EFFECTIVENESS OF ENERGY CONSERVATION MEASURES IN RESIDENTIAL SECTOR OF JAPANESE CITIES

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ABSTRACT

Energy consumption by residential sector of 20 Japanese cities was modeled at the city-scale. In the model, households were classified into 228 categories based on the family and building type. We evaluated the effectiveness of energy conservation measures, such as improving energy efficiency of home appliances, improving heat insulation of buildings, changing preset temperature, and all family members watching TV together. In addition, we also discussed differences in energy saving effects between cities.

KEYWORDS

Residential energy consumption, Household type distribution, City-scale evaluation, Comparison of cities, Energy-saving measures

INTRODUCTION

In Japan, energy consumption by the residential sector has increased steadily in response to improvements in the standard of living, which has become manifested as an increase in the size of houses, use of electric home appliances, and the number of single households. In the last 25 years, energy consumption by the residential sector has doubled while the population has increased by only 10% (The Energy Conservation Center, 2002).

Consequently, “the New Climate Change Policy Program”, adopted by the Japanese government in March 2002, sought to maintain CO_2 emissions attributed to energy usage at 1990 levels. In April 2005, the “Kyoto Protocol Target Achievement Plan” was also adopted. By improving the energy efficiency of buildings and appliances, the intention of the plan was to reduce CO_2 emissions from the residential sector to levels that were only 6% higher than they were in 1990. An outcome of a revision of the Law Concerning Rational Use of Energy was the establishment of one of the highest energy efficiency standards in the world for electric home appliances. The standard, commonly referred to as the “Top-runner Standard”, required that the average energy efficiency of an appliance manufacturer in 2004 had to be greater than that of the most efficient model outcome in 1999. This standard was revised in 2005 to extend the potential application of the standard to include a greater variety of appliances. In addition to the top-runner standard, the New Climate Change Policy Program prescribed a variety of energy conservation measures, including increased energy efficiency of residential buildings, reduced standby power, and promoted the use of more efficient water heaters. The program also encouraged changes in consumer behavior, such as “changing the preset temperature – increase for cooling and decrease for heating”, “encouraging family members to spend more time together in the living room as opposed to staying in their individual rooms” and “reducing the number of hours spent watching TV”.

It is known that residential energy consumption varies in response to factors such as family type, building type, floor area, and climate (Shimoda Y., 2007). Since these factors vary markedly depending on geographical location, the impact of energy conservation measures varies between cities. The objectives of this study were thus to investigate the differences in the energy demand structure between cities, and to assess optimal measures for each.

Among the energy saving measures examined, those affecting heating and cooling are evaluated in this study since the effects vary markedly between cities. We therefore examined the effects of measures designed to improve the thermal insulation of houses and the energy efficiency of appliances, change preset temperature, and have the occupants of a household watch TV together as opposed to separately, and compared the effects in 20 Japanese cities. In the final part of this paper, the effects by combining multiple measures are also evaluated.

SIMULATION MODEL

Structure of the simulation model

The authors developed an original bottom-up model to simulate city-scale energy consumption in the residential sector that considers the diversity of family and building types. In the simulation, the annual energy consumption of one household is calculated iteratively for 19 household categories, as well as 12 building categories – six of which were classified as detached houses and the other six as apartments depending on floor area. In addition, five different building insulation levels were classified. In the appliance energy use model, the energy use of each appliance was simulated separately and is based on occupant behavior. For the heating and cooling model, dynamic heat load simulations were conducted using both building data and weather data. Ventilation and heat conduction between rooms was considered using a thermal circuit network method. Heating and cooling loads were simulated relative to the internal heat gain, which is calculated using the appliance energy use model and the behavior of the occupants. Time step of the heat-load and energy-use simulation was five minutes.

Total residential energy consumption in the target region was estimated by multiplying simulated energy consumption by the number of households in each category and then summing them up.

The authors previously developed a "Stock model" (Shimoda Y., 2007), which is used here to estimate the average energy efficiency of appliances and the distribution of building's insulation levels in the target region. This model will enable us to generate input data such as the average energy efficiency of appliances in the target year.

Simulation results for present conditions and verification of the model

Figure 1 shows a comparison between the simulated annual primary energy consumption and actual energy supply for the residential sector of Osaka City in 2000. Actual electricity supply data was acquired from utility companies and the amount of kerosene supplied was examined as units per household and obtained from Annual Report on the Survey of Household Economy.

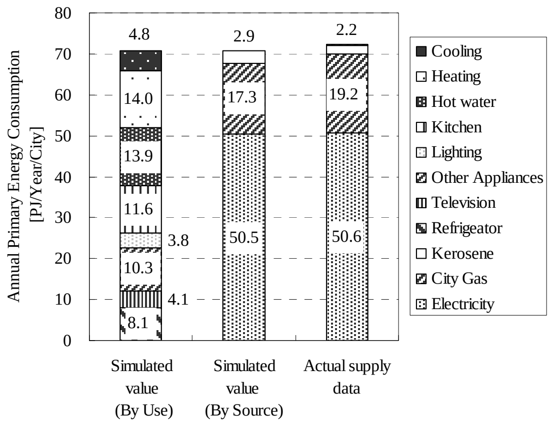

Figure 1 Simulated annual primary energy consumption and actual energy supply in Osaka City

The simulated total energy consumption was within 2.0% of the actual primary energy supply. The errors associated with estimates for electricity, city gas and kerosene supplies are -0.3%, -10.2%, and 29.9%, respectively. These figures are in good agreement with actual data.

SIMULATION RESULTS FOR THE CITIES EXAMINED

Subject cities

Twenty representative cities were selected for evaluation in Japan (Figure 2). These cities covered Regions I to VI as defined by the Law Concerning Rational Use of Energy. Ten cities were selected from Region IV because this region contains a large quantity of households.

Figure 2 Target cities

Region I: Asahikawa, Sapporo

Region II: Morioka

Region III: Akita, Sendai

Region IV: Utsunomiya, Tokyo (special wards), Niigata, Kanazawa, Nagano, Shizuoka, Nagoya, Osaka, Matsue, Hiroshima, Takamatsu

Region V: Kochi, Fukuoka, Kagoshima

Region VI: Naha

The parameters examined for respective cities

The parameters that were examined for respective cities are as follows:

- Number of households in each category
- Weather data
- Thermal resistance of insulation
- Duration of heating and cooling
- Number of appliances
- Equation for estimating city water temperature
- Frequency of bathing
- Energy source, and relative proportion, for hot water (electricity, city gas, kerosene)

- Energy source, and relative proportion, for heating (electricity, city gas, kerosene)
- Relative proportion of room air conditioner and electric heater
- Heating schedule

The most important of these parameters are explained in detail in the following section.

Thermal resistance of insulation

Heating and cooling loads were simulated for five levels of insulation: no insulation, insulation below the 1980 standard, insulation up to the 1980 standard, insulation up to the 1992 standard, and insulation up to the 1999 standard. Values for thermal resistance of insulation for exterior walls in each region are shown in Table 1.

The heating and cooling energy consumption for each family and building category was obtained from the weighted average of simulation results for each insulation level relative to the proportion of each insulation level estimated using our stock model (Figure 3). Since there was no obligations regarding building insulation in Japan, the proportions of houses that meet the 1992 and 1999 standards is very small.

Table 1 Thermal resistance of exterior wall insulation

Apartment	Themal resistance [m^2K/W]					
	Region I	Region II	Region III	Region IV	Region V	Region VI
No insulation	-	-	-	-	-	-
Below 1980	0.56	0.38	0.38	0.25	0.00	-
1980 Standard	1.13	0.75	0.75	0.50	0.00	-
1992 Standard	1.72	0.95	0.95	0.77	0.52	0.00
1999 Standard	2.30	1.80	1.10	1.10	1.10	0.30
Detached house	Themal resistance [m^2K/W]					
	Region I	Region II	Region III	Region IV	Region V	Region VI
No insulation	-	-	-	-	-	-
Below 1980	1.10	0.45	0.45	0.30	0.00	-
1980 Standard	2.20	0.90	0.90	0.60	0.00	-
1992 Standard	2.49	0.95	0.95	0.86	0.52	0.00
1999 Standard	3.30	2.20	2.20	2.20	2.20	2.20

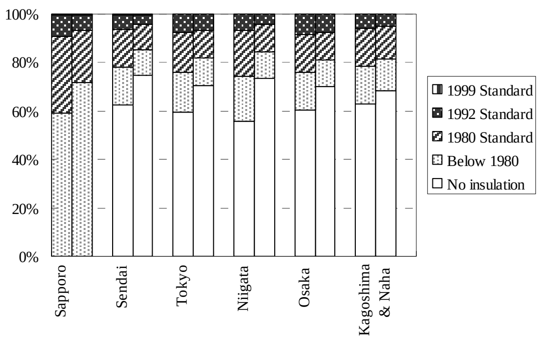

Figure 3 Proportion of each insulation level (left bar: apartment, right bar: detached house)

Duration of heating and cooling

The duration of heating and cooling was defined as for SMASH; the Japanese residential thermal load calculation model. Table 2 shows the duration of heating and cooling in each city.

Table 2 Duration of heating and cooling

	Duration of Heating	Duration of Cooling
Sapporo	25-Sep - 9-Jun	10-Jun - 24-Sep
Sendai	11-Oct - 16-May	17-May - 10-Oct
Niigata	19-Oct - 10-May	11-May - 18-Oct
Tokyo	2-Nov - 22-Apr	23-Apr - 1-Nov
Osaka	7-Nov - 15-Apr	16-Apr - 6-Nov
Kagoshima	3-Nov - 20-Apr	21-Apr - 2-Nov
Naha	-	1-Jan - 31-Dec

Energy source for hot water

Energy sources and relative proportion, used for hot water (electricity, city gas, kerosene) were extracted from the Annual Report on Residential Energy (Table 3).

Table 3 Energy source for hot water (electricity, city gas, kerosene)

	Electricity	City Gas	Kerosene
Sapporo	7.4%	40.6%	52.0%
Sendai	6.7%	49.4%	43.9%
Niigata	14.9%	64.2%	20.9%
Tokyo	3.6%	84.1%	12.3%
Osaka	6.2%	83.0%	10.8%
Kagoshima	12.1%	64.7%	23.5%
Naha	12.1%	64.7%	23.5%

Energy source for heating

Energy sources for heating (electricity, city gas, kerosene) were extracted from the Annual Report on Residential Energy (Table 4).

Table 4 Energy sources for heating (electricity, city gas, kerosene)

	Electricity	City Gas	Kerosene
Sapporo	8.2%	1.9%	89.9%
Sendai	10.5%	6.7%	82.8%
Niigata	14.4%	19.0%	66.6%
Tokyo	36.9%	20.8%	42.3%
Osaka	43.2%	23.4%	33.4%
Kagoshima	31.0%	8.6%	60.4%
Naha	31.0%	8.6%	60.4%

Relative proportion of room air conditioner and electric heater

The split between of room air conditioners (RAC) and electric heaters varied according to city. The relative proportion of air conditioners and electric heaters could be estimated (Table 5) from the numbers of electric heaters and room air conditioners (Economic Planning Agency of Japan, 1999, The Institute of Energy Economics, 2000). To estimate heating energy demand, an average COP of 3.12 was used for each air conditioner (Jyukankyo Research Institute Inc., 1999).

Table 5 Relative Proportion of air conditioners and electric heaters

	Apartment		Detached house	
	Electric Heater	RAC	Electric Heater	RAC
Sapporo	57.6%	42.4%	71.6%	28.4%
Sendai	57.6%	42.4%	71.6%	28.4%
Niigata	38.4%	61.6%	53.6%	46.4%
Tokyo	23.6%	76.4%	21.6%	78.4%
Osaka	25.4%	74.6%	21.3%	78.7%
Kagoshima	21.0%	79.0%	19.9%	80.1%
Naha	21.0%	79.0%	19.9%	80.1%

Heating/cooling schedule

In this model, heating/cooling while sleeping was estimated using a timer-controlled operation (Table 6). In Region I, heating was assumed to extend throughout the night.

Table 6 Probability of using timer-controlled heating (except Region I)

	Heating	Cooling
Not used	60.0%	20.0%
1 hour	10.0%	25.0%
2 hour	10.0%	20.0%
3 hour	10.0%	15.0%
4 hour	5.0%	10.0%
5 hour	3.0%	5.0%
throughout the night	2.0%	5.0%

Annual energy consumption in 20 cities

Applying this model to each city, annual primary energy consumption could be simulated. Figure 4 shows a comparison of simulation results for energy use per household and per person.

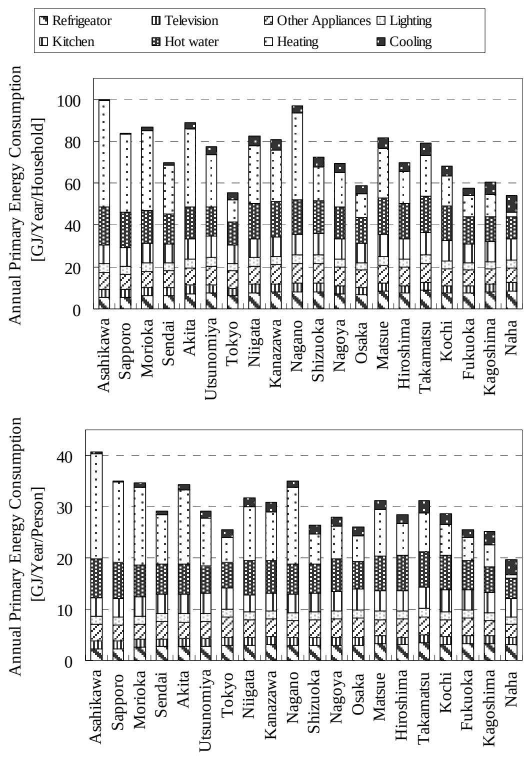

Figure 4 Simulated annual primary energy consumption (top: per household; bottom: per person)

Interestingly, energy consumption per household for heating and cooling vary markedly between cities, with differences in other energy use categories being relatively small.

Also, while energy consumption for heating was high in Asahikawa, Sapporo, Morioka, Akita, and Nagano, in Sendai, despite being located in a cold area, heat consumption was relatively low. The reason for this apparent anomaly is because Sendai has a high percentage of apartments.

The difference in energy consumption per household was greater than the difference observed per person. This is because it is the average number of people per household that affects energy consumption.

EVALUATIONS OF DIFFERENT ENERGY CONSERVATION MEASURES

The effects of energy saving measures were compared in seven cities (Sapporo, Sendai, Tokyo, Niigata, Osaka, Kagoshima, and Naha). Specifically, the measures evaluated included:

- Energy efficiency standard for home appliances
- Energy efficiency standards for air conditioners
- Improvements in building heat insulation
- Changing preset temperature
- All family members watching TV together

Energy efficiency standards for home appliances

Energy saving effects were evaluated for appliances that had been adapted to top-runner standard (except air conditioners), including all refrigerators, televisions, lighting devices, VCRs, shower toilets, and gas and oil water-heaters (The Energy Conservation Center, Japan, 1999-2005) in cities. Table 7 shows the base and top-runner appliance efficiencies and their associated power consumption.

Table 7 Base and top-runner appliance efficiency and power consumption

	Base		Top-runner	
	Operation Mode [W]	Stanby Mode [W]	Operation Mode [W]	Stanby Mode [W]
Television	114.0	2.4	104.3	0.2
VCR	21.0	3.7	10.5	0.9
Shower Toilet	0.0	35.0	0.0	20.0

	Electric Power Consumption [W/m^2]	
	Base	Top-runner
Lighting	5.0	4.6

	Efficiency [%]	
	Base	Top-runner
Gas Water Heater	78.0	92.0
Oil Water Heater	80.0	86.8

		Electric Power Consumption [kWh/Year]	
		Base	Top-runner
Refrigeator	200-250l	543	304
	300-350l	597	361
	350-400l	691	162
	400-450l	784	162
	450-500l	1219	486
	500l-	1219	532

Energy reduction rates associated with improved energy efficiency of appliances are shown in Figure 5. Here, primary energy consumption was reduced by 7-14% in respective cities. Reduction rates were relatively higher in the warmer cities since the ratio of energy used for heating to total energy consumption is low while ratio for appliances is high. In addition, given the decrease in the heat gain of appliances with improved energy efficiency, the energy used for cooling decreased slightly while that employed for heating increased.

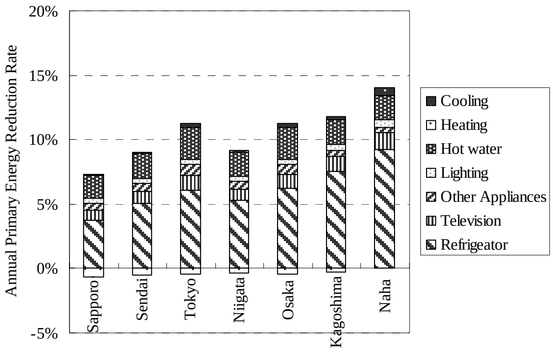

Figure 5 Energy reduction rates by improved energy efficiency of appliances

Energy Efficiency Standard for Air Conditioners

The case was adopted in which all room air conditioners in cities conform to the latest top-runner standard (The Energy Conservation Center, Japan, 1999-2005). Table 8 shows the rated COP of conventional and top-runner air conditioners.

Table 8 The rated COP of base and top-runner air conditioners

Unit [-]	Base		Top-runner	
Cooling Capacity	Rated COP (Cooling)	Rated COP (Heating)	Rated COP (Cooling)	Rated COP (Heating)
2.2kW	2.77	3.23	5.64	5.42
2.5kW	3.07	3.47	5.38	5.41
2.8kW	3.04	3.43	5.38	5.42
3.6kW	2.85	3.35	4.78	5.03
4.0kW	2.58	2.93	4.08	4.35

The energy reduction rates achieved by improving the rated COP of air conditioners are shown in Figure 6.

In this case, primary energy consumption is reduced by 0.5-6% in the cities examined. This reduction is most apparent in warm cities since most primary energy reduction is attributed to cooling.

Conversely, reduction rates associated with heating are not high. The reason for this is because other heating appliances, such as electric heaters, city gas heaters and kerosene heaters are also used for heating besides air conditioner.

The energy reduction rate associated with heating showed a similar tendency to the proportion of air conditioners to heating demand.

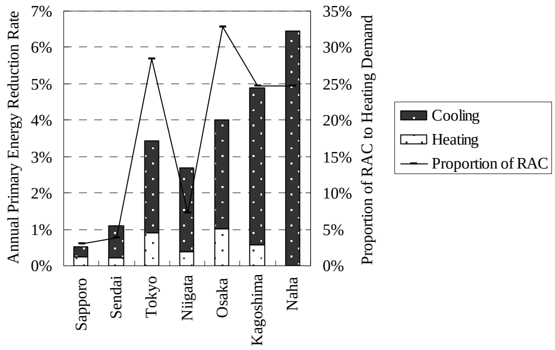

Figure 6 Energy reduction rates by improving rated COP of RAC and proportion of RAC to heating demand

Improvements in building heat insulation

In the base case, heating and cooling energy consumption was obtained from the weighted average of simulation results for each insulation level with the proportion of each insulation level (Figure 3). In this case, all houses in the city conform to the 1999 standard, the "Next Generation Energy Conservation Standard" (Ministry of construction, 1999).

The energy reduction rates that can be achieved by improving the heat insulation level of a building are shown in Figure 7. Here, the primary energy consumption was reduced by 7-18% in the cities examined. The figure shows that the rate of reduction is higher in colder cities. Energy consumption used for cooling is slightly increased in Sapporo and Sendai, because, in colder regions, consumption is affected by internal heat gains due to improvements in the heat insulation of a building.

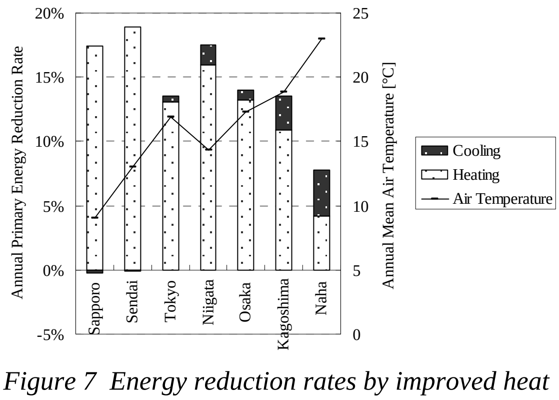

Figure 7 Energy reduction rates by improved heat insulation and mean annual air temperature

Changing preset temperature

In the base case, preset temperature vary by heat insulation level of a building. In this case, the cooling preset temperature is increased and heating preset temperature is decreased as shown in Table 9.

Table 9 Preset temperature

	Heating [°C]		Cooling [°C]	
	Base case	Easing Set Room	Base case	Easing Set Room
No insulation	18	18		
Below 1980	20	19		
1980 Standard	21	20	27	28
1992 Standard 1999 Standard	22	21		

The energy reduction rates achieved when preset temperature is changed are shown in Figure 8. Here, primary energy consumption is reduced by 1.0%-2.5% in the cities examined.

In Sapporo, the energy consumption due to heating is very high since heating is used all night long. Conversely, the energy consumption due to cooling was higher in warmer city.

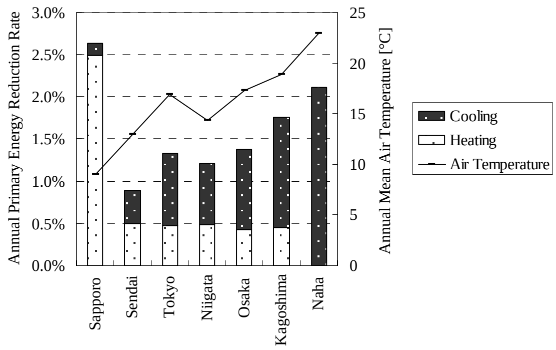

Figure 8 Energy reduction rates by changing preset temperature and annual mean air temperature

All family members watching TV together

Here, the room supporting the activity of "watching TV" and "resting" is shifted from each family member's bedroom to the living room in order to reduce energy consumption by the television, lighting, and heating or cooling in the bedroom.

In the case where all family members watch TV together, the energy reduction rates are shown in Figure 9. In this case, the primary energy consumption was reduced by 1-4% in the cities examined due to reduction in energy consumption by the TV, lighting, and heating or cooling.

Energy reduction for cooling was greater in warmer city. Similarly, the reduction in energy for heating was higher in colder city with the exception of Sapporo. In addition, there was a tendency toward an increase in energy reduction rate in the cities where the average number of people per household is large.

In Sapporo, the rate of heating reduction was relatively low. This is because, in apartments such as that shown in Figure 10, occupants usually watch TV in their bedrooms, which unlike living rooms, do not usually face towards the outside of the building. Even so, in Sapporo, which is a very cold city, the consumption of energy for heating is influenced by the outside air temperature and the reduction effect is relatively low.

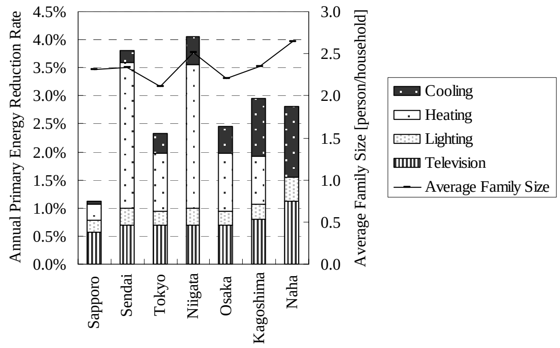

Figure 9 Energy reduction rates by all family members watching TV together and average family size

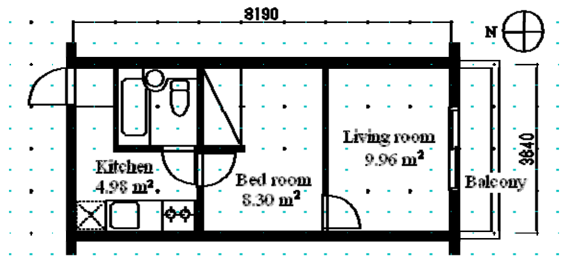

Figure 10 Example of the plan of the house (Apartment 29.88m^2)

THE TOTAL EFFECT BY COMBINING MULTIPLE MEASURES

Outline of evaluation of multiple measures

Since the effect of each energy efficiency measure interacts with the other measures, the combined effect of some measures cannot be estimated by simply summing each of the effects shown in Figures above. Therefore, simulations of energy saving for multiple measures were performed according to the following five steps:

1) Step 1: Energy efficiency standard for home appliances.

2) Step 2: Step 1 + Energy efficiency Standard for air conditioner.

3) Step 3: Step 2 + Improvement in heat insulation of a building.

4) Step 4: Step 3 + Changing preset temperature.

5) Step 5: Step 4 + All family members watching TV together.

The savings associated with implementing Step 1 and Step 2 can be expected in the near future since the necessary legislation has already been promulgated.

For Step 3, at present there are no obligations regarding building insulation levels. However, this requirement could be legislated with relative ease. Step 4 and Step 5 are both measures that are expected to have very significant effects, but they would be difficult to formalize.

The potential cumulative effect achieved by combining multiple measures

Energy reduction rates achievable by employing multiple measures and the annual energy consumption per city for each step are shown in Figures 11 and 12.

For Step 1, the energy reduction rates due to improvements in the energy efficiency of appliances tend to be high in warm cities.

For Step 2, the increasing tendency in energy consumption reduction rates in warmer cities was more marked due to improvements in the rated COP of air conditioners. This is because air conditioners are seldom used for heating in cold cities (Tables 4 and 5).

The marked effect of building insulation in Step 3 was demonstrated in most cities and the difference in energy reduction rates between cities decreased. This was because the energy consumption for heating is considerably reduced in cold cities in which the reduction effects attributed to Steps 1 and 2 are relatively low.

In Step 4, the energy reduction rates are increased by approximately only 1% in each city. After the improvements associated with the rated COP of air conditioners and the improvements associated with the heating insulation of buildings, the reduction effects associated with changing preset temperature were small.

In Step 5, where all family members watch TV together, the energy reduction rates increase to approximately 2% in respective cities.

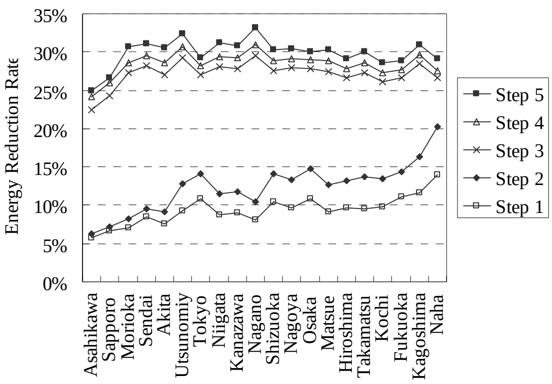

Figure 11 Energy reduction rates by multiple measures

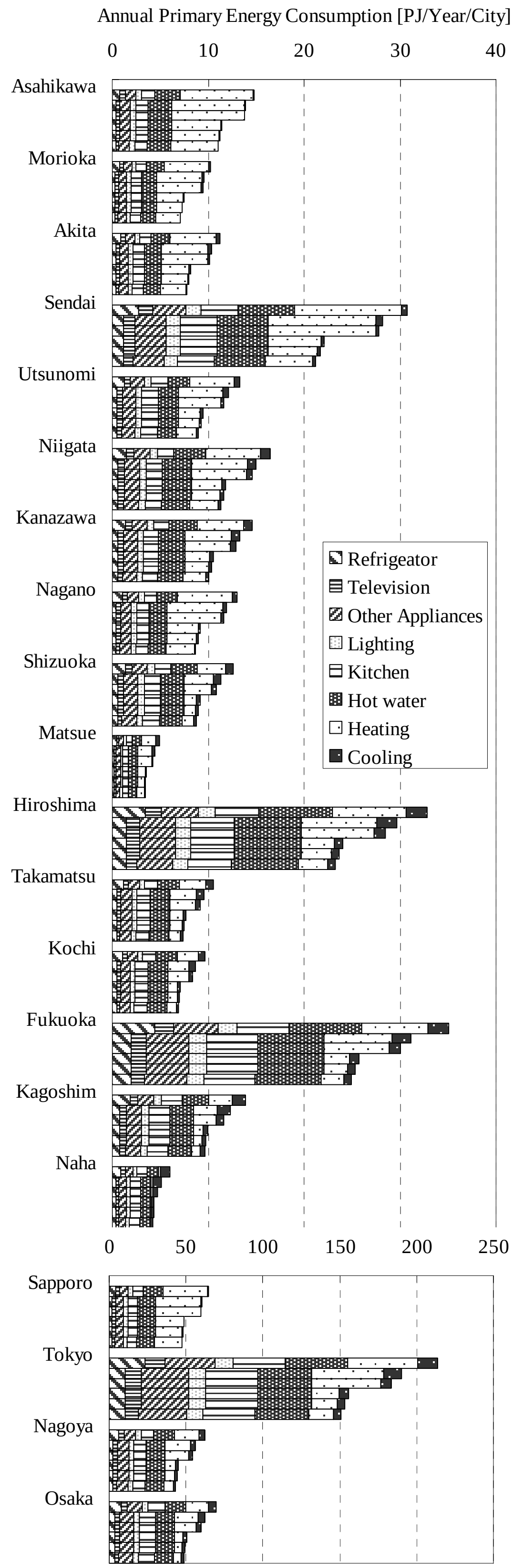

Figure 12 The annual primary energy consumption per city in each step

CONCLUSION

In this paper, differences associated with the potential of energy conservation measures in respective cities in Japan were evaluated using a residential energy end-use model developed by the authors. We estimated the potential reductions in energy consumption associated with the implementation of five energy saving measures – energy efficiency standard for home appliances excluding air conditioners, energy efficiency standard for air conditioners, improvements to heat insulation of buildings, changing preset temperature , all family members watching TV together – are adopted independently or in combination, and the differences in the potentials between cities were discussed.

When each measure was adopted independently, the effect of improved building insulation was the most marked in each city except Naha and this measure has marked effect in cold cities.

In warm cities, improved appliance efficiency is as effective as improved building insulation and the effect of improvements to rated COP of room air conditioners was also considerable. In addition, the effect of all family members watching TV have an effect in cities that have many households with large families.

In adopting the combined measures, the effects are largest in warmer cities for Steps 1 and 2. In Step 3, the energy reduction rates are increased in cold cities and the difference between cities decreased due to improvements in building insulation. For Step 4 and 5, energy reduction rates increased by 1-2% in each city. The biggest effect was observed for improved heat insulation in buildings in most cities.

Based on these results, it became apparent that improved heat insulation in buildings is an important mitigation measure against global warming in Japan. Since thermal insulation levels are not mandatory at present, it is important to apply high thermal insulation levels to newly built residential buildings and to improve the thermal insulation of existing residential buildings.

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