DEVELOPMENT AND VALIDATION OF A RESIDENTIAL SECTOR ENERGY END-USE PREDICTION MODEL TO ESTIMATE RESIDENTIAL ENERGY CONSUMPTION IN JAPAN

Takuya Aoki, Hiromi Habara, Yoshiyuki Shimoda
Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

ABSTRACT

We developed a "data preparation model" to complement the database for the estimation of energy consumption in the Japanese residential sector from 1990 to 2010. In particular, we developed a "stock model" for water heaters to estimate the diffusion of high-efficiency water heaters. Energy consumption is estimated by a "residential sector energy end-use prediction model" which was developed originally by our research group. In addition, we validated the results and analyzed the dominant factors related to energy consumption in the residential sector. The simulated total energy consumption was within 17% of the actual energy supply in 1990 and 2000, while the result in 2010 was underestimated by 24–35%. The most important factor for reducing energy consumption was found to be an improvement in appliance efficiency.

INTRODUCTION

Recently, the Japanese government has been discussing a new energy plan, and in particular, the need for energy savings and certainty of supply. A number of measures have been suggested; however, a concrete plan has yet to be finalized. A method that can be used to evaluate the effectiveness of these measures is required to support the decision regarding the measures that need to be implemented. In particular, measures to reduce energy consumption in the residential sector are needed, since energy consumption in the Japanese residential sector has steadily increased, because the standard of living has increased. Along with an increase in the standard of living, there have been concomitant increases in house sizes and home electric appliance usage.

In Japan, the energy consumption per household significantly varies according to the size of household, and the efficiency of appliances used in the house. In addition to the number of members of the household, the usage pattern for each appliance depends on their collective lifestyles. Therefore, it is difficult to estimate the potential energy saving that each mitigation measure can make on either a city-wide or national scale.

We developed a bottom-up "residential sector energy end-use prediction model" (Shimoda.Y., et al., 2007) to estimate energy consumption based on occupant behavior over 5 minutes and a number of factors (e.g., energy efficiency of appliances, insulation performance of buildings). Bottom-up approaches can assess the energy usage based on the modeling of building physics to calculate the energy usage of individual buildings on a monthly or hourly basis (Mata.E. et al., 2013). These models also extrapolate the results; thus, they can be applied to a region or a country. However, they reported that with the bottom-up approach, its data availability may determine the model structure. The bottom-up model requires data from a number of sources to estimate energy usage based on a range of household; however, the existing household energy data is limited. Mata.E et al developed a bottom-up model to simulate hour-by-hour usage on the basis of available simplified data. Nevertheless, their model is unable to consider the temporal demand changes that result from changes in occupancy and the usage of different appliances. Therefore, more detailed simulations are required to evaluate complex energy saving measures including the management of room environment or behavioral changes.

To solve the data limitation problem and achieve more detailed simulation, we developed a data preparation model that estimated data unavailable from existing statistics In particular, the data preparation model for new residential water heaters was developed herein to account for data paucity regarding the proportions of each type of water heater.

The purposes of this study were as follows:

1) To modify the method to update the database and the data preparation model.

2) To apply the model to the energy usage in the Osaka Prefecture from 1990 to 2010 and to validate estimated energy consumption results.

3) To analyze the dominant factors for energy consumption to suggest effective energy saving measures.

SIMULATION MODEL

Structure of the simulation model

We developed a original bottom-up residential sector energy end-use prediction model to simulate city-scale energy consumption in the residential sector. Figure 1 shows the simulation model flow chart. In the simulation, the diversity of family and building types is considered, and the energy consumption of one household is iteratively calculated for 19 household types and 12 building designs—six of which are classified as detached houses and the other six are classified as apartments dependent on floor area. Four levels of building insulation are included in the model. The total residential energy consumption in the target region was estimated by multiplying the simulated energy consumption of one household by the number of households in each category. The number of households classified by household type and building type are estimated based on the National Population Census(Statistics Bureau, 2010).

To calculate the total energy consumption of the Japanese residential sector, Japan is divided into 17 regions based on the climate zone classification by the Japanese Energy Conservation Law (Agency for Natural Resource and Energy and Energy Conservation Center, 2005).

The model has 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. In addition, the “Database” includes the data estimated in the “Data preparation model.”

The “Data preparation model” consists of the following components: an “Occupant behavior schedule model,” a “Household categorize model” and a “Stock model.” The stock model was previously described (Shimoda Y., 2007) and is used to estimate the average energy efficiency of appliances and the distribution of building insulation levels in the target region. The model enables us to prepare input data including the average energy efficiency of appliances in the target year. In this paper, the “Stock model” for water heaters was modified.

Energy consumption was simulated by the “Energy-use model” based on occupant behavior, which is estimated using the “Occupants behavior schedule model.” In the heating and cooling model, simulations of the dynamic heat load are conducted using building and climatic data. Heating and cooling loads are simulated using the internal heat gain, which is calculated using the appliance energy-use model and occupant behavior. The time step of both the heat-load and energy-use simulations was 5 minutes.

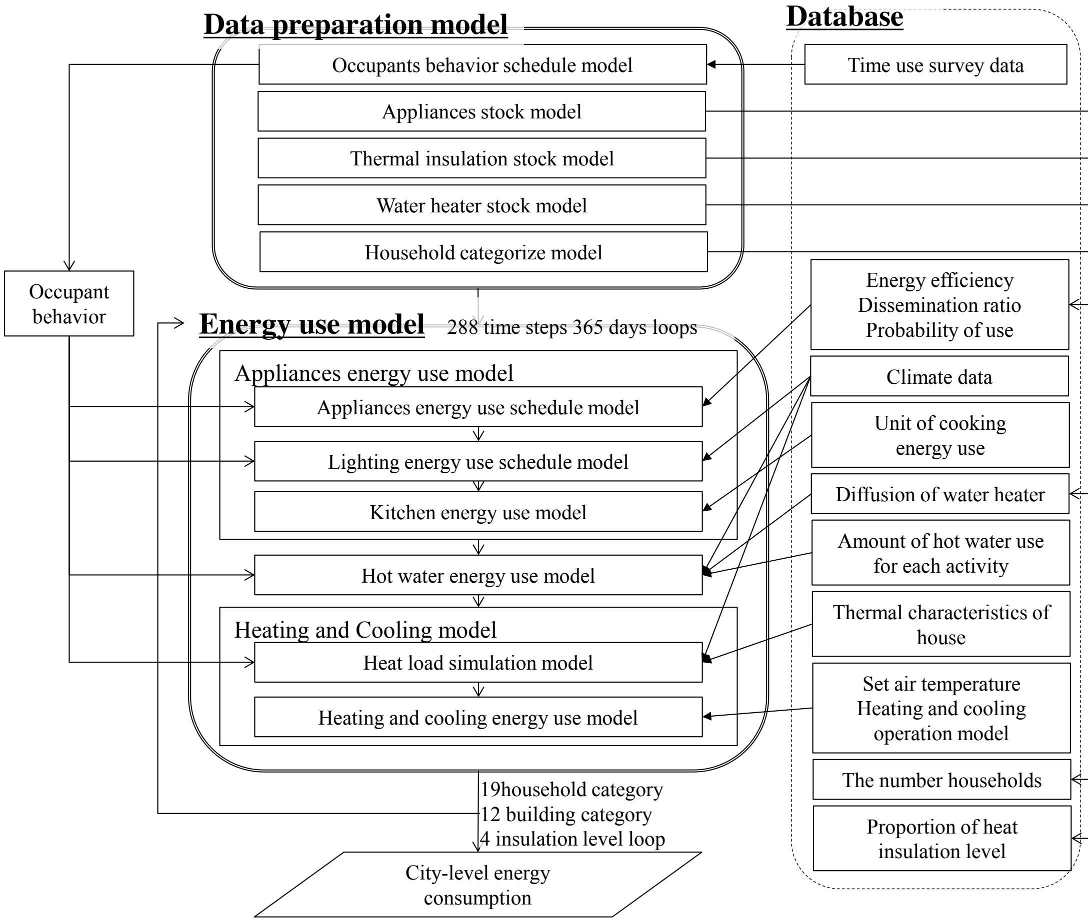

Figure 1: The structure of the simulation model

Construction of the database

Our model combined a number of factors that reflect the geographical and social conditions used in the energy simulation. The parameters that reflect the geographical and social condition are divided to two groups: geographical and time-series parameters. The geographical parameters are determined on the basis of 17 Japanese regions, according to the Japanese Energy Conservation Law (Agency for Natural Resource and Energy and Energy Conservation Center, 2005). Time-series parameters are determined by region and the target year. They were set annually to consider any changes in social conditions.

The parameters considered in the model were as follows:

Geographical parameters:

- Heating and cooling degree day
- Estimated water temperature in the city
- Bathing frequency of residents
- Number of households in each category

Time-series parameters:

- Climatic data
- Proportion of new houses that have adopted thermal insulation
- The number of appliances owned in the city
- Energy performance of appliances
- Energy sources used for heating (electricity, city gas, and kerosene) and their relative proportions Relative proportion of room air conditioners and electric heaters
- Number of water heaters used in the city.

The data source for the model was previously reported by our research group (Shimoda.Y, 2007). In this paper, data from 2005 to 2010 was added to the existing database, and some of the parameters were modified to fit the present conditions. In particular, the energy efficiency rating of selected home appliances was revised on the basis of the information obtained from the catalogs from Japanese manufacturers in 2010 (Table 1).

Data preparation model

An "Appliance Stock model" was developed to estimate the average energy efficiency of each appliance. The appliances included in the "Stock model" included televisions (TVs), DVD/VHS recorders, personal computers, refrigerators, and air conditioners, since they typically consume more electricity in comparison with other household appliances. The energy efficiency of these appliances was assumed on an annual basis. The model used statistics including the appliance's the dissemination ratios, the number of shipments, and the distribution of appliance energy efficiency in each year of manufacture after 1975. In addition, lifetime distributions are set for each appliance. From this data, the energy efficiency of each appliance that was purchased in a particular year is estimated. Figure 2 shows the estimated result for TVs in 2010. The graph depicts the distribution of the estimated sales volumes of TVs in each year of manufacture from 1995 to 2010. The line shows the fluctuation in energy performance of the latest model of TVs manufactured in each year. Figure 3 shows the fluctuations in the average efficiency of four of the appliances in the model. Power consumption of refrigerator is modeled as a function of outdoor air temperature and average performance.

The proportions of insulation levels in the stock buildings were estimated from the number of newly built houses, the percentages of insulation levels adopted to the newest houses, and estimated lifetime distributions. Figure 4 shows the transitions of the proportions of the standard of insulation levels in the stock homes.

The "Household category model" estimated the number of members of a family or of building types. Figure 5 shows the transition of the number of households categorized in the model.

Table 1: Setting of home appliance efficiency

Category	Appliances	Power consumption(W)	
		Operation mode	Standby
Kitchen	Rice cooker	240.6	18.6
	Dishwasher	387.8	1.5
	Thermos	815.8	32.9
	Microwave	410.7	-
	Toaster	1071	-
Home Appliance	Fan	20.0	-
	Washing Machine	111.8	-
	Machine Tumble dryer	1251.7	-
	Hair dryer	633.3	-
	Desk lamp	30.0	-
	Vacuum	623.2	-
	Iron	1212.5	-
	Radio	100.0	14.0
	CD player	100.0	14.0
	PC networking equipment	-	11.9
	BS tuner	-	1.3
	Fax	-	1.5
	Telephone	-	2.9
	Heated toilet seat	-	24.3
Heat and Cooling	Kotatsu(foot warmer)	518.3	-
	Electric carpet	265.8	-

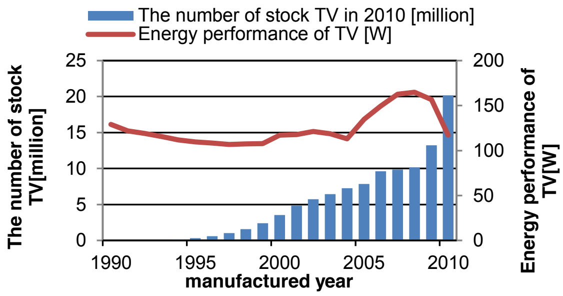

Figure 2: Number of stock TVs in 2010 and energy performance of TV in a particular manufactured year

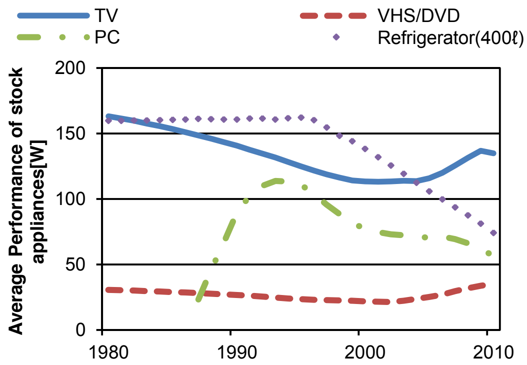

Figure 3: Average efficiency of stock appliances

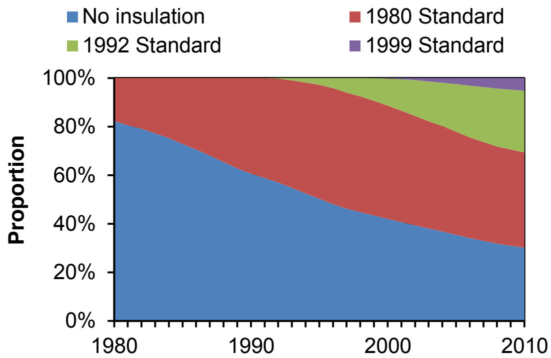

Figure 4: Proportions of building insulation level (based on apartment houses in the Osaka Prefecture)

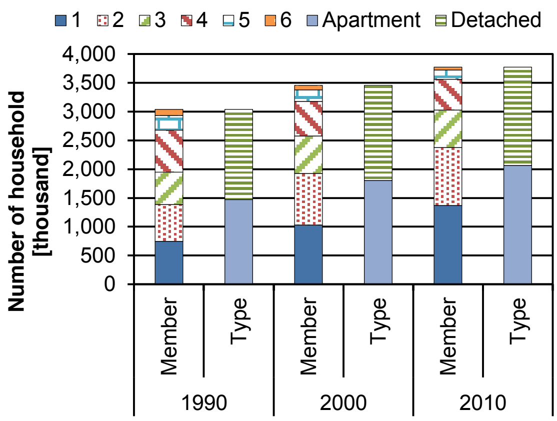

Figure 5: Number of households categorized by occupant numbers and building type

STOCK MODEL FOR NEW RESIDENTIAL WATER HEATER

Water heater stock model

Recently, a new type of a highly efficient water heater has been released for sale in the Japanese residential sector. The "stock model" created for this study estimated the dissemination ratio of conventional water heaters (electric water heater, gas water heater, and oil water heater) and the highly efficient water heaters (CO_2 heat pump water heater and latent heat recovery gas water heater). The model is shown in Figure 6.

The proportion of each energy source (electricity, gas and oil) used for heating water is determined on the basis of the Annual Residential Energy Report (Jyukankyo Research Institute Inc., 2010). Electricity and gas demand are divided into the demand satisfied by conventional water heaters and that for the highly efficient heater due to the dissemination ratio of each heater. The dissemination ratio of each stock water heater were calculated from the number of shipments and the remaining ratio. Remaining ratio is the probability that the equipment remains to be used from installed to the house to the target year.

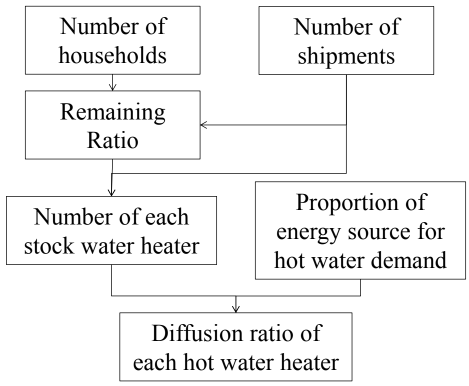

Figure 6: Structure of a water heater stock model

Relative proportion of energy sources in hot water demand

The primary energy demand for hot water in each region in Japan was obtained from the Annual report of household energy statistics (Jyukankyo Research Institute Inc., 2010). The relative proportion of each energy source used to heat water was calculated by dividing the primary demand for each energy source by the efficiency of each water heater. Figure 7 shows the transition of the relative proportions of energy sources (e.g., electricity, gas, and oil) for heating water in the Osaka Prefecture.

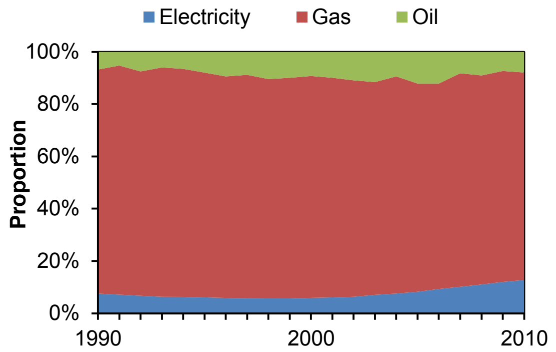

Figure 7: Proportion of energy source in the Osaka Prefecture

Water heater shipments

The number of water heater units shipped was determined from the shipping statistics. In particular, two documents were reviewed: the Japan Industrial Association of Gas and Kerosene Appliances (2012) and the Japan Refrigeration and Air Conditioning Industry Association (2011). In addition, production survey data was also reviewed (Ministry of Economy, Trade and Industry, 2012). Figure 8 shows the transition of water heater shipments.

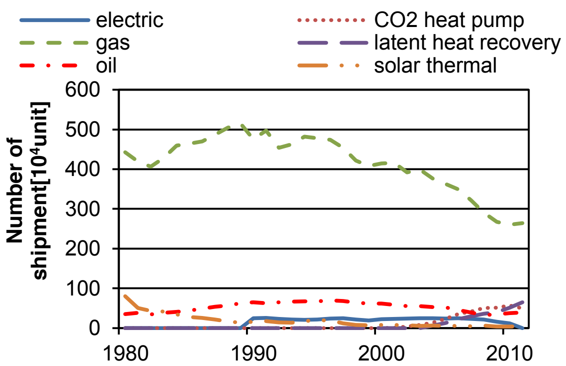

Figure 8: Water heater shipments

Remaining ratio

The remaining ratio for water heaters was estimated by applying a Weibull distribution to the waste ratio for water heaters. Waste ratio is the probability that an equipment is demolished in the target year from purchase. The Weibull distribution was determined by a scale and a shape parameter (Equation (1)). The scale parameter represented the period of time for half of the newly installed equipment to be wasted (e.g., discarded after it is no longer useable). In this study, the value of the scale parameter was set to 11.7 based on research data (Japan Industrial Association of Gas and Kerosene Appliances, 2007). The shape parameter represented the shape of the waste probability distribution. The value of the shape parameter was set to 3 so as to fit the estimated number of stock water heaters to the number of households. Figure 9 shows the estimated waste ratio and remaining ratio.

$$W(y)= b/a(y/a)^{(b-1)}\exp[-(y/a)^{b}] \qquad (1)$$

W (y): distribution of waste ratio
y: duration of the shipment
a: scale parameter
b: shape parameter

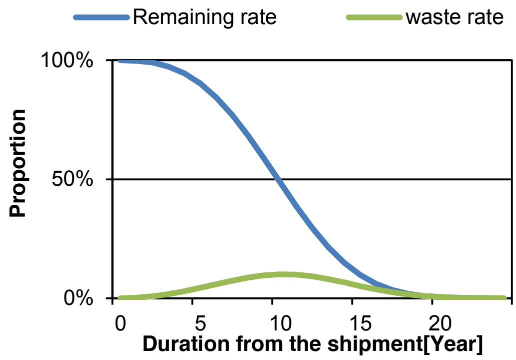

Figure 9: Waste ratio and remaining ratio

Estimation of the number of stock water heaters

The number of stock water heaters from a particular manufacturing year was calculated by multiplying the number of shipments and the remaining ratio for that year. The total number of stocks in a particular year was estimated by summing the number of remaining systems from that year. Figure 10 shows the transition of the number of stock water heaters.

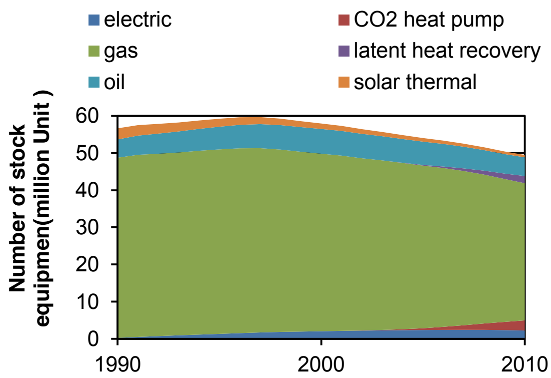

Figure 10: Number of stock water heaters

Dissemination ratio of each water heater

The dissemination ratio of each water heater was estimated by categorizing the demand for water heating from electric and gas sources into the conventional and highly efficient water heater according to the stock volumes of each water heater. The dissemination ratio of each water heater in the Osaka Prefecture in 2010 is shown in Figure 11. The highly efficient water heater is owned in approximately 10% of households in the Osaka Prefecture in 2010.

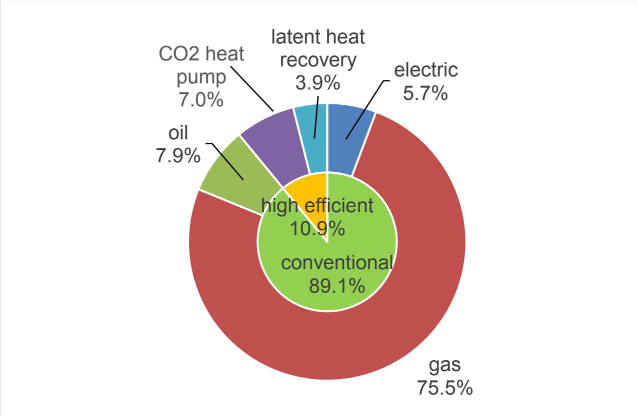

Figure 11: Dissemination ratio of water heater stocks by type (2010, Osaka Prefecture)

SIMULATION VALIDATION AND RESULTS

Simulation

In this study, our model was applied to estimate residential energy consumption in 1990, 2000, and 2010 in the Osaka Prefecture. The estimated result was compared to the official statistics to verify the accuracy of the model.

Validation of simulated residential energy consumption in Osaka prefecture

The simulated total residential energy end-use in Osaka prefecture in 1990, 2000, and 2010 was compared to the estimated energy consumption from three sources: The first source is the Energy Balance statistics table annually provided by Agency for Natural Resource and Energy in the Ministry of Economy, Trade and Industry (Agency for Natural Resource and Energy, 2012). The statistics table is based on some national statistics about energy supply and demand. The second one is the Annual Report of household energy statistics published by Jyukankyo Research Institute Inc. ,a Japanese think tank (Jyukankyo Research Institute Inc, 2010). The residential energy consumption in each prefecture is estimated in the Annual Report based on the questionnaire about household expenditure (approximately 9000 samples in Japan). The last one is the Osaka Statistics Year Book (Osaka Prefecture, 2012). The book shows the electricity and gas demand in Osaka prefecture according to the data from electric and gas utility.

Figures 12 and 13 compare the simulated annual primary energy consumption and energy supply statistics for the Osaka Prefecture residential sector in 1990, 2000, and 2010. Figure 12 shows the energy consumption by energy source. In 2000, the difference between our simulated results and the other statistics was approximately 10%, and the simulated composition of electricity was similar to the other results. However, although our results in 1990 were higher than the statistics by 9–17%, the results from 2010 were lower than other statistics by 24–35%. Figure 13 shows a comparison of energy consumption by energy usage. The simulated composition of appliances and hot water was smaller than other statistics.

The results of our simulation underestimated the increase in energy use from 1990 to 2010. Possible reasons are that the energy usage from miscellaneous appliances was not considered in our model and that the service life of an appliance is typically shorter than the actual life. The shorter life of an appliance means that they tend to be replaced more quickly. This potentially increases the sales volumes for more efficient appliances. Including miscellaneous appliances and modifying the service life of appliances in the model may increase the accuracy of the simulation. Other possible reason for the difference is that the simulation consider only the reasonable energy use and does not consider the unreasonable one (e.g., leaving lighting, air-conditioning and appliances switched-on while the room is unoccupied).

In addition, our simulation results tended to underestimate gas consumption by approximately 10% in 1990, 30% in 2000, and 40% in 2010. Figure 14 shows a comparison between the simulated monthly gas consumption and gas supply statistics. The simulated results were similar to the supply statistics for a number of months; however, there was a larger difference in spring (the simulated results were much smaller). It is possible that the gas demand for spring is based on old statistics (e.g., the questionnaire that our research group implemented and circulated in 2004). Therefore, updating the hot water demand may decrease the difference between simulated results and the statistics.

Analysis of the dominant factors of annual end-use energy consumption in the Osaka Prefecture

Figure 15 shows the dominant factors that contributed to the change in annual primary energy consumption in the Osaka Prefecture between 1990 and 2000 and between 2000 and 2010 based on our simulation.

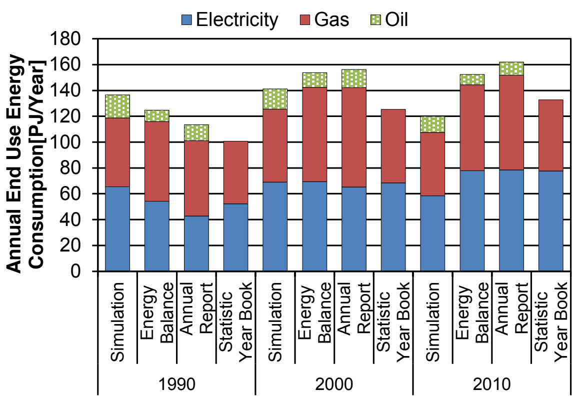

Figure 12: Simulated annual primary energy consumption and actual energy supply in Osaka Prefecture by energy source

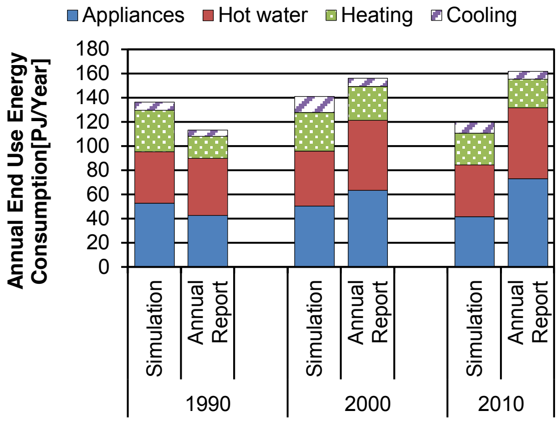

Figure 13: Simulated annual primary energy consumption and actual energy supply in Osaka Prefecture by energy usage

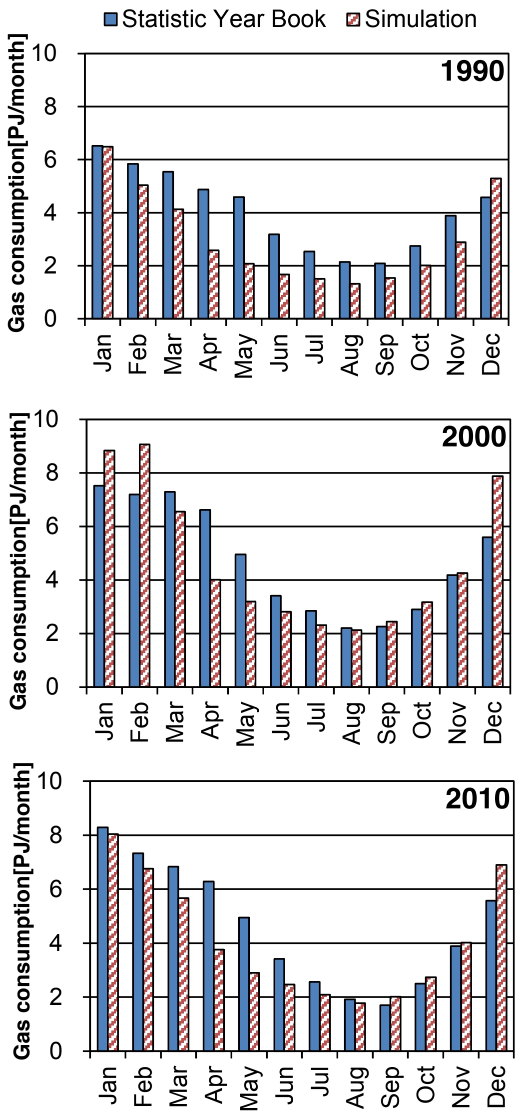

Figure 14: Simulated monthly gas consumption and actual gas consumption in the Osaka Prefecture

From 1990 to 2000, the energy consumption increased by 3.5%. The factors that accounted for a total decrease of 15.7% included improvements in appliance efficiency (11.4%) and in building insulation (2.6%). However, the factors accounting for a larger total increase (20.9%) in this period included an increase in the number of households (8.0%), diffusion of appliances (5.2%), and the difference in climatic conditions (4.2%).

In the period from 2000 to 2010, the total energy consumption decreased by 15.1%. The growth in the number of households, especially families with lower numbers, increased the energy consumption by 4.4% during this period. However, the greatest contributors to the 15.1% decrease in energy consumption included improvements in appliance efficiency (12.2%), diffusion of the new hot water heater (4.0%), the difference in climatic conditions (3.8%), and improvements in building insulation (2.7%).The results showed that the improvements in appliance efficiency was the largest contributor to reducing energy consumption. Although the model underestimated the energy consumption of home appliances, it could be improved if the replacements of appliances are estimated more accurately by modifying the "Appliances Stock model." The most influential factor in the increase in energy consumption was the growing number of households; thus, it is important that this factor is accurately reported.

In addition, the increasing sales volumes of new hot water heaters in homes could considerably decrease energy consumption. The analysis of sales volumes and improvements in the efficiency of water heaters must be considered important factors.

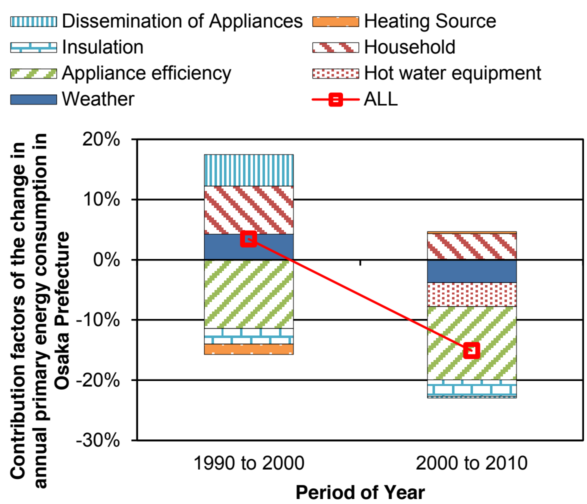

Figure 15: Factors contributing to the change in annual primary energy consumption in the Osaka Prefecture

Estimated energy consumption per household and per person

Figure 16 and 17 shows simulated energy consumption per household and per person in Osaka prefecture in 1990, 2000, and 2010. Energy consumption per household and per person has been basically decreased by the energy saving measures. In addition, the increase of small size households decreased energy consumption per household; however, energy consumption per person increased from 1990 to 2000. Two possible reason are that home appliances diffused and that the person in small size household increased, who use more energy than in large one. People in small size household cannot share the energy-use appliances with their family. Therefore, they use more energy than one in large size household.

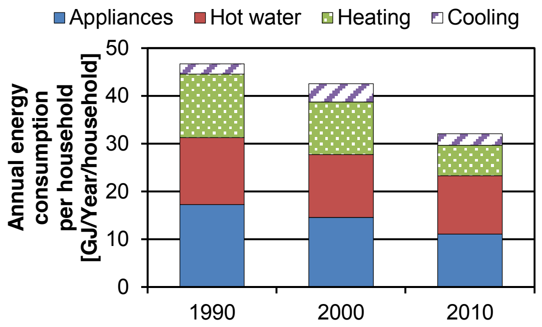

Figure 16: Simulated energy consumption per household

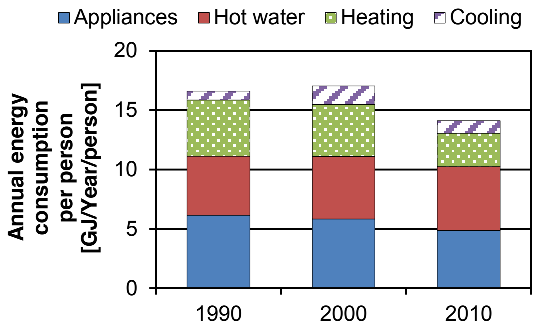

Figure 17: Simulated energy consumption per person

CONCLUSION

A "data preparation model" that estimated a number of data for our end-use model (not available from existing statistics) was created. The data preparation model for new residential water heaters was also developed in this study. The results showed that approximately 10% of households in the Osaka Prefecture in 2010 owned a highly efficient water heater.

Energy consumption from 1990 to 2010 in the Osaka Prefecture was estimated by our end-use model and compared to the statistics data for validation purposes. In 2000, the difference between our simulated results and the statistics was approximately 10%; however, in 1990, the simulated results were 9–17% higher. In 2010, the results of the simulation were 24–35% lower than the statistics. The results of our simulation underestimated the increase in energy use over the 20 years; however, the accuracy could be improved by updating the appliance and hot water usage figures.

According to our model, the most influential factor for the decrease in energy consumption was the improvement in appliance efficiency. In terms of increasing energy consumption, the most important factor was the increase in the number of households. In addition, the sales volumes of new (more efficient) hot water heaters decreased the energy consumption. Therefore, a data preparation model for a water heater was required to accurately estimate the influence of the new more efficient water heaters.

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