Evaluation of the Greenhouse Gas Reduction Effect in the Japanese Residential Sector Considering the Characteristics of Regions and Households

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Abstract

The present study attempts to demonstrate the effectiveness of a bottom-up-type simulation model in designing or evaluating an energy/greenhouse gas (GHG) reduction policy in the residential sector. The model considers a diversity of factors such as the number of family members, the climate condition, the insulation level of the building, and the dissemination ratio and energy efficiency of appliances. The accuracy of the simulated energy consumption of the Japanese residential sector in fiscal year (FY) 2013 is verified. We estimate the GHG reduction effects for fiscal year (FY) 2030 by the most recent Japanese energy efficiency measures for the residential sector. As a result, the importance of selecting appropriate high efficiency water heaters by the policy is clarified.

Introduction

In 2015, the Japanese government announced a new target for greenhouse gases (GHG) reduction as Japan's Intended Nationally Determined Contribution (INDC) (Global Warming Prevention Headquarters, 2015). The target is a 26% GHG reduction by FY2030 from the FY2013 level. In particular, a 39% reduction is planned for the residential sector. The reduction target of energy-related CO_2 emissions is based on the Long-term Energy Supply and Demand Outlook (Ministry of Economy, Trade and Industry (METI), 2015). Approximately half of the CO_2 emission reduction in the residential sector is expected to be obtained by increasing the use of CO_2-free power sources, such as renewable and nuclear sources. The remainder of the reduction is expected by energy end-use reduction in the residential sector.

Generally, energy end-use reduction is estimated by bottom-up calculation of the effect of each energy-saving measure. However, there is a serious deficit in the calculation. The government estimated the reduction effects multiplying the constant energy reduction amount of each measure by the number of households in Japan.

The amount of energy consumption in the residential sector varies considerably based on various factors, such as the number of family members, the type and size of the house, the climate condition, and the energy efficiency of appliances and equipment. These factors differ depending on the family and the region in Japan. Therefore, consideration of the distribution of these factors is very important for accurate estimation of energy consumption.

In addition, it is noteworthy that the aggregation of the energy efficiency measures is non-linear in nature. For example, the increasing use of heat insulation in buildings reduces heat load and, consequently, reduces the energy-saving effect of introducing high-efficiency room air conditioners (RACs). Thus, the government overestimates the actual effects of energy efficiency measures.

A number of studies have estimated national-scale energy consumption in the residential sector by aggregating the energy consumption of the representative buildings (Ghedamsi et al., 2016, Papachristos., 2015, Swan et al., 2013 and Palmer et al., 2006). For example, a model using a neural network (Swan et al., 2013) can estimate individual components of energy use, such as heating, cooling, water heating, appliances, and lighting in detail, but requires numerous actual end-use data. Moreover, considering the UK housing stock of 431 building categories, the model can estimate energy consumption (Palmer et al., 2006). However, in their study, occupant and appliance heat gains and hot water use are based on typical values. In contrast, a bottom-up-type simulation model developed by the authors can accurately estimate the energy consumption by considering the influences of various factors that differ among households or regions based on information obtained through various questionnaires and statistics.

A Research question of this study is to exam whether the reduction effect can be obtained even if the distribution is taken into account. Thus, we estimate Japanese GHG reduction effects in FY2030 by implementing energy efficiency measures for the residential sector according to Japanese Long-term Energy Supply and Demand Outlook (2015) using the simulation model developed by the authors. In particular, we emphasize the importance of considering differences in reduction effects depending on household type by demonstrating the differences in energy reduction effects as a result of introducing high-efficiency water heaters.

Simulation model

Figure 1 shows an outline of the simulation model developed by Shimoda et al., (2007). The simulation model consists of an occupant behavior model, an appliance energy-use model, a hot water energy-use model, a heating and cooling energy-use model. The model estimates energy consumption of selected representative households. In addition, a diversity of

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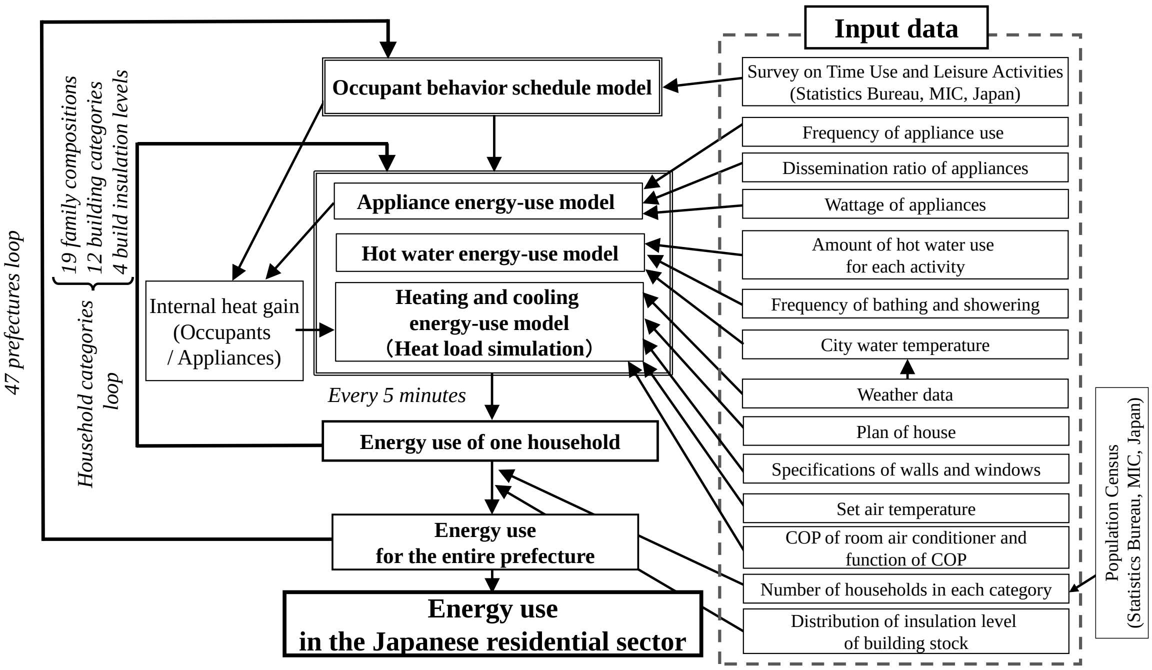

Figure 1: Outline of the residential energy end-use model

energy consumptions among households and regions is reproduced by developing various kinds of input data. In the present paper, after developing databases, the reproducibility of model is validated by comparing with statistic value for energy consumption of the Japanese residential sector in FY2013. Then the reduction effect by GHG reduction policy for FY 2030 is verified and sensitivity analysis of installation of high efficiency water heater is performed.

Selection of representative households

This model considers 912 household categories that consist of 19 family compositions, 12 building categories (six categories for detached houses and six categories for apartments, depending on the floor area), and four building insulation levels. The households in the target region are classified into 912 categories based on the National Population Census (Statistics Bureau, 2010) and insulation level percentages for residential building stocks. Maintaining the distribution among the household categories, 0.05% of each household category is chosen to represent the target region.

Occupant behavior schedule model

A behavior schedule for every occupant in each representative household is created at five-minute intervals using the occupant behavior schedule model (Yamaguchi et al., 2014). The behavior schedules are created considering the occupant attributes, age, gender, length of working hours, and whether the household includes a child/children.

Appliance energy-use model

The appliance operation schedule is determined stochastically from the occupant behavior schedule and the frequency of appliance use. Based on the specifications of each household appliance, the model then estimates the energy consumption of appliances.

Hot water energy-use model

Energy consumption for water heating is calculated based on the amount of hot water use, the set temperature, the city water temperature, and the energy performances of water-heating equipment. The city water temperature is considered to be a function of the daily outdoor air temperature.

Heating and cooling energy-use model

The heating and cooling energy consumption is estimated through a dynamic heat load calculation using a thermal circuit network method (Shimoda et al., 2007). The heat load calculation is carried out based on the occupant presence, the building thermal insulation performance, and the weather conditions. The internal heat gains, which were calculated based on the appliance energy consumption and the occupant behavior schedule, are also used in this model.

The energy consumption of the entire region is estimated by aggregating the simulation results of each representative household. There are 47 prefectures in Japan, and this procedure is carried out for each prefecture. By summing the results of 47 prefectures, the energy consumption in the Japanese residential sector is calculated.

Data Preparation

In order to simulate city-scale or larger-scale residential energy consumption, it is important to consider the variety of factors that affect energy consumption. In the present study, the following input parameters are prepared for each region:

- Number of households of each household category
- Insulation level percentages for housing stocks
- Weather condition
- Dissemination ratio of appliances
- Share of heating equipment
- Share of water-heating equipment

The number of households of each household category is based on the National Population Census (Statistics Bureau, 2010). The four building insulation levels (no insulation, 1980 standard, 1992 standard, and 1999 standard) were set to achieve the Japanese Energy Conservation Standard. The dissemination ratio of appliances is based on the National Survey of Family Income and Expenditure (Statistics Bureau, 1994–2014). The shares of heating and water-heating equipment were based on questionnaire responses across Japan (MyVoice Communications, Inc., 2009, 2015). The numbers of responses to questionnaires related to heating equipment and water-heating equipment exceeded 12,000 and 13,000, respectively. The main simulation conditions for the Japanese residential sector in FY2013 are shown in Table 1.

Weather conditions

The model uses weather data observed in each prefecture (Japan Meteorological Business Support Center, 2014) as input. Therefore, the heating and cooling energy use simulation can reflect the characteristics of the weather conditions, such as the outdoor air temperature and humidity in the target region.

Share of heating equipment

In Japan, RACs, electric space heaters, gas heaters, and kerosene heaters are commonly used for heating in residential buildings. Figure 2 shows the share of heating equipment in each prefecture based on the above-mentioned questionnaire survey. The model considers shares of heating equipment for each prefecture.

Table 1: Simulation conditions for Japanese residential sector in FY2013 and FY2030

Year		FY 2013	FY 2030
Population		124,638,133[a]	112,218,978
Households	Total	51,756,509[a]	50,670,133
	Single households	16,784,507[a]	18,717,900
Average number of family members		2.41	2.21
Average total floor area per household [㎡]		80.32	74.06
Insulation levels of building stock	No insulation	27.0%	12.8%
	1980 standard	38.7%	27.1%
	1992 standard	26.7%	27.3%
	1999 standard	7.6%	32.8%
Rated COP of RACs (cooling mode / heating mode)	2.2 kW	5.01 / 5.52	5.90 / 6.51
	2.5 kW	4.94 / 5.55	5.82 / 6.54
	2.8 kW	4.76 / 5.33	5.61 / 6.28
	3.6 kW	3.80 / 4.53	4.49 / 5.34
	4.0 kW	3.76 / 4.35	4.43 / 5.13
Appliance power consumption [W] (operation mode)	TV	129.93	81.73
	Video recorder	36.25	37.74
	PC accessories[b]	3.87	6.50
	Rice cooker	240.62	232.20
	Shower toilet[b] (winter/summer/other season)	24.30 / 3.36 / 13.50	20.91 / 2.89 / 11.63
Refrigerator power consumption [kWh/year]	≤250L	517	429
	300 - 350L	554	431
	350 - 400L	536	433
	400 - 450L	502	334
	450 - 500 L	511	280
	>500L	654	367
Lightig power consumption [W/room] (living room in detached houses)	≤40m^2 (total floor area)	59	36
	40 - 60m^2	62	47
	60 - 80m^2	121	83
	80 - 100m^2	124	94
	100 - 120m^2	124	94
	>120m^2	132	99
Installation of hot water equipment	HP water heater	4,220,000	14,000,000
	Condensing gas/oil water heater	4,480,000	27,000,000
	PEFC cogeneration system	50,000	5,300,000
CO_2 emission factor	Electricity [kg-CO_2/kWh]	0.57	0.37
	Gas [kg-CO_2/GJ]	53.9	53.9
	Kerosene [kg-CO_2/GJ]	68.6	68.6

[a]The data of the 2010 Population Census are used as the input data of FY2013.

[b]This appliance constantly operates electricity in this model.

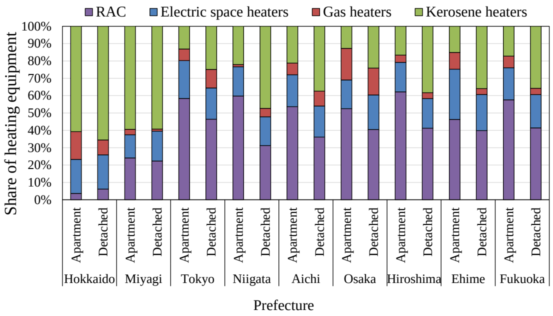

Figure 2: Share of heating equipment in various prefectures

Share of water-heating equipment

The share of water-heating equipment for each household category in each region depends on the network of city gas supply, the initial cost, and the limitations of the installation location. Therefore, the share differs among regions, building type (detached house or apartment), and family types. The share of water-heating equipment in each prefecture is shown in Figure 3, and that for each family size category is shown in Figure 4. These shares are based on the above-mentioned questionnaire survey. The proposed model considers a conventional gas water heater, a conventional oil water heater, an electric-resistance water heater, a heat pump (HP) water heater, a condensing gas water heater, a condensing oil water heater, and a polymer electrolyte fuel cell (PEFC) cogeneration system. The detail of this equipment is described in detail in a previous paper (Shimoda et al., 2010).

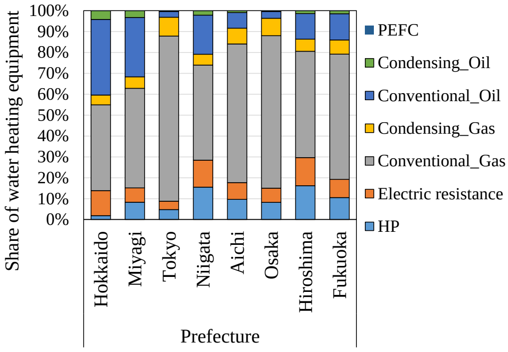

Figure 3: Share of water-heating equipment in various prefectures in FY2013

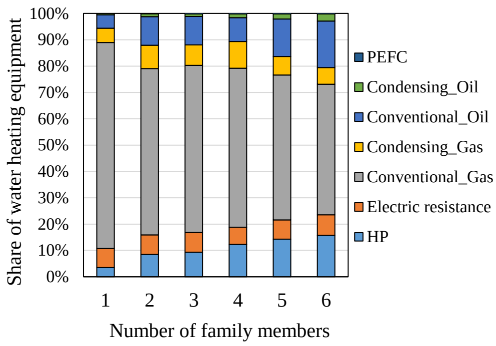

Figure 4: Share of water-heating equipment for each family size in FY2013

Simulation results in FY2013

Energy consumption in FY2013

Figure 5 compares the simulated annual secondary energy consumption in the Japanese residential sector with statistical data (Agency for Natural Resources and Energy of METI, 2015). The values of the simulated gas and kerosene consumptions agree with the statistical data. The simulated electricity consumption is lower than the statistical data by 18%. A possible reason for this is that the model cannot consider households that are extremely wasteful with respect to energy.

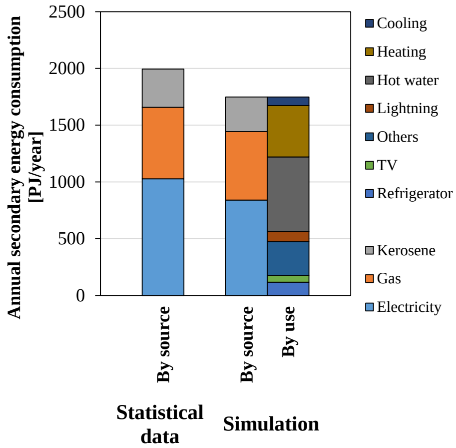

Figure 5: Annual secondary energy consumption in FY2013

CO2 emissions in FY2013

Figure 6 shows the annual CO_2 emissions in FY2013 calculated from the energy consumption of each source (Figure 5). The value of 0.57 kg-CO_2/kWh (The Federation of Electric Power Companies of Japan, 2014) is adopted as the CO_2 emission factor of electricity. The values for gas and kerosene are 53.9 kg-CO_2/GJ and 68.6 kg-CO_2/GJ, respectively (Agency for Natural Resources and Energy, 2015). The difference in the total CO_2 emissions between the simulation result and the statistical data is approximately 15%. The difference of CO_2 emissions due to electricity consumption is approximately 18%.

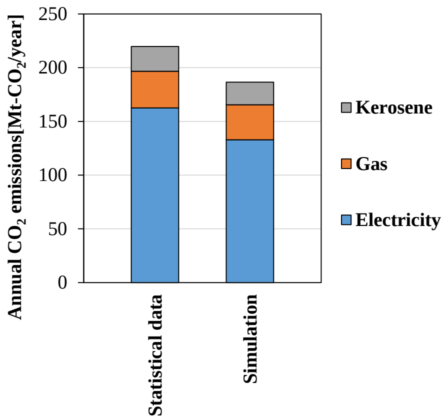

Figure 6: Annual CO_2 emissions in FY2013

Prediction of GHG emission reduction effects in FY2030

In this section, we evaluate the effect of the CO_2 emission reductions resulting from the implementation of the energy-saving measures to meet the FY2030 goals. In order to estimate the GHG emissions in FY2030, some input parameters are modified from the current condition (FY2013). The number of households, the population, and the distribution of households among categories in FY2030 are set based on population projections (National Institute of Population and Social Security Research, 2013). The details of the simulation conditions for FY2030 are shown in Table 1. For the weather condition, FY2013 weather data are adopted for the weather conditions.

In the preset study, we predict the CO_2 reduction effects of the following five energy-saving measures:

- Improvement of insulation level of building stock
- Changes in energy efficiency of appliances
- Dissemination of high-efficiency water-heating equipment
- Dissemination of LED lighting devices
- Improvement in CO_2 emission factor of the electricity grid

Improvement of insulation level of building stock

The percentage for each building insulation level is calculated by considering building replacement based on the predicted number of newly built houses, the insulation level percentages of newly built houses in each year, and building lifetimes. The heat transmission coefficient of each insulation level is set as the minimum value of each standard. According to the Long-term Energy Supply and Demand Outlook, it is assumed that all newly built houses will achieve the standard of building insulation by 2020.

Changes in energy efficiency of appliances

The power consumptions of appliances are based primarily on manufacturer catalogues. The power consumptions of major appliances, such as RACs, TVs, and refrigerators, are set based on an appliance stock model (Shimoda et al., 2010) considering the replacement of appliance stock for each year based on the number of shipments, the energy efficiency distribution for the manufacturing year, and the appliance service life. The efficiency and diffusion of appliances, including RACs, TVs, refrigerators, video recorders, PC accessories, rice cookers, and shower toilets, were considered.

Dissemination of high-efficiency hot water equipment

The Long-term Energy Supply and Demand Outlook proposes that HP water heaters, condensing gas/oil water heaters, and PEFC cogeneration systems will be widespread by FY2030 as shown in Table 1. The Share of high-efficiency water heaters introduced for each prefecture and each family size category is determined by the share of conventional water heaters, i.e. electricity driven and fuel fired. Figure 7 and Figure 8 show the predicted shares of water-heating equipment for various prefectures and family size category, respectively.

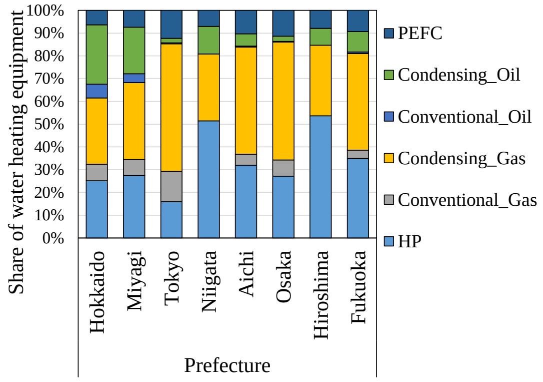

Figure 7: Share of water-heating equipment in various prefectures in FY2030

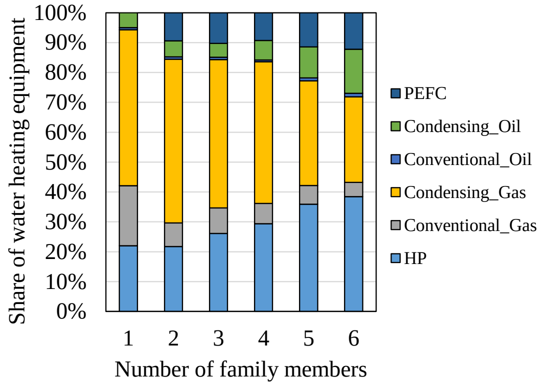

Figure 8: Share of water-heating equipment for each family size category in FY2030

Dissemination of LED lighting devices

In the simulation of FY2013, we assumed that all households used fluorescent lamps for lighting. In FY2030, it is assumed that LED lamps will have replaced fluorescent lamps.

Improvements in CO_2 emission factor of the electricity grid

The Japanese government plans to expand the introduction of renewable energy and the operation of nuclear power plants. The government aims to improve the CO_2 emission factor of the electricity grid to 0.37 kg-CO_2/kWh (The Federation of Electric Power Companies of Japan et al., 2015). This value is used in the CO_2 emission calculation for FY2030.

Simulation results in FY2030

Figure 9 shows the simulated annual primary energy consumptions in the Japanese residential sector in FY2013 and FY 2030. The reduction rate of total energy consumption is 18%. The reduction of electricity consumption is dominant (427 PJ/year) mainly because of the reduction in electricity consumption of heating equipment. With the respect of usage, hot water energy consumption decreases by 190 PJ/year due to widespread use of high-efficiency hot water equipment.

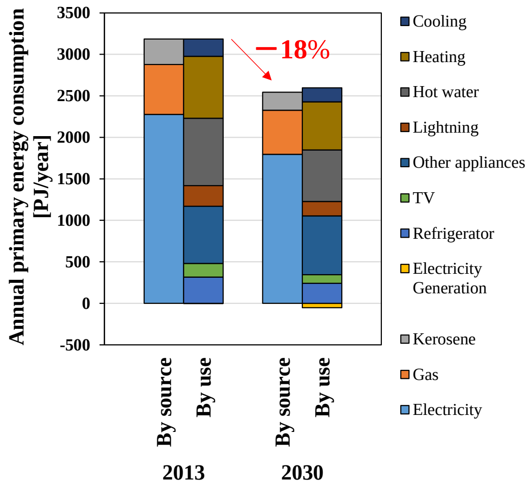

Figure 9: Changes in annual primary energy consumption from FY2013 to FY2030

The simulated annual CO_2 emission in FY2030 shown in Figure 10 is 108 Mt-CO_2/year. The reduction rate of CO_2 emissions is 42%. These results demonstrate that the target value of the CO_2 reduction in the residential sector (39% (79 Mt-CO_2/year), Global Warming Prevention Headquarters, 2015) can be achieved, even if the difference in energy-saving effects among households is taken into account. The CO_2 emissions due to electricity consumption decrease by 62 Mt-CO_2/year. This value includes the reduction related to the change in the CO_2 emission factor, which corresponds to 38 Mt-CO_2/year. By using the method of this study, reduction effects for each use can be obtained. Therefore, it can be used for further investigation of future measures.

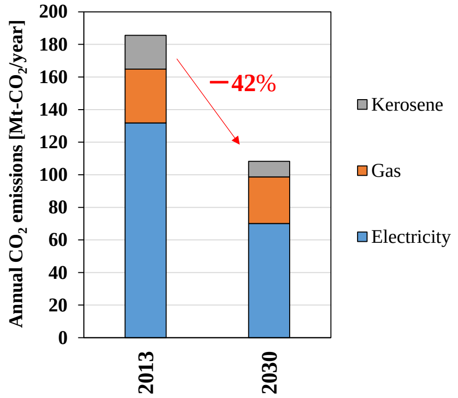

Figure 10: Annual CO_2 emissions in FY2013 and FY2030

A case study in the distribution of water-heating equipment

Figure 11 compares the annual CO_2 emissions due to water-heating equipment among family size categories. The reduction effects vary widely depending on the family size. For example, the difference between CO_2 emissions due to HP water heaters and conventional gas water heaters in six-person households is approximately seven times as large as the difference for single-person households. The figure suggests that the difference in CO_2 emissions among households may affect national-scale CO_2 emissions if the distribution of water-heating equipment (Figure 8) changes.

In this section, this model assesses the impacts of the change of the distribution of water-heating equipment on the national-scale CO_2 emissions. In the present study, we evaluate two cases. In Case 1, the same share is adopted for all households (Figure 12), and, in Case 2, high-efficiency water-heating equipment is distributed preferentially to households in which the CO_2 emission reduction effects are large (Figure 13).

Figure 14 shows the change of annual CO_2 emissions from Figure 10 for each case. The figure demonstrates that the CO_2 emissions vary with the distribution of water-heating equipment among family size categories. Compared with Figure 10, the emissions increase by 0.7% for Case 1 and decrease by 2.0% for Case 2. The reduction effects in Case 1 are relatively small. In this case, HP water heaters and PEFC cogeneration systems are installed not only in households with large families but also in households with smaller families. In single-person households or two-person households, the reduction effects are low because the amount of hot water use is small. In contrast, the reduction effect in Case 2 is larger because high-efficiency water heaters are installed in households with large families, for which the reduction effects are large.

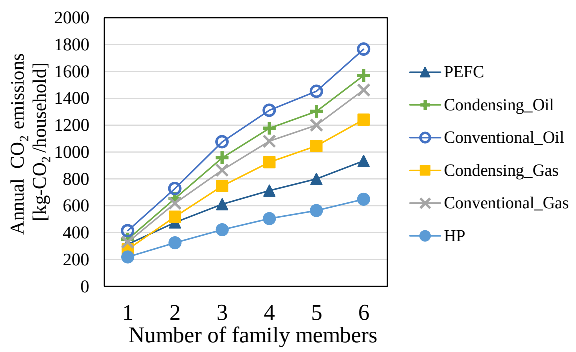

Figure 11: Difference in annual CO_2 emissions by water-heating equipment

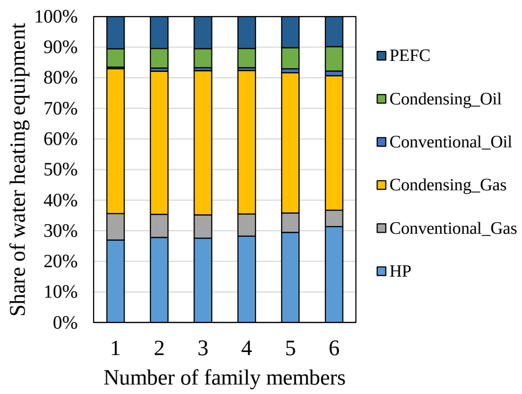

Figure 12: Share of water-heating equipment (Case 1)

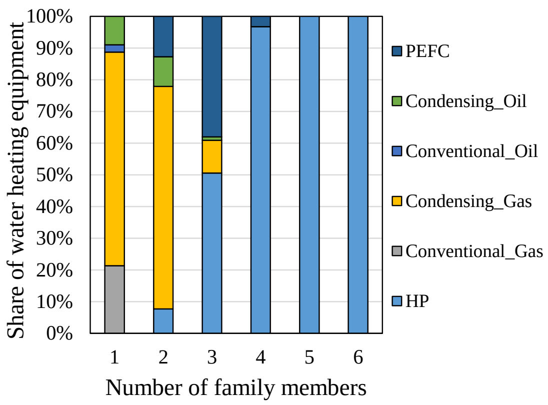

Figure 13: Share of water-heating equipment (Case 2)

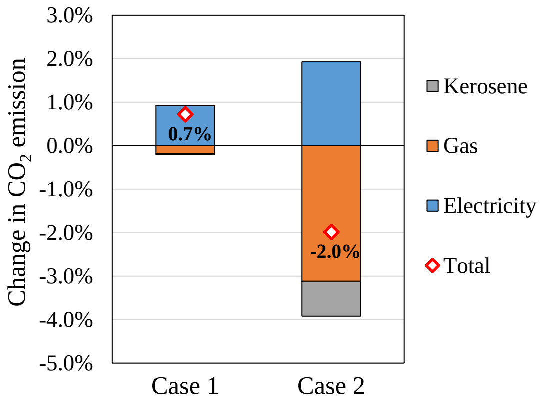

Figure 14: Change in CO_2 emission from the national-scale CO_2 emissions in FY2030

Discussion

In the present paper, we demonstrated the application of the bottom-up-type building energy simulation model to the evaluation of national energy policy for the residential sector. This model can consider the variation of reduction effects by household type and region. In order to ensure the applicability of the model as a policy tool, the following two considerations are important.

Consideration of regional and household characteristics

The determinants of residential energy consumption vary from household to household and region to region, as shown in Figure 3 and Figure 4. By considering these determinants, it became possible to estimate more realistically, reflecting the difference in reduction effect among households and regions. The variety is caused by weather conditions, availability of energy infrastructure, and income level. Therefore, the consideration of these varieties is especially important for the correct estimation of the energy consumption of an entire nation.

Developing and maintaining the database

In the present study, we constructed a database for the consideration of the variety of determinants related to energy consumption in the residential sector. For example, the shares of equipment according to region and the number of family members were estimated. The obtained database contributes to accurate evaluation for the purpose of policymaking. However, the construction of the database was difficult because data for the input conditions of the building energy performance simulation are somewhat different from the data that are usually collected through government surveys. Therefore, when considering another region, or country, we must conduct detailed surveys in order to collect various input data on appliances, building specifications, and lifestyles. However, it is usually difficult to maintain all these input data, so at least it is necessary to have data that greatly affects the difference in energy consumption among households, such as the distribution by each household category and the spread of heating equipment.

In addition, it is difficult to consider households that consume extremely large amounts of energy. Moreover, some households exhibit extreme occupant behaviors, ownership, and appliance usage. Since such households have large potential energy savings, databases should have realistic distributions.

Conclusion

The present study demonstrated the effectiveness of a bottom-up-type simulation model when designing or evaluating an energy/GHG reduction policy for the residential sector.

The total energy consumption of the Japanese residential sector was simulated using a database that considers the variety of energy-use-related parameters of households and regions. Next, this model was used to estimate the GHG emissions reduction in FY2030 by implementing energy-saving measures for the Japanese residential sector. The simulation result for annual CO_2 emissions in FY2030 was 108 Mt-CO_2/year. The CO_2 reduction rate from FY2013 to FY2030 was 42%, and this value is close to the national target value of 39%. Moreover, in order to demonstrate the importance of considering the difference of reduction effects depending on households, the effects of installing high-efficiency water-heating equipment were simulated for two dissemination scenarios.

In the future, we intend to improve the database for input data of the end-use simulation model and conduct various case studies in order to evaluate national and regional GHG reduction policies.

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