Evaluation on Residential Energy Efficiency Programs Using the City-Scale End-Use Simulation Model

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ABSTRACT

In this paper, energy conservation policies are evaluated by a model, which simulates city-level energy consumption in the residential sector whilst considering the diversity of household and building types. In this model, all households in the city are classified by household and building type into 460 categories. The energy consumption for each household category is simulated by the energy use schedule, hot water supply, and heating and cooling models. Since the energy use of each appliance is simulated respectively every five minutes, this model can not only evaluate the energy saving measures from improving building and appliances, but also the measures by changing occupant activities. In this paper, the model is applied to Osaka City, Japan, where the present amount of energy consumption is estimated and compared with the statistical value. Simulated energy consumption is smaller than the statistical value; one of the reasons for this is that the simulation does not take into consideration unreasonable energy use, e.g., leaving appliances switched-on while the room is unoccupied. The electricity load curve of the residential sector in the city is also simulated. In the last part of this paper, various types of energy conservation measures stated in the Japanese "New Climate Change Policy Program" are simulated and each measure is evaluated quantitatively. The results indicate that the heat insulation standard and energy efficiency standard for home electrical appliances will greatly impact energy conservation in the residential sector.

Introduction

In Japan, energy consumption in the residential sector is increasing continuously due to improvements in living standards, such as larger houses, the popular use of various kinds of home electrical appliances, and the increasing number of smaller sized families. In the last 25 years, energy consumption of the residential sector has doubled while the population has increased by only 10%.

To achieve the 6% greenhouse gas reduction commitment in the Kyoto Protocol, various measures were proposed for the residential sector in Japan. The "New Climate Change Policy Program", which was adopted in March 2002, aims to keep the CO_2 emission from energy use at 1990 levels. As part of this program, the Law Concerning Rational Use of Energy established one of the highest energy efficiency standards in the world for home electrical appliances, commonly known as the "Top-Runner Standard". In this standard, an appliance manufacturer's average energy efficiency in 2004 must be higher than the most efficient model in 1999. Besides the Top-Runner Standard, the New Climate Change Policy Program specifies:

- Development and dissemination of home energy management systems
- Increase of energy efficient residential buildings
- Reduction of stand-by power
- Promotion of high efficiency water heaters
- Development of high efficiency lights
- Change in life style, such as: easing set room air temperature, family members staying together in a living room not in their individual rooms, and reducing TV watching hours

Generally, it is very difficult to estimate the effect of these measures quantitatively on a city or nationwide level. So far, the quantitative evaluation of energy conservation measures has been based on simulated results for the 'standard household', a family with two adults and two children. However, the energy consumption of each household differs considerably, depending on the household type (number and age of members), dwelling type, number and efficiency of appliances, and other factors.

The authors (Shimoda et. al. 2004) have developed a bottom-up simulation model, which simulates city-level energy consumption in the residential sector whilst considering the diversity of household and building type. In this model, all of the households in the city are classified by household and building type into 460 categories. The hourly energy consumption for each household category is simulated by the energy use schedule, heating and cooling, and hot water supply models. In the energy use schedule model, energy use of appliances is simulated individually, based on schedule data of the occupant's behavior. In the heating and cooling model, cooling and heating load is calculated from building and weather data. Internal heat gain and occupants' schedule, which are calculated by the energy use schedule model, are also used in this model. To avoid excessive computation load, we developed a simple heat load calculation model in this study. Since intermittent air-conditioning by air conditioners and heaters equipped in each room is common in Japan, consideration of the occupant's schedule is necessary to estimate energy consumption for heating, cooling and lighting correctly, as well as energy consumption of appliances such as televisions. In Japan, time allocation of living activities is surveyed every five years (Broadcasting Culture Research Institute, 2001). These results can be used for modeling the occupants' energy use schedule.

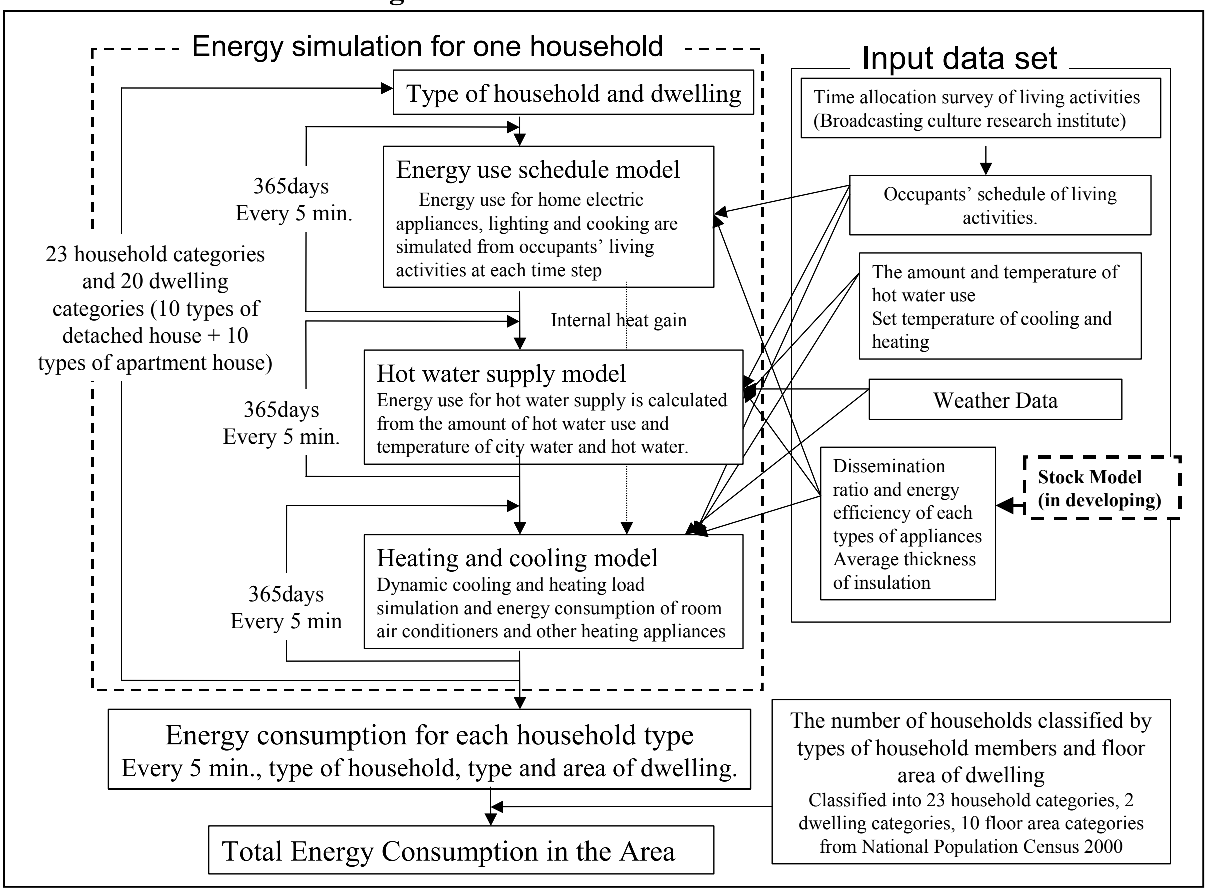
In this paper, our previous model was improved in the heat load calculation and occupants' schedule simulation. The new model has been applied to Osaka City (population: 2,600 thousand, households: 1,058 thousand). The present amount of energy consumption in the residential sector is estimated and compared with statistical data. In the final part of this paper, the energy saving effects of measures proposed in the "New Climate Change Policy Program" are evaluated quantitatively.

Simulation Model

Structure of the Simulation Model

Figure 1 shows the whole structure of the simulation model. In this simulation, annual energy consumption of one household is calculated iteratively for 23 household categories and 20 dwelling categories (10 categories for detached houses and 10 categories for apartment houses). Each occupant's time allocation for living activities, amount and temperature of hot water supply, set heating and cooling temperature, weather data, appliance energy efficiency properties, and building heat insulation properties must be provided as input data. Multiplying the simulated energy consumption by the number of households in each category, and then summing them up, can estimate the total energy consumption by the residential sector in the object region. The authors are also developing the 'stock model', which estimates the distribution of appliance energy efficiency, building heat insulation properties, and the ages among household members in the object region. This model will enable us to simulate the dynamic transition of energy consumption caused by energy conservation policy and other factors.

Figure 1. Flowchart of the Simulation



Energy Use Schedule Model

Schedule of living activities. To determine the occupant's schedule of living activities, the results of the time allocation survey of living activities have been used. In the former model (Shimoda et. al. 2004), the living activity of an occupant at each time step is expressed as a percentage of probability. In the new model, the living activity is determined by the multi-agent simulation to express the distribution of activities among occupants within the same category and difference of activities day-by-day.

Linking between living activities and energy use. Each living activity calculated by this simulation is linked with energy use of appliances and hot water use. The probability of appliance use is also considered. From the links between each family member and room, the room where each living activity occurs is also identified to determine energy use for heating, cooling and lighting. Table 1 shows the power consumption and standby power of home electrical appliances used in this simulation. Dissemination ratios of these appliances are also considered in this model.

Hot Water Supply Model

Energy consumption of hot water use is calculated from the amount of hot water, hot water temperature and city water temperature. City water temperature is considered to be the function of outdoor air temperature.

Table 1. Power Consumption of Home Electric Appliances Used in this Simulation

Appliances	Room	Number of holding (per 100 households)	Power consumption [W]	
			Operating mode	Standby
Rice cooker	Kitchen	88.2	225.0	31.0
Dishwasher	Kitchen	11.0	1000.0	3.0
Thermos	Kitchen	55.0	66.0	No standby
Microwave	Kitchen	101.1	200.0	2.8
Oven	Kitchen	79.0	1000.0	2.8
Toaster	Kitchen	79.0	500.0	2.8
TV	Living & bedroom	227.3	120.0	2.0
Refrigerator*	Kitchen	118.4	600.0	No standby
Fan	Kitchen	100.0	20.0	0.0
Washing Machine	Bathroom	106.6	126.0	0.0
Tumble dryer	Bathroom	28.2	1300.0	0.0
Hair dryer	Bathroom	86.0	450.0	0.0
Desk lamp	Bedroom	100.0	30.0	0.0
Vacuum	Living room	144.1	200.0	0.0
Iron	Living room	90.0	500.0	0.0
VCR	Living & bedroom	127.1	120.0	6.2
Radio	Living & bedroom	57.1	100.0	14.0
CD player	Bedroom	117.0	100.0	14.0
PC	Bedroom	48.1	300.0	1.5
BS tuner	Living & bedroom	46.9	**	12.3
Fax	Living room	39.9	**	20.0
Telephone	Living room	138.6	**	5.0
Shower toilet	Toilet	49.4	**	35.0
Kotatsu (foot warmer)	Living room	117.1	500.0	0.0
Electric carpet	Living room	108.0	580.0	0.0

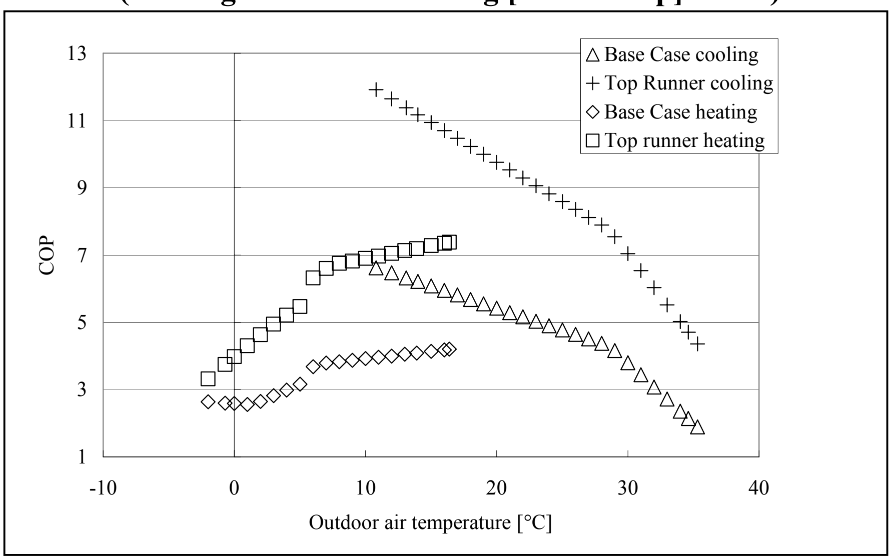
*Power consumption of refrigerator is modeled as a function of outdoor air temperature.
**Operating mode is not considered.

Heating and Cooling Model

Heat load simulation. By setting a standard floor plan for each category of dwelling type and floor area, dynamic heat load simulation can be carried out. In the former model, heat conduction and ventilation between rooms was not considered. In the new model, these factors are taken into account by the thermal circuit network method. In this method the room air, thin wall or window is expressed as one node and thick wall is expressed as two nodes (inside and outside). Heat transfer between these two nodes is calculated from thermal resistance and temperature difference. In this model, all detached houses are assumed to be wooden buildings and all apartment houses assumed to be reinforced concrete buildings. Heat insulation property is set as the estimated average value in 1997 (See table 2, Jukankyo Research Institute, 1999).

Room air conditioner model. The Coefficient of Performance (COP) of room air conditioners is modeled as a function of outdoor air temperature; it varies at each time step. This function is derived from the calculation method of SEER for room air conditioners (Japan Refrigeration and Air Conditioning Industry Association, 1999). Figure 2 shows the COP of current room air conditioners and adapted to the 1999 Law Concerning Rational Use of Energy ('Top-Runner Standard'). The operation probability function of hour and room air temperature is also considered in this model. In Japan, most air conditioners operate in heat pump mode. Energy consumption for heating is calculated from the estimated share and efficiency of room air conditioners, and electric and oil heaters.

Figure 2. Relationship between Outdoor Air Temperature and COP. (Cooling Mode and Heating [Heat Pump] Mode)



Classification of Households

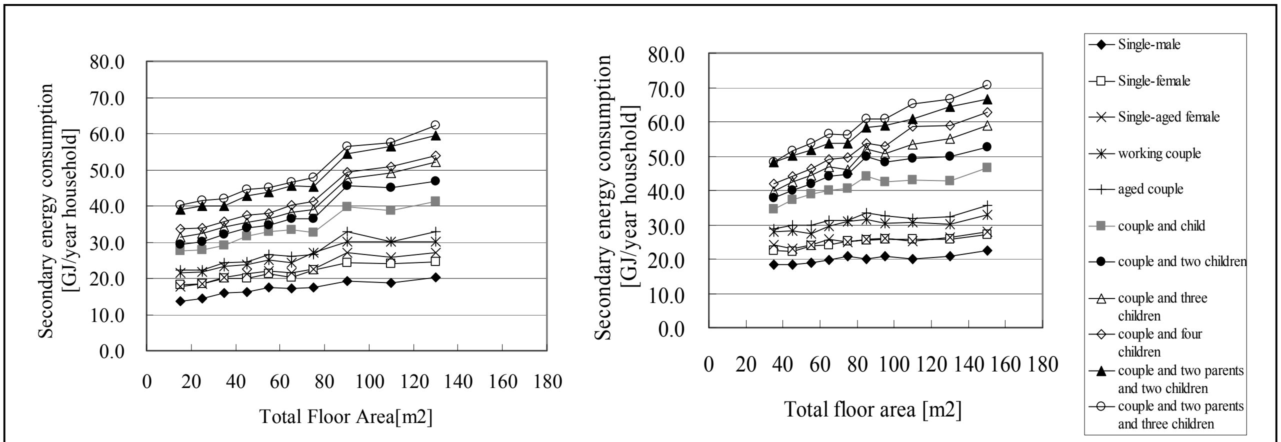
Using the results of the National Population Census (Statistics Bureau and Statistics Center, 2000), all households in Osaka City are classified into 23 household categories, 2 dwelling categories (detached house or apartment house), and 10 floor area categories for each dwelling categories.

Simulation Results for Present Condition

Simulation Results for Each Household

Figure 3 shows the distribution of simulation results of the total annual energy consumption of one household in a detached house and an apartment house respectively. These figures show that total energy consumption depends more on the number of family members than total floor area. The influence of total floor area on energy consumption is stronger in larger families, since the number of occupied rooms and energy use for lighting, heating and cooling increases with the number of family members. In addition, energy consumption by TV usage is increased with the number of rooms occupied, since a TV is assumed to be available in the living room and all bedrooms. (By this assumption, the total number of TV holding becomes closer to the statistic value shown in Table 1.)

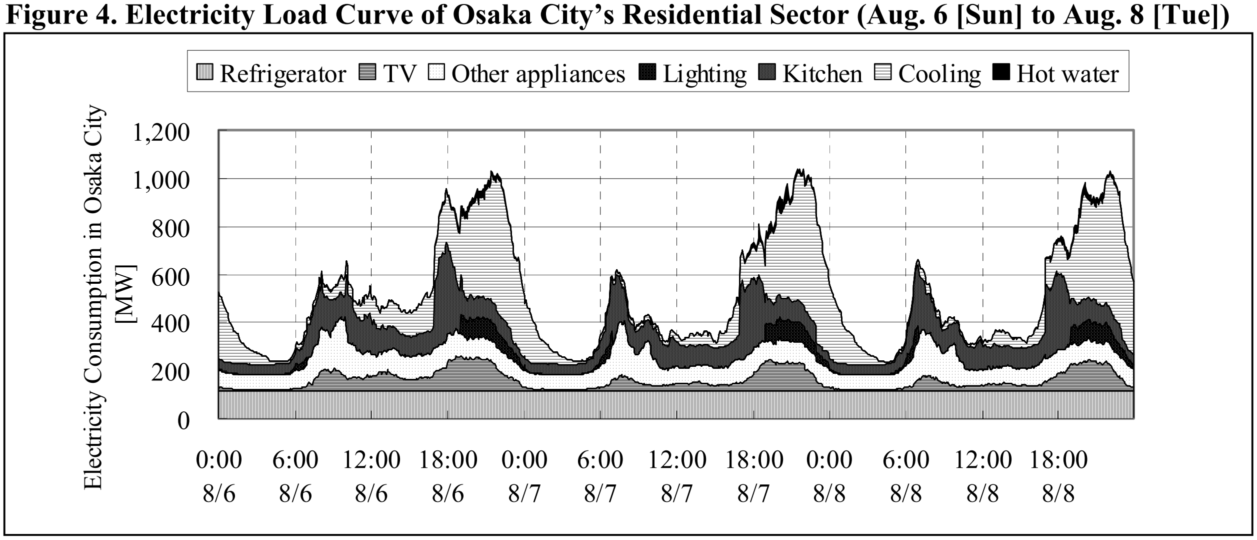
Figure 3. Distribution of the Total Energy Consumption for Apartment House [Left] And Detached House [Right]



Total Energy Consumption in City and Comparison with Statistical Data

Figure 4 shows the electrical load curve of Osaka city's residential sector. Improvement on the energy use schedule model (introduction of multi-agent simulation) makes this load curve more realistic than that of the previous model. (Shimoda et. al. 2004)

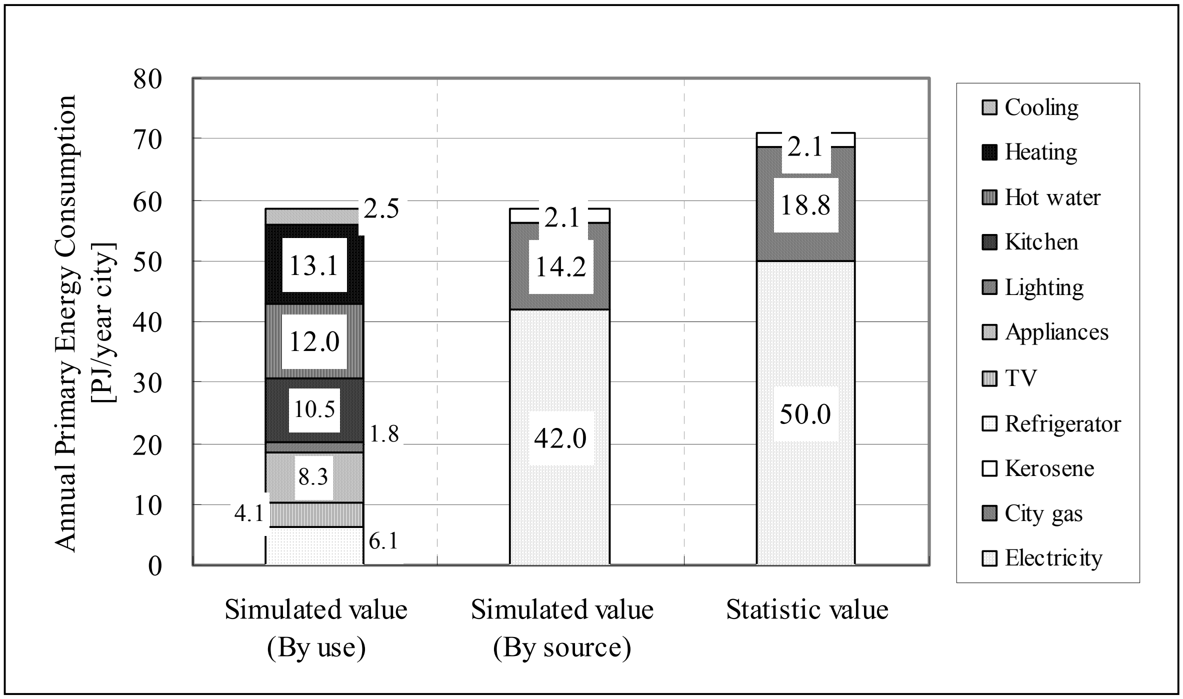
Figure 4. Electricity Load Curve of Osaka City's Residential Sector (Aug. 6 [Sun] to Aug. 8 [Tue])



* 'Kitchen' means six appliances from the top of table 1.
** Energy use of refrigerator is modeled as the function of daily average outdoor air temperature. Hourly change is not modeled.

Figure 5 shows the comparison between the simulated annual primary energy consumption and statistical values of the residential sector in Osaka City. Simulated energy consumption is smaller than the statistic value by 18%. In addition to the errors in the set values and assumptions, the reason for the difference is that the simulation does not take unreasonable energy use into consideration, e.g., leaving lighting, air conditioning and other electrical appliances switched-on while a room is unoccupied.

Figure 5. Comparison Between Simulation Result and Statistic Value



Evaluation on Energy Saving Measures for Heating and Cooling by the Model

One of the significant advantages of the model is that it simulates heating and cooling load precisely by coupling the dynamic heat load simulation and energy use schedule model. It enables us to consider the change in energy consumption by heat insulation of dwelling, climate condition, and schedule of living activities. Accordingly, the effect of a heat insulation standard and an energy efficiency standard of room air conditioners is predicted as an example of energy conservation policy evaluation by this simulation model.

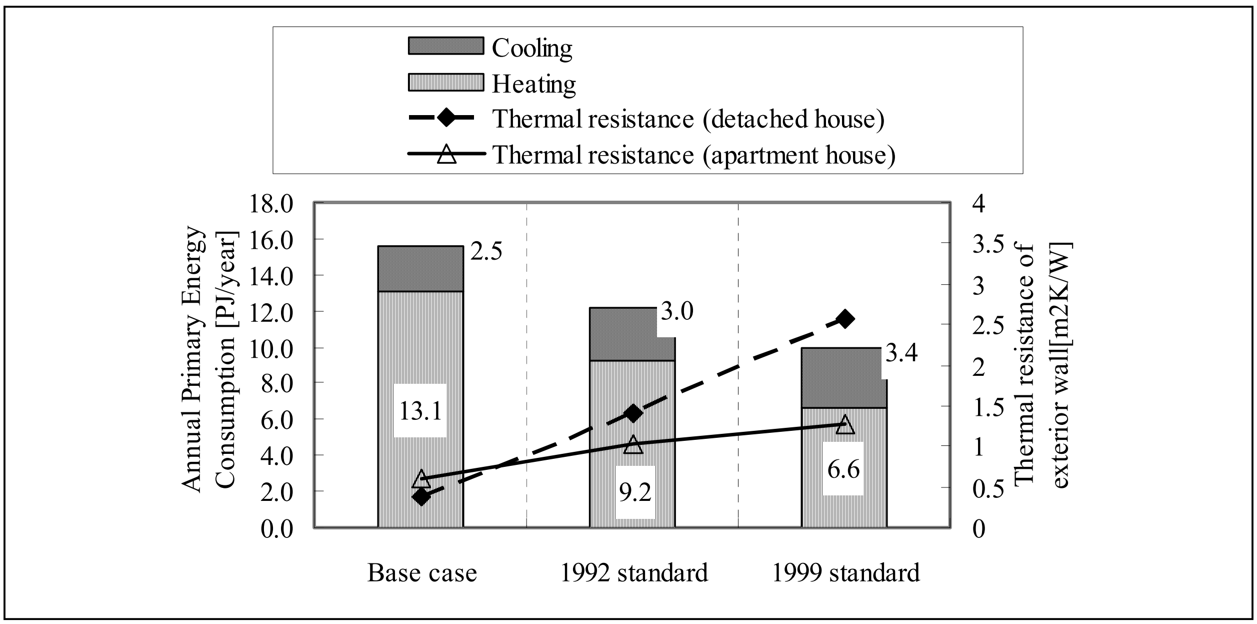
Heat Insulation of Exterior Walls

Figure 6 shows the simulated total energy consumption for heating and cooling in the Osaka City area under the following three heat insulation conditions: 1) Base case; 2) 1992 Standard ('New Energy Conservation Standard'); and 3) 1999 Standard ('Next Generation Energy Conservation Standard'). These conditions are shown in table 2. Thermal resistances of exterior walls under these conditions are also shown in figure 6. As the heat insulation property improves, energy consumption for heating decreases greatly. If all dwellings adapt to the 1999 standard, heating energy consumption is reduced by 6.4 PJ/year from the base case. This amount is equal to 11% of the total primary energy consumption of the residential sector in Osaka City. On the other hand, with the increasing heat insulation property of the exterior wall, energy consumption for cooling is slightly increased. This is because the internal heat gain is accumulated by insulation, since ventilation by opening a window is not considered in this model.

Table 2. Heat Insulation Conditions Used in this Study

Standard	Exterior wall		Window
(Detached house)			
Base case	Glass wool (0.036W/mK)	14.9mm	Single glazing (6.51W/m2K)
1992 Standard	Glass wool (0.036W/mK)	55.0mm	Single glazing (6.51W/m2K)
1999 Standard	Glass wool (0.036W/mK)	90.0mm	Double glazing (4.65W/m2K)
(Apartment house)			
Base case	Polystyrene foam (0.040W/mK)	24.0mm	Single glazing (6.51W/m2K)
1992 Standard	Polystyrene foam (0.040W/mK)	35.0mm	Single glazing (6.51W/m2K)
1999 Standard	Polystyrene foam (0.028W/mK)	35.0mm	Double glazing (4.65W/m2K)

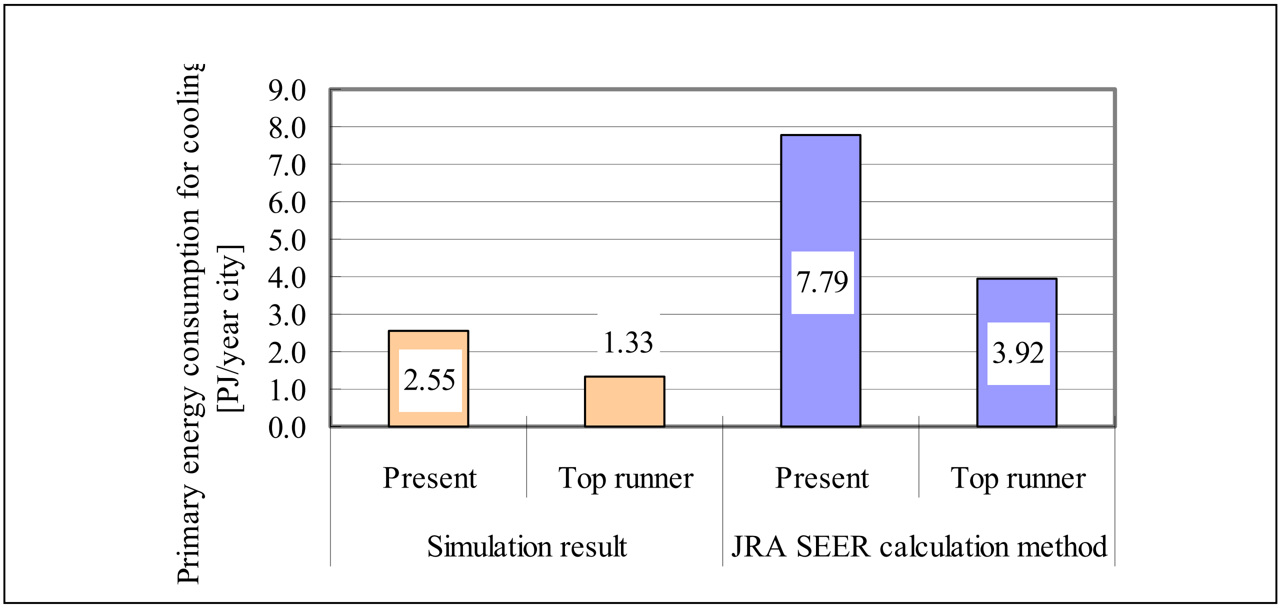
Figure 6. The Effect of Heat Insulation on Total Energy Consumption for Heating and Cooling in Osaka City



Room Air Conditioner

Figure 7 shows the change in energy consumption in Osaka City for cooling under the current energy efficiency and efficiency adapted to the 1999 Law Concerning Rational Use of Energy ('Top-Runner Standard'). Figure 7 also shows the same changes predicted by the JRAIA SEER calculation method (Japan Refrigeration and Air Conditioning Industry Association, 1999). In the latter prediction, annual cooling energy consumption predicted by the JRAIA method is multiplied by the total number of room air conditioners in Osaka City, defined by our simulation model for each cooling capacity respectively. From the simulation result, primary energy consumption for cooling in Osaka City is reduced by 1.22PJ and this amount is equal to 2.1% of the total primary energy consumption in Osaka City. Both the present energy consumption and the energy saving by the Top-runner Standard predicted by the JRAIA method are much larger than the simulated result. Although an 18-hour operation (from 6 AM to 12 AM) per day is assumed in the JRAIA SEER calculation method, room air conditioners are not operated often during the daytime in Japanese residences. In our simulation model, the operation of a room air conditioner during the day on weekdays is restrained by introducing operation probability as a function of time (hour), as shown in figure 4. For that reason, the energy consumption and energy saving by the Top-runner Standard predicted by the JRAIA method is overestimated.

Figure 7. Change of Energy Consumption of Room Air Conditioner By Energy Efficiency Standard



Evaluation on the "New Climate Change Policy Program"

In addition to the results mentioned above, major energy conservation measures in the residential sector stated in the "New Climate Change Policy Program" were evaluated quantitatively. The energy conservation measures considered in this paper and these simulation methods are shown as follows:

- **Easing set room temperature.** Set room temperature is changed from base case (27°C in cooling and 20°C in heating) to 28°C in cooling and 19°C in heating.
- **Adaptation to Top-Runner Standard for refrigerator.** Annual energy consumption is reduced from 600kWh to 400kWh.
- **Adaptation to Top-Runner Standard for television.** Energy consumption in operation mode is reduced from 120W to 103W and standby power is also reduced from 2.0W to 0.6W.
- **Adaptation to Top-Runner Standard for all other home appliances.** All luminaries, VCRs, showers, toilets, gas water heaters and oil water heaters are adapted to their "Top-Runner Standard".
- **Introduction of water saving shower-head.** 50% of hot water use for showers is reduced.

- **All the members of family watching TV together.** In the energy use schedule model, the room where the activity of 'watching TV' and 'taking a rest' occurs is changed from each member's bedroom to the living room.
- **Shorten TV watching by one hour.** In the occupant's schedule of living activities, the time for TV watching is shortened by one hour for every household member.
- **Shorten showering time by one minute.** In the occupants' schedule of living activities, the time for showering is shortened by one minute for every household member.

Figure 8 shows the energy conservation effects in Osaka City by all measures, including the heat insulation of exterior walls and Top-Runner Standard for room air conditioners in order of energy conservation effect. The result shows that the energy conservation standards for heat insulation and home electrical appliances are effective for city scale energy conservation. On the other hand, lifestyle changes, such as 'watching TV together' and 'shortening showering time' without 'easing set room temperature' are less effective.

Conclusion and Future Work

In this paper, various types of energy conservation measures in the residential sector proposed by the Japanese government are evaluated quantitatively by the simulation model developed by the authors. When discussing the nationwide effect of these measures from the results of this paper, it must be noted that, in comparison to many other cities, the proportion of single families and small dwellings in Osaka City is large[1]. Nonetheless, the authors feel that this model for Osaka City, a typical business city in Japan, can be applied to many other locations and various types of measures. This model permits the application of various types of conditions, such as the performance of each appliance in the city, weather condition, demographic condition and different energy conservation measures. The authors will improve this model by comparing it with the field measurement results and applying this model to other areas and occasions.

Acknowledgements

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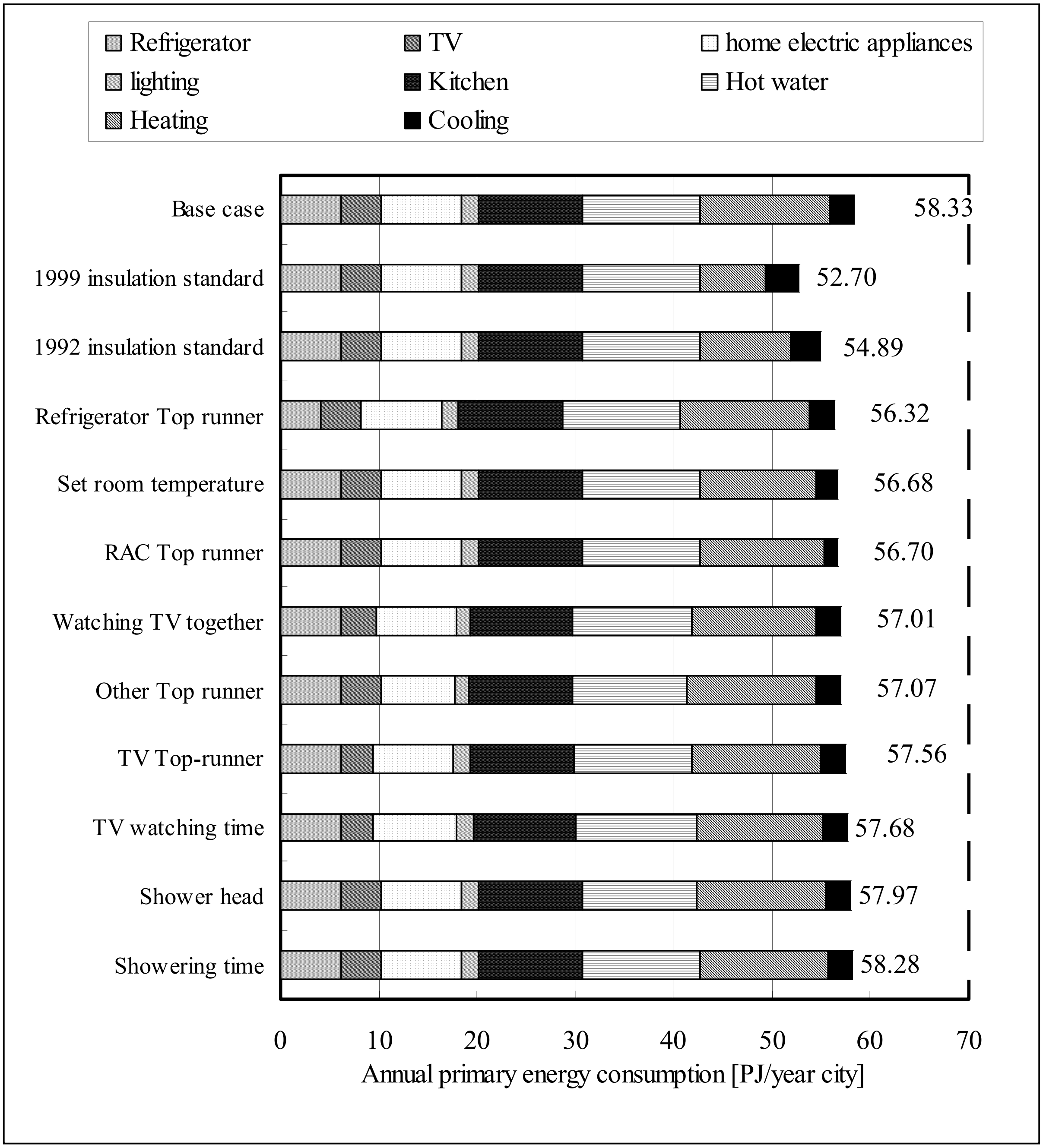
[1] The proportion of single families in Osaka City is 40.3%. Japanese average is 27.4%.

Figure 8. Energy Conservation Effects of each Measure in Osaka City



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