in every household. In this case, these heaters are replaced by a high-efficient hot water supply system, i.e., an LHB, CO_2HP, MGE, PEFC, or SOFC system.

Figure 10 shows the relationship between Rc and the annual CO_2 emission reduction in Osaka Prefecture. The colors of the plots represent the type of conventional water heater before the replacement. The plot types indicate the number of household members, and the plots indicate the value in the situation that all households of the category installed the system. The plots are in ascending order of marginal abatement cost of CO_2.

When all households install an LHB in Osaka Prefecture, Rc is 953 billion yen and the CO_2 emission reduction is 1,199 thousand t-CO_2/year. On the other hand, when all households install the SOFC, Rc is 6,699 billion yen and the CO_2 emission reduction becomes 2,582 thousand t-CO_2/year. If 1,000 billion yen (= 8.3 billion US$) is invested, the annual CO_2 emission reduction effect of MGE is the largest among the systems, followed, in order, by PEFC, CO_2HP, LHB, and SOFC. By investing 4,000 billion yen, the annual CO_2 emission reduction effect of the PEFC is the largest among the systems, followed, in order, by SOFC, MGE, CO_2HP, and LHB.

The figure indicates that it is better to replace an ER water heater with a high-efficiency hot water supply system prior to replacing other conventional systems. Moreover, it is better to replace the systems owned by large families prior to replacing the systems owned by small families.

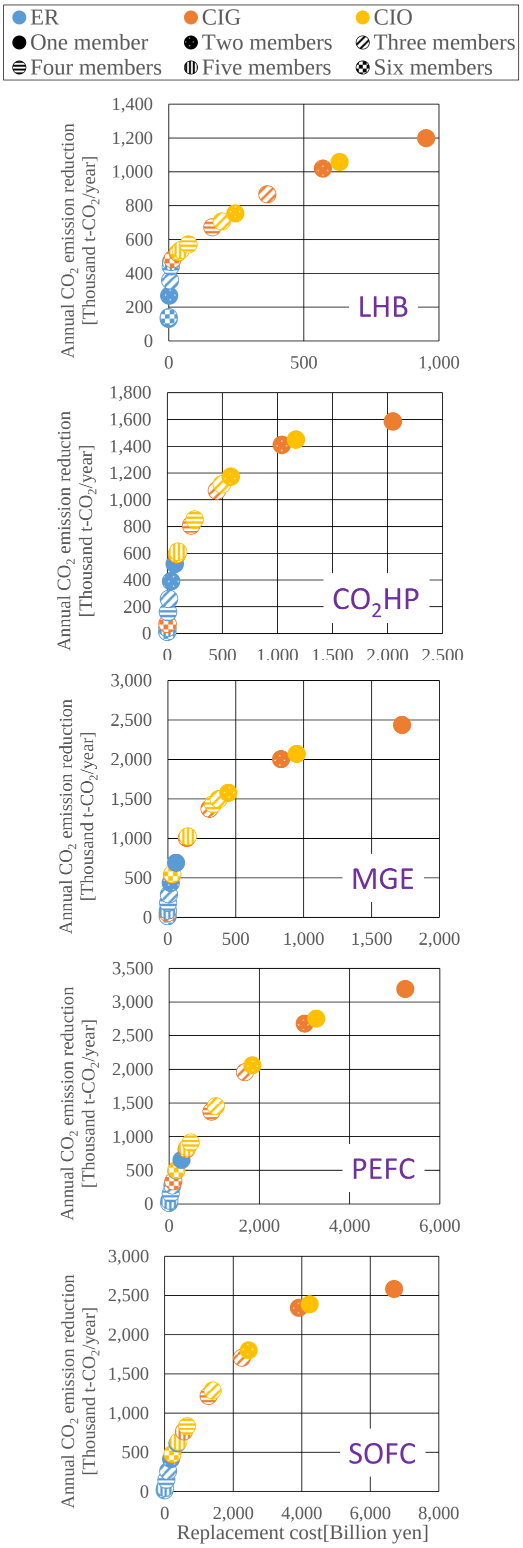


Figure 10 Relationship between Rc and annual CO_2 emission reduction in Osaka Prefecture

Selection of an optimum system for each household category

Figure 11 shows the optimum CO_2 emission reduction system, and Figure 12 shows the optimum replacement cost system for each household category with the standard thermal insulation level for 1999 (Ministry of Economy, Trade and Industry 2013). Since the thermal insulation level only slightly affects the selection of the optimum system, here we address only family compositions and building types.

In the case of installing an optimum CO_2 emission reduction system, the PEFC is selected for most household categories. In the case of installing an optimum Rc system, the LHB is selected for most household categories involving small families. On the other hand, the MGE is selected for most household categories involving large families, because the initial cost of the MGE is comparatively low and the CO_2 emission reduction effect of the MGE is greater than that of the LHB.

▩ MGE ░ PEFC ▥ SOFC ▤ LHB ▧ CO2HP

	Total Floor Area[m^2]											
Household category*	Apartment						Detached house					
	0-20	20-40	40-60	60-80	80-100	100-150	0-40	40-60	60-80	80-100	100-120	120-150
1-a	▩	░	░	░	░	░	░	░	░	░	░	░
1-b	░	░	░	░	░	░	░	░	░	░	░	░
1-c	▩	░	░	░	░	░	░	░	░	░	░	░
1-d	░	░	░	░	░	▥	░	░	░	░	░	░
2-a	░	░	░	░	░	░	░	░	░	░	░	░
2-b	░	░	░	░	▥	░	░	░	░	▥	▥	▥
2-c	░	░	░	▥	░	░	░	░	▥	░	▥	▥
2-d	░	░	░	░	░	░	░	░	░	░	░	░
2-e	░	░	░	░	▥	░	░	░	░	░	▥	░
3-a	░	░	░	░	░	░	░	░	░	░	░	░
3-b	░	░	░	░	░	░	░	░	░	░	░	░
3-c	░	░	░	░	░	░	░	░	░	░	░	░
3-d	░	░	░	░	░	░	░	░	░	░	░	░
4-a	░	░	░	░	░	░	░	░	░	░	░	░
4-b	░	░	░	░	▥	░	░	░	░	░	░	░
5-a	░	░	░	░	░	░	░	░	░	░	░	░
5-b	░	░	░	░	░	░	░	░	░	░	▥	░
6-a	░	░	░	░	░	░	░	░	░	░	░	░
6-b	░	░	░	░	░	░	░	░	░	░	░	░

*The abbreviations of Household categories are shown in Table1.

Figure 11 Optimum CO_2 emission reduction system for each household category

	Total Floor Area[m^2]											
Household category*	Apartment						Detached house					
	0-20	20-40	40-60	60-80	80-100	100-150	0-40	40-60	60-80	80-100	100-120	120-150
1-a	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
1-b	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
1-c	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
1-d	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
2-a	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
2-b	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
2-c	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
2-d	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
2-e	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
3-a	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
3-b	▤	▤	▤	▤	▩	▤	▤	▤	▤	▤	▩	▤
3-c	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
3-d	▤	▤	▤	▤	▩	▤	▤	▤	▤	▤	▩	▤
4-a	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
4-b	▤	▤	▩	▤	▩	▩	▤	▤	▩	▤	▩	▩
5-a	▤	▤	▤	▤	▤	▩	▤	▤	▤	▤	▤	▩
5-b	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
6-a	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
6-b	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩

*The abbreviations of Household categories are shown in Table1.

Figure 12 Optimum Rc system for each household category

Comparison of each case

Figure 13 shows the relationship between the replacement cost and the annual CO_2 emission reduction for the case in which each household in Osaka Prefecture installed the selected system. In the case of the installation of an optimum CO_2 emission reduction system, Rc is 5,235 billion yen and the CO_2 emission reduction is 3,219 thousand t-CO_2/year, which is 24% of the total residential CO_2 emissions of the baseline. On the other hand, in the case of installing an optimum Rc system, Rc becomes 905 billion yen and CO_2 emission reduction become 1,508 thousand t-CO_2/year, which is 11% of the total residential CO_2 emissions of the baseline.

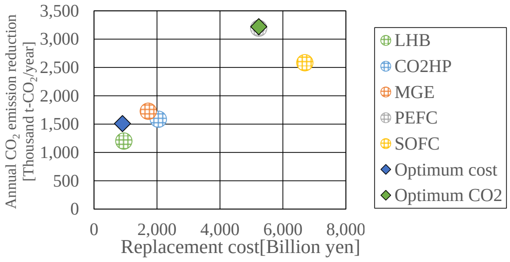


Figure 13 Relationship between Rc and annual CO_2 emission reduction for each case

SENSITIVITY ANALYSIS OF HOT WATER USE

In this section, the sensitivity of the selection results for an optimum CO_2 emission reduction system to the amount of hot water use in a household is analyzed. The impact on CO_2 emission reduction in Osaka Prefecture is evaluated.

Setting the amount of hot water use

In the baseline, the amount of hot water used for each behavior (as shown in Table 1) is set based on the average measured demand of approximately 200 households in Osaka Prefecture (Ukawa et al., 2014). In this subsection, two demand profiles, low demand and high demand, are assumed in order to consider the diversity of hot water use.

Figure 14 shows the cumulative frequency distribution for the estimated amount of hot water use related to each behavior based on the measured demand of approximately 200 households in Osaka Prefecture (Ukawa et al., 2014). In this cumulative frequency distribution, the low demand is considered to be the average amount of hot water use in the 33% lowest-use households, and the high demand is considered to be the average amount of hot water use in the 33% highest-use households.

Table 9 shows the quantity of hot water needed for each demand and the difference in the hot water amount from the average demand in winter. Face washing shows the largest difference from the average demand, and the difference is approximately 40% for both demands.

Table 9 Results for each demand profile

Quantity of hot water for each use (Difference of the hot water amount from "Average demand")			
[ℓ/min]	Low Demand	Average Demand	High Demand
Bathing	2.42 (-26%)	3.25	4.17 (28%)
Bathtub Filling	8.65 (-8%)	9.43	10.12 (7%)
Face Washing	1.4 (-35%)	2.17	3.08 (42%)
Cooking and Dish Washing	1.36 (-26%)	1.85	2.39 (29%)

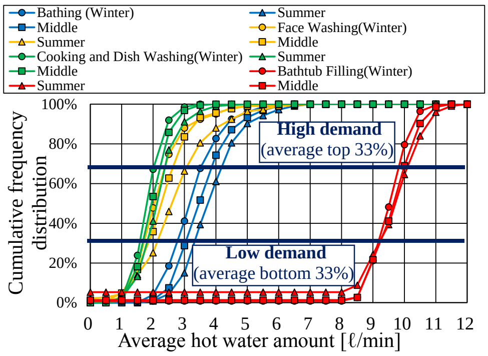
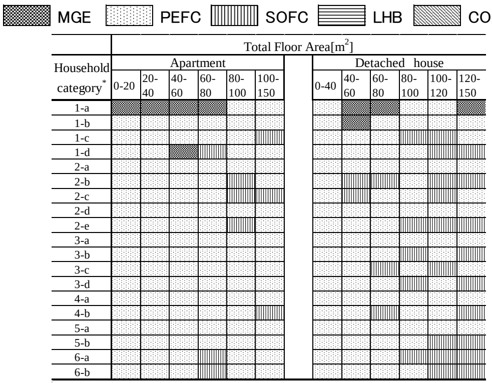


Figure 14 Cumulative frequency distribution of hot water amount

Impact of selection of an optimum CO_2 emission reduction system

Figure 15 shows the optimum CO_2 emission reduction system for each household category in the case of low demand, and Figure 16 shows that in the case of high demand. In the case of low demand, the number of household categories that select SOFC increases. On the other hand, in the case of high demand, the number of household categories that select PEFC increases. This tendency is considered to be due to the operation of each system. While a PEFC is operated depending on the hot water demand, a SOFC is operated depending on the electricity demand. Therefore, when the amount of hot water use decreased, the partial load factor, operation hours, and the overall efficiency of PEFC decrease, and the relative advantage of SOFC improved.

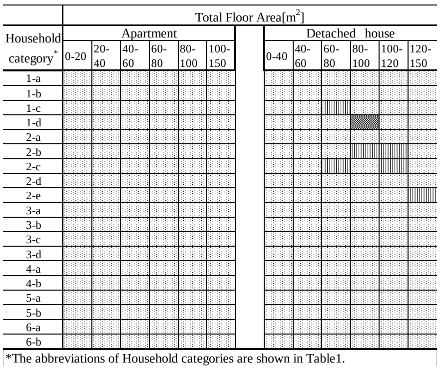


▩ MGE ░ PEFC ▥ SOFC ▤ LHB ▨ CO2HP

	Total Floor Area[m^2]											
Household category*	Apartment						Detached house					
	0-20	20-40	40-60	60-80	80-100	100-150	0-40	40-60	60-80	80-100	100-120	120-150
1-a	▩	▩	▩	▩	░	░	░	▩	▩	░	░	▩
1-b	░	░	░	░	░	░	░	▩	░	░	░	░
1-c	░	░	░	░	░	▥	░	░	░	▥	▥	░
1-d	░	░	▩	▥	░	░	░	░	░	░	▥	▥
2-a	░	░	░	░	░	░	░	░	░	░	░	░
2-b	░	░	░	░	▥	░	░	▥	▥	░	▥	▥
2-c	░	░	░	░	▥	▥	░	▥	░	░	▥	░
2-d	░	░	░	░	░	░	░	░	░	░	░	░
2-e	░	░	░	░	▥	░	░	░	░	▥	▥	▥
3-a	░	░	░	░	░	░	░	░	░	░	░	░
3-b	░	░	░	░	░	░	░	░	░	▥	░	▥
3-c	░	░	░	░	░	░	░	░	▥	░	▥	░
3-d	░	░	░	░	░	░	░	░	░	▥	░	▥
4-a	░	░	░	░	░	░	░	░	░	░	░	░
4-b	░	░	░	░	░	▥	░	░	▥	░	░	▥
5-a	░	░	░	░	░	░	░	░	░	░	░	░
5-b	░	░	░	░	░	░	░	░	░	░	▥	▥
6-a	░	░	░	▥	░	░	░	░	░	▥	▥	▥
6-b	░	░	░	▥	░	░	░	░	░	░	▥	▥

*The abbreviations of Household categories are shown in Table1.

Figure 15 Optimum CO_2 emission reduction system for each household category (low demand)



Household category*	Apartment 0-20	20-40	40-60	60-80	80-100	100-150	Detached house 0-40	40-60	60-80	80-100	100-120	120-150
1-a	░	░	░	░	░	░	░	░	░	░	░	░
1-b	░	░	░	░	░	░	░	░	░	░	░	░
1-c	░	░	░	░	░	░	░	░	▥	░	░	░
1-d	░	░	░	░	░	░	░	░	░	▩	░	░
2-a	░	░	░	░	░	░	░	░	░	░	░	░
2-b	░	░	░	░	░	░	░	░	░	▥	▥	░
2-c	░	░	░	░	░	░	░	░	▥	░	▥	░
2-d	░	░	░	░	░	░	░	░	░	░	░	░
2-e	░	░	░	░	░	░	░	░	░	░	░	▥
3-a	░	░	░	░	░	░	░	░	░	░	░	░
3-b	░	░	░	░	░	░	░	░	░	░	░	░
3-c	░	░	░	░	░	░	░	░	░	░	░	░
3-d	░	░	░	░	░	░	░	░	░	░	░	░
4-a	░	░	░	░	░	░	░	░	░	░	░	░
4-b	░	░	░	░	░	░	░	░	░	░	░	░
5-a	░	░	░	░	░	░	░	░	░	░	░	░
5-b	░	░	░	░	░	░	░	░	░	░	░	░
6-a	░	░	░	░	░	░	░	░	░	░	░	░
6-b	░	░	░	░	░	░	░	░	░	░	░	░

Total Floor Area[m^2]

*The abbreviations of Household categories are shown in Table1.

Figure 16 Optimum CO_2 emission reduction system for each household category (high demand)

Impact on CO_2 emission in Osaka Prefecture

Figure 17 shows the annual CO_2 emission of the baseline (for which all households installed a conventional water heater, such as a CIG, CIO, or ER.) and the case of installing an optimum CO_2 emission reduction system for each demand pattern in Osaka Prefecture. The CO_2 emissions for the baseline of low demand is 5% lower than that of the average demand, and that of high demand is 4% higher than that of average demand. The CO_2 emission reduction for high demand is approximately 26% more than that for average demand, and the CO_2 emission reduction for low demand is approximately 22% less than that for average demand.

As a result, after installing optimum CO_2 emission reduction systems, the difference in CO_2 emission between low demand and high demand becomes small.

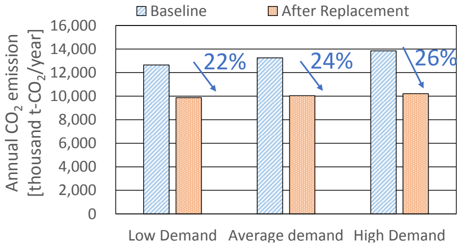


Figure 17 Annual CO_2 emission for each demand pattern

CONCLUSION

In the present paper, using the residential energy end-use model, which is a bottom-up type simulation model developed by our research group, the effects of the installation of high-efficiency hot water supply systems for each different household categories were evaluated. Furthermore, the potential of CO_2 emission reductions and mitigation costs by installing optimum systems in Osaka Prefecture was evaluated, and sensitivity of hot water use on the potential was examined.

The annual CO_2 emission reduction effect of PEFC was very high compared to the other systems, but the replacement cost was very high. On the other hand, the annual CO_2 emission reduction effect of the LHB and MGE was inferior to that of the PEFC, but the replacement cost was very low. Therefore, in the case of installing an optimum CO_2 emission reduction system, the CO_2 emission reduction was 3,219 thousand t-CO_2/year, which corresponds to 24% of the total residential CO_2 emissions in the baseline. In the case of installing an optimum replacement cost system, the CO_2 emission reduction became 1,508 thousand t-CO_2/year, which corresponds to 11% of the total residential CO_2 emissions in the baseline. Therefore, it is important to select an optimum system for each household according to the hot water and electricity profile.

In addition, the impact of the amount of hot water use for CO_2 emission reduction was evaluated. The CO_2 emission reduction for high demand was approximately 13% larger than that for average demand, and the CO_2 emission reduction for low demand was approximately 14% smaller than that for average demand.

Based on the results, selection of optimum systems and the CO_2 emission reduction potential were influenced by household categories and the amount of hot water use. Therefore, in order to contribute to policy making, it is important to be evaluated by the model which considers variety of households and hot water use.

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