EVALUATION OF ENERGY SAVING MEASURES IN LONG-TERM SCENARIO IN JAPANESE RESIDENTIAL SECTOR

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Summary

Energy consumption in the residential sector of Japan was modeled on a nation-wide scale. In this study, we estimated the energy consumption and CO_2 emissions from 2005 to 2025, considering the change in various parameters with time. In addition, we evaluated the effect of implementing energy conservation measures in this period, such as improving the thermal insulation in buildings, introducing high-efficiency water heaters and distributed generation systems, and changing the preset temperature. If all the energy-saving measures are implemented by 2025, the energy consumption and CO_2 emissions will be reduced by 41.1% and 50.5%, respectively, as compared to the 2005 levels. Consequently, it was proved that only a combination of measures that are already feasible will have a drastic effect in 2025.

1. Introduction

In Japan, the energy consumption in the residential sector has increased steadily in response to the increase in the standard of living, which has resulted in larger houses, widespread use of various types of appliances, and increase in the number of small families. In the last 25 years, energy consumption in this sector has doubled, while the population has increased by only 10% (The Energy Conservation Center, 2002).

Consequently, the “Guideline for Measures to Prevent Global Warming,” adopted by the Japanese government in March 2002, aims to maintain CO_2 emissions related to energy usage at the 1990 levels. In April 2005, the “Kyoto Protocol Target Achievement Plan” was also adopted. By improving the energy efficiency of household appliances and improving buildings’ thermal insulation, the objective of the plan was to reduce CO_2 emissions from the residential sector to a level that is only 6% higher than that in 1990. A revision of the “Law Concerning Rational Use of Energy” established one of the highest energy efficiency standards in the world for appliances. The standard, commonly referred to as the “top runner standard,” required that the average energy efficiency of an appliance manufactured in 2004 had to be higher than that of the most efficient model manufactured in 1999. This standard was revised in 2005 to extend its application to a greater variety of appliances. In addition to the top runner standard, the Guideline for Measures to Prevent Global Warming prescribed a variety of energy conservation measures, including increasing energy efficiency of residential buildings, reducing standby power consumption, and promoting the use of high-efficiency water heaters. The program also encouraged changing the consumer behavior, such as changing the preset temperature, encouraging family members to spend more time together in the living room, and reducing the time watching TV (Global Warming Prevention Headquarters, 2002).

Thus far, we have evaluated the potential of various energy-saving measures. However, these evaluations are not realistic because all the measures have been implemented at once. We have to consider the update rate of houses or home appliances stock to evaluate the measures practically.

In this study, we evaluate the effect of introducing 7 energy-saving measures—improving energy efficiency of household appliances, improving thermal insulation in buildings, introducing high-efficiency water heaters and distributed generation systems, changing preset temperature, and all family members watching TV together—for a long period from 2005 to 2025, considering the rate at which each measure is implemented.

2. Simulation Model

2.1 Structure of End-use Simulation Model

The authors developed an original bottom-up model to simulate the city-scale energy consumption in the residential sector considering various types of households and buildings. In the simulation, the annual energy consumption of one household is calculated iteratively for 19 household categories and 12 building categories, six of which were classified as detached houses and the other six as apartments depending on the floor area. In addition, four different thermal insulation levels in buildings were considered. In the model for appliance energy consumption, the energy consumption of each appliance was simulated separately, which depended on the consumer behavior. For heating and cooling of rooms, dynamic heat load simulations were carried out using both building data and weather data. The ventilation and heat conduction between rooms were determined using a thermal circuit network. Heat loads were simulated relative to the internal heat gain, which was calculated using the appliance energy consumption model and the behavior of the family members. The time step of the heat load and energy consumption simulations was 5 min.

The total residential energy consumption in the target region was estimated by multiplying the simulated energy consumption by the number of households in each category and summing up the results. Further, it was confirmed that the results of our model was in a good agreement with actual data (Shimoda Y, 2007).

2.2 Structure of Stock Simulation Model

The authors have previously developed a “stock model” (Shimoda Y, 2007), which has been used in this study to estimate the average energy efficiency of appliances and the distribution of buildings’ thermal insulation levels in the target region. This model enables us to generate input data, e.g., the average energy efficiency of appliances, for the target year. Figure 1 shows the change in the efficiency of appliances estimated by the stock model.

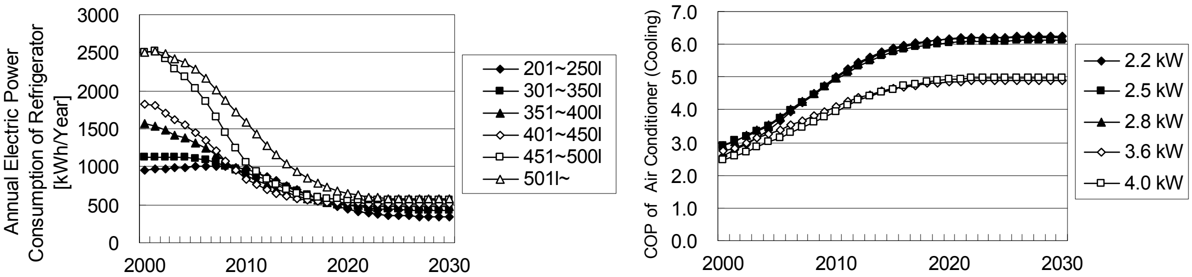

Figure 1 Change in efficiency of appliances (left: refrigerator, right: room air conditioner)

3. Simulation Results for 2005

3.1 Region-wise Classification and Major Cities

The climate of Japan varies significantly from north to south. In addition, the standards set by the Law Concerning Rational Use of Energy with regard to households vary for different regions. Therefore, when we calculated the energy consumption in the Japanese residential sector, we divided the entire country into small regions, calculated the energy consumption in each region and then summed up the results.

Table 1 lists the region-wise classification based on the Law Concerning Rational Use of Energy and the major cities, which are the most populous cities in the region. We used the weather data from the major cities and the others from the prefectures included in the regions.

Table 1 Region-wise classification and major cities

	Prefectures in the Region	Major Cities
I - 1	Eastern Hokkaido	Asahikawa
I - 2	Western Hokkaido	Sapporo
II	Iwate, Aomori, Akita	Morioka
III - 1	Miyagi, Fukusima, Yamagata	Sendai
III - 2	Ibaragi, Tochigi, Gunma, Yamanashi	Utsunomiya
III - 3	Niigata	Niigata
III - 4	Toyama, Isikawa, Fukui, Shiga	Otsu
III - 5	Nagano	Nagano
IV - 1	Saitama	Urawa
IV - 2	Chiba, Tokyo, Kanagawa, Shizuoka	Tokyo
IV - 3	Gifu, Aichi, Mie	Nagoya
IV - 4	Kyoto, Nara	Kyoto
IV - 5	Osaka, Hyogo, Wakayama	Osaka
IV - 6	Tottori, Shimane, Okayama, Hiroshima, Kagawa, Ehime, Tokushima, Kochi	Hiroshima
IV - 7	Yamaguchi, Fukuoka, Saga, Nagasaki, Kumamoto, Oita	Fukuoka
V	Miyazaki, Kagoshima	Kagoshima
VI	Okinawa	Naha

3.2 Parameters Examined for Each Region

The parameters that have been examined for each region are as follows:

- Thermal resistance of insulation
- Duration of heating and cooling
- Proportion of different energy sources used for heating rooms and water
- Heating schedule at nigh in Hokkaido
- Number of households in each category
- Weather data
- Relative proportion of room air conditioners and electric heaters
- Frequency of bathing
- Equation for estimating city water temperature

- Number of appliances

3.2.1Thermal Resistance of Insulation

Heating and cooling loads were simulated for four levels of thermal insulation: no insulation, insulation up to the 1980 standard, insulation up to the 1992 standard, and insulation up to the 1999 standard. The values of thermal resistance of insulation for the exterior walls of the buildings in each region are listed in Table 2. We assumed that there were no houses with no insulation in Hokkaido and made original standard; below 1980.

Table 2 Thermal resistance of exterior wall insulation

	Thermal Resistance [m^2·K/W] (Apartment)						Thermal Resistance [m^2·K/W] (Detached House)					
	Region I	Region II	Region III	Region IV	Region V	RegionVI	Region I	Region II	Region III	Region IV	Region V	RegionVI
Below 1980	0.56	-	-	-	-	-	1.10	-	-	-	-	-
1980 Standard	1.13	0.75	0.75	0.50	0.00	-	2.20	0.90	0.90	0.60	0.00	-
1992 Standard	1.72	0.95	0.95	0.77	0.52	0.00	2.49	0.95	0.95	0.86	0.52	0.00
1999 Standard	2.30	1.80	1.10	1.10	1.10	0.30	3.30	2.20	2.20	2.20	2.20	2.20

The energy consumption in heating and cooling for each category of household and buildings was obtained from the weighted average of the simulation results for each thermal insulation level relative to the proportion of each thermal insulation level estimated using our stock model (Figure 2). Since there was no regulation regarding buildings' thermal insulation in Japan, the proportion of houses that conformed to the 1992 and 1999 standards was very less.

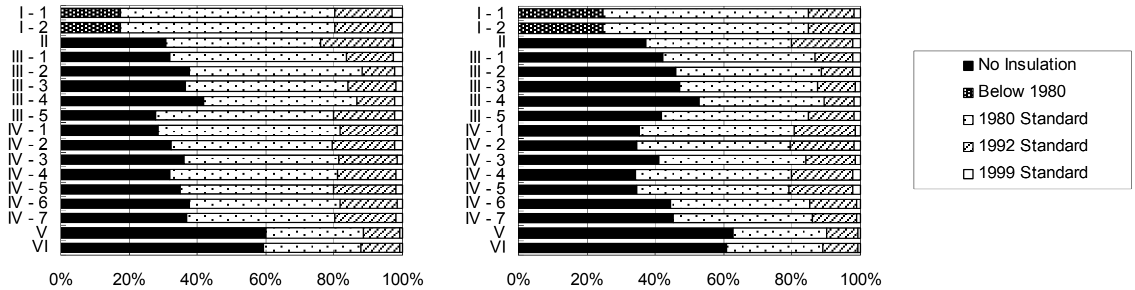

Figure 2 Proportion of different thermal insulation levels (left: apartments, right: detached houses)

3.2.2 Duration of Heating and Cooling

The duration of heating and cooling was defined as for SMASH; the Japanese residential thermal load calculation model.

3.2.3 Proportion of Energy Sources Used for Heating and Hot Water

The proportion of energy sources used for heating and hot water (electricity, city gas, and kerosene) was obtained from the Annual Report on Residential Energy (Tables 3 and 4).

Table 3 Energy sources used for heating

	Electricity	City Gas	Kerosene
Hokkaido	6.3%	33.6%	60.1%
Tohoku	8.2%	47.0%	44.9%
Kanto	4.4%	83.0%	12.6%
Hokuriku	15.8%	60.7%	23.5%
Tokai	12.7%	72.8%	14.5%
Kinki	7.8%	81.6%	10.5%
Chugoku	18.8%	54.2%	27.0%
Shikoku	19.9%	53.3%	26.8%
Kyusyu	14.4%	61.2%	24.4%

Table 4 Energy source used for heating water

	Apartment			Detached House		
	Electricity	City Gas	Kerosene	Electricity	City Gas	Kerosene
Hokkaido	4.6%	1.6%	93.8%	4.0%	1.6%	94.4%
Tohoku	9.7%	3.6%	86.7%	8.6%	3.6%	87.8%
Kanto	36.4%	23.7%	39.9%	37.2%	23.4%	39.4%
Hokuriku	30.9%	18.7%	50.5%	35.7%	17.4%	46.9%
Tokai	18.6%	20.0%	61.4%	13.6%	21.2%	65.2%
Kinki	47.7%	18.8%	33.5%	49.5%	18.1%	32.4%
Chugoku	36.3%	10.6%	53.2%	38.0%	10.3%	51.7%
Shikoku	38.1%	8.8%	53.1%	39.8%	8.6%	51.6%
Kyusyu	32.8%	10.1%	57.1%	33.2%	10.0%	56.7%

3.2.4 Heating Schedule at Night in Hokkaido

In this model, heating/cooling at night was estimated using a timer-controlled operation. In Hokkaido, it was assumed that heating continued throughout the night.

3.3 Annual Energy Consumption in Residential Sector

Figure 3 shows the simulation results for energy consumption per household and per person. Interestingly, the energy consumption per household for heating and cooling vary significantly for different regions, while the energy consumption for other purposes was considerably low. Further, the energy consumption for heating was high in I-1, II, III-3, III-4, and III-5, while the energy consumption was considerably low in I-2 and III-2, despite the regions being located in a cold area. The reason for this apparent anomaly is I-2 and III-2 have a high proportion of apartments.

The difference in energy consumption per household has been found to be higher than that per person. This is because it is the average number of people per household that affects the energy consumption.

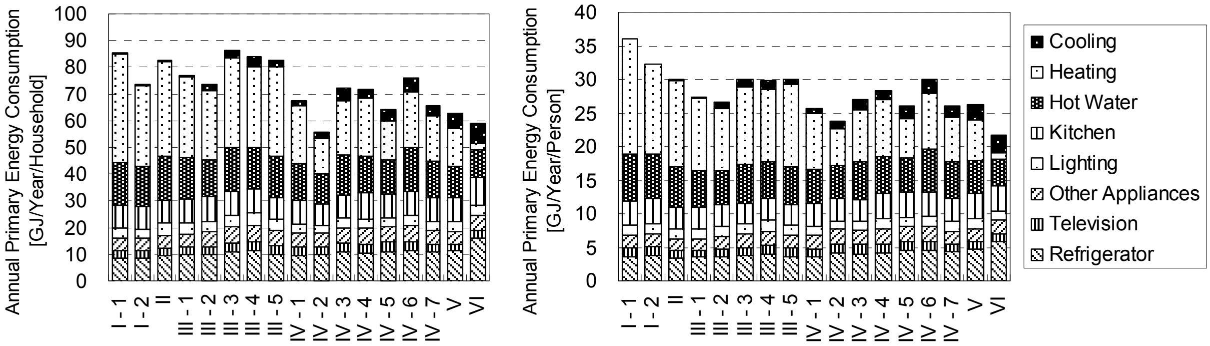

Figure 3 Simulated annual primary energy consumption (left: per household, right: per person)

4. Simulation Results for the Period 2005-2025

4.1 Parameters Examined for Each Year

The parameters that have been examined for each year are as follows:

- Number of households in each category
- Proportion of different thermal insulation levels of house stock
- Number of appliances
- Efficiency of appliances
- Proportion of energy sources used for heating rooms
- Electric power generation efficiency and CO_2 emission rate during electricity generation

4.1.1 Number of Households in Each Category

The numbers of households in each category for the period 2005–2025 were estimated on the basis of the estimation results obtained from the "National Institute of Population and Social Security Research." Initially, we estimated the number of households in each category in a prefecture and summed up the results to obtain the number of households in each category for the 17 regions. Figure 4 shows the change in the number of households in each category in Japan.

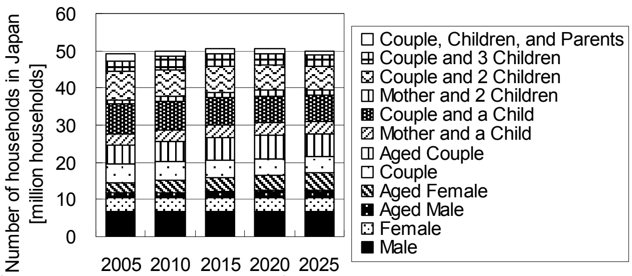

Figure 4 Change in the number of households in each category in Japan

4.1.2 Proportion of Different Thermal Insulation Levels of House Stock

The proportion of different thermal insulation levels of house stock for the period 2005–2025 was estimated by accumulating data of new houses considering house type, thermal insulation level, lifetime function, and the year in which they were built. Figure 5 shows the proportion of different thermal insulation levels, for example, in Tokyo.

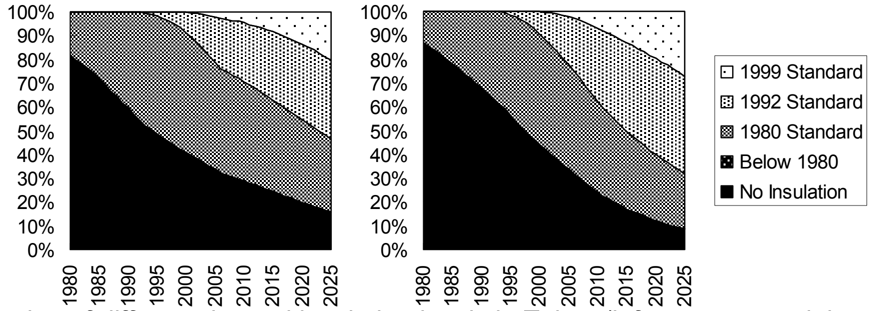

Figure 5 Proportion of different thermal insulation levels in Tokyo (left: apartment, right: detached house)

4.1.3 Number of Appliances

Figure 6 shows the change in the numbers of some appliances for the period 2005–2025, which were estimated by classifying the appliances into 3 groups: (1) Constant appliances which spread enough, (2) gently increasing appliances which spread in part, and (3) increasing appliances which not spread.

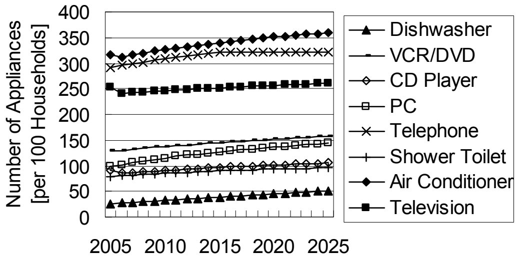

Figure 6 Change in the number of appliances for the period 2005–2025

4.1.4 Efficiency of Appliances

The efficiency of TVs, PCs, refrigerators, VCR/DVDs, and air conditioners for the years 2005 and 2025 was estimated. The efficiency of other appliances did not change. The efficiency was estimated by accumulating data of new appliances considering type, efficiency, lifetime function, and the year of manufacturing (Table 5).

Table 5 Efficiency of appliances

	Power Consumption [W]					
	TV		VCR/DVD		PC	
	Operating	Standby	Operating	Standby	Operating	Standby
2005	114	1.6	23	3.7	58	2.0
2025	198	0.5	26	4.2	52	1.2

	Annual Electric Power Consumption of Refrigerator [kWh/Year]					
	201~250l	301~350l	351~400l	401~450l	451~500l	501l~
2005	1002	1116	1320	1446	2031	2291
2025	356	437	475	515	556	582

	COP of Air Conditioner									
	Cooling					Heating				
	2.2 KW	2.5 KW	2.8 KW	3.6 KW	4.0 KW	2.2 KW	2.5 KW	2.8 KW	3.6 KW	4.0 KW
2005	3.65	3.73	3.78	3.40	3.16	3.96	4.10	4.08	3.93	3.47
2025	6.22	6.10	6.21	4.89	4.99	6.71	6.53	6.52	5.70	5.58

4.1.5 Proportion of Energy Sources Used for Heating

We converted the energy consumption of each source in statistics into demand, and the proportion of demand was set as the proportion of energy source for heating. The proportion of energy sources for the future was estimated from the past trend. Figure 7 shows the change in the proportion of energy sources in Hokkaido and Tokyo.

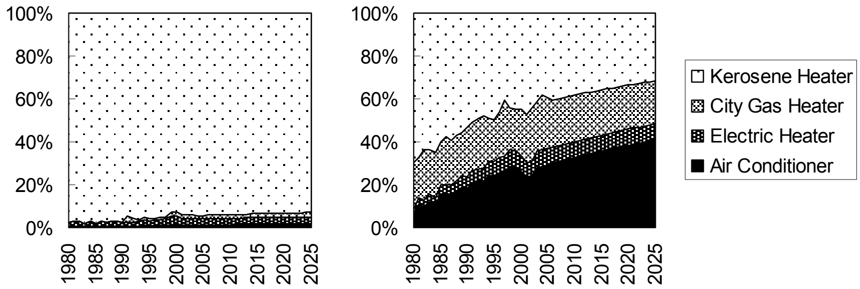

Figure 7 Change in the proportion of energy sources used for heating (left side: Hokkaido, right side: Tokyo)

4.1.6 Electric Power Generation Efficiency and CO_2 Emission Rate during Electricity Generation

We set the electric power generation efficiency and CO_2 emission rate for the future on basis of the target values for 2015 by different electric power generation companies (Figure 8).

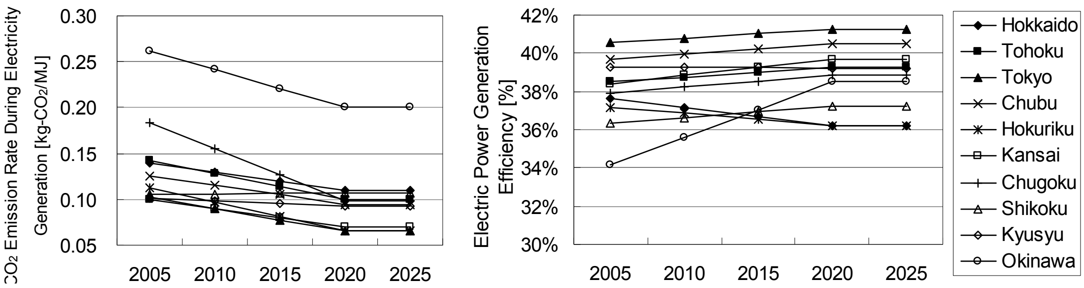

Figure 8 Electric power generation efficiency and CO_2 emission rate during electricity generation

4.2 Annual Energy Consumption in Japanese Residential Sector

Figure 9 shows the simulation results for the energy consumption in Japan. In Japan, the energy consumption in the residential sector changed from 3311 to 2649 [PJ/Year], and the proportion of change was –20.0%. This change was influenced by the population, number of households in each category, efficiency of electric power generation, etc. Figure 10 shows the various factors influencing the change in energy consumption from 2005 to 2025.

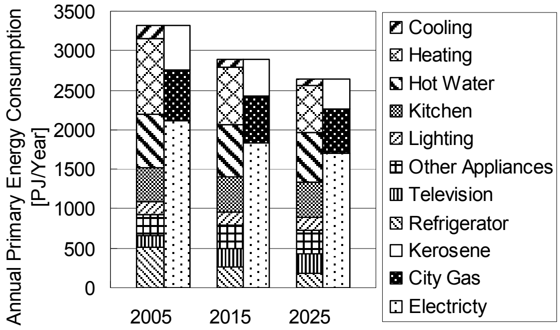

Figure 9 Annual primary energy consumption

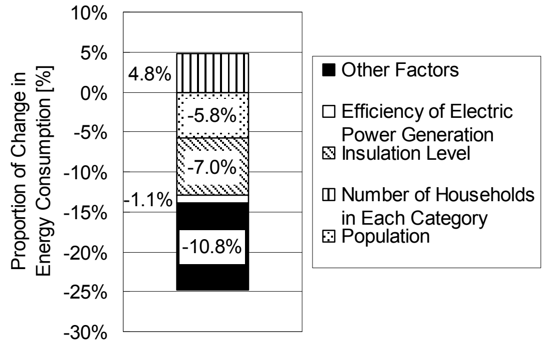

Figure 10 Proportion of change in energy consumption

5. Evaluation of Long-term Effects of Energy-saving Measures

The effects of the energy-saving measures have been evaluated for the period from 2005 to 2025, considering the update rate of houses or household appliances stock. The measures are as follows:

- Step 1: Setting an energy efficiency standard for household appliances
- Step 2: Improvement in buildings' thermal insulation
- Step 3: Introduction of high-efficiency water heaters and distributed generation systems
- Step 4: Introduction of HEMS (Home Energy Management System)
- Step 5: Change in the type of house—from a detached house to an apartment
- Step 6: Change in preset temperature
- Step 7: All family members watching TV together

These measures are implemented in the order mentioned above. From steps 1 to 5, the measures can be implemented without affecting the quality of life, but the measures in steps 6 and 7 affect the quality of life.

5.1 Step 1: Setting an Energy Efficiency Standard for Household Appliances

In this step, we set an additional top runner standard and evaluated the effects. Table 6 shows the efficiency and power consumption of various appliances.

Table 6 Efficiency of appliances (step1)

Annual Electric Power Consumption of Refrigerator [kWh/Year]					
201~250l	301~350l	351~400l	401~450l	451~500l	501l~
320	370	394	422	432	462

Power Consumption [W]					
TV		VCT/DVD		PC	
Operating	Standby	Operating	Standby	Operating	Standby
145.5	0.10	32	2.0	51	1.2

COP of Air Conditioner									
Cooling					Heating				
2.2 KW	2.5 KW	2.8 KW	3.6 KW	4.0 KW	2.2 KW	2.5 KW	2.8 KW	3.6 KW	4.0 KW
6.47	6.25	6.36	5.26	5.19	6.76	6.51	6.60	5.68	5.65

5.2 Step 2: Improvement in Buildings' Thermal Insulation

In this step, all new houses built after 1999 conform to the 1999 standard. Figure 11 shows the proportion of different thermal insulation levels in Tokyo calculated by our stock model for this step.

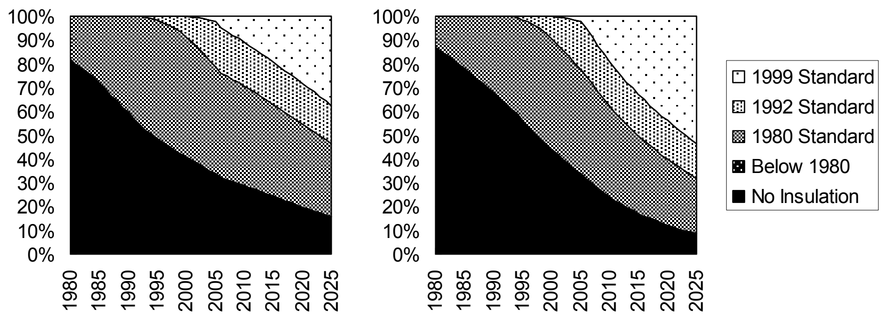

Figure 11 Proportion of different thermal insulation levels in Tokyo (left: apartment, right: detached house)

5.3 Step 3: Introduction of High-efficiency Water Heaters and Distributed Generation Systems

In this step, we evaluated the effect of the introduction of high-efficiency water heaters and distributed generation systems, such as a high-efficiency gas water heater (HEGWH) that can recover the latent waste heat, solar thermal water heater (STWH), heat pump water heater (HPWH), and micro gas engine cogeneration system (MGECGS). Initially, we calculated the energy consumption for each household when a system was introduced and determined suitable systems for each household for reducing CO_2 emissions. Then, assuming that the lifespan of water heaters were around 10 years and all water heaters have to be replaced in 2025, we calculated the energy consumption in the Japanese residential sector and evaluated the effect when the suitable systems were introduced in all households. Figure 12 shows the proportion of suitable systems in each region for the reduction in CO_2 emissions.

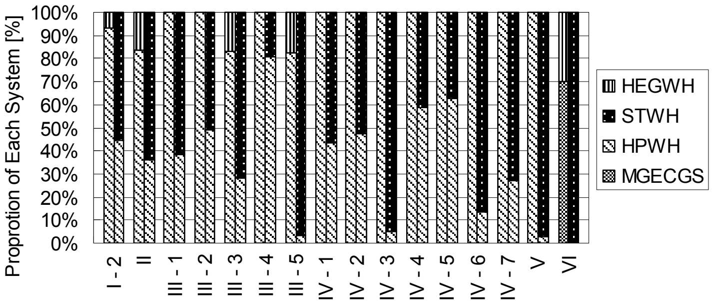

Figure 12 Proportion of systems in different regions (left bar: apartment, right bar: detached house)

5.4 Step 4: Introduction of HEMS

In this step, we evaluated the effect of the introduction of HEMS. By the introduction of HEMS, the standby energy consumption of some appliances was reduced, and thermal insulation mode of electric pots and rice cookers was set off as it was not required.

5.5 Step 5: Change in House Type—from Detached House to Apartment

In this step, we increased the proportion of apartments by using an estimation method (Figure 13).

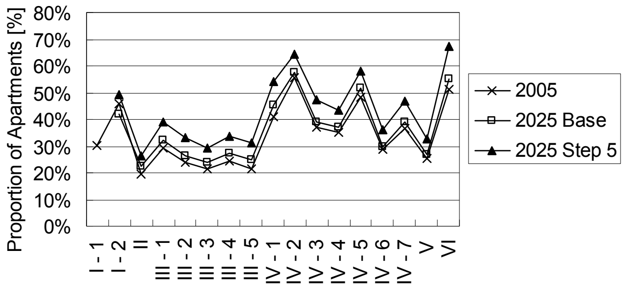

Figure 13 Proportion of apartments

5.6 Step 6: Change in Preset Temperature

The implementation of this measure affects the quality of life. In this step, the heating and cooling preset temperatures were changed as listed in Table 7.

Table 7 Preset temperature

	Heating [°C]		Cooling [°C]	
	Base Case	Step 6	Base Case	Step 6
No Insulation	18	18		
Below 1980	20	19		
1980 Standard	21	20	27	28
1992 Standard 1999 Standard	22	21		

5.7 Step 7: All Family Members Watching TV Together

In this step, the family members watch TV and relax together in the living room in order to reduce the energy consumption of TVs, lighting, and heating or cooling.

5.8 Results of Each Step

Figure 14 shows the results of each step. It reveals that we could bring out a gradual reduction in the energy consumption and CO_2 emissions. In the business as usual case (BAU), CO_2 emissions reduced by 27.2% as compared to the 2005 level because of the change in various parameters such as efficiency or diffusion of household appliance, thermal insulation levels in buildings, and population. In step 1, CO_2 emissions reduced by 29.4% as compared to the 2005 level because of the enhancement of the efficiency of appliances. In step 2, by improving buildings' thermal insulation, CO_2 emissions reduced by 30.4% as compared to the 2005 level. In step 3, CO_2 emissions reduced drastically by 43.0%; hence, the introduction of high-efficiency water heaters and distributed generation systems were highly effective in saving energy. In step 4, since the standby energy consumption of some appliances has reduced by the introduction of HEMS, CO_2 emissions reduced by 45.3% as compared to the 2005 level. In step 5, by increasing the proportion of apartments, CO_2 emissions reduced by 47.5% as compared to the 2005 level. In step 6, by changing the preset temperature of heating and cooling, the energy consumption due to air conditioning reduced and CO_2 emissions also reduced by 48.6% as compared to the 2005 level. In step 7, because the energy consumption of TVs, lighting, heating, and cooling reduced due to the family members spending more time in the same room, CO_2 emissions reduced by 50.5% as compared to the 2005 level.

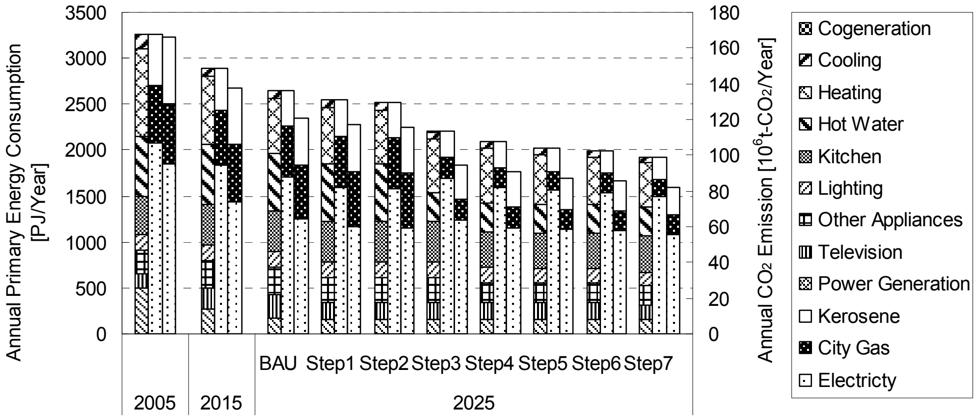

Figure 14 Annual primary energy consumption and CO_2 emissions in each step (left bar: energy consumption based on use, middle bar: energy consumption based on sources, right bar: CO_2 emissions)

6. Conclusion

In this study, the implementation of energy conservation measures in the Japanese residential sector was evaluated for a long period using a residential energy end-use model developed by us. We estimated the practical reduction in energy consumption associated with the implementation of 7 energy-saving measures—setting an energy efficiency standard for household appliances, improvement of thermal insulation in buildings, introduction of high-efficiency water heaters and distributed generation systems, introduction of HEMS, changing house type from a detached house to an apartment, changing preset temperature, all family members watching TV together—which were implemented in succession.

As a result, the annual primary energy consumption and CO_2 emissions reduced by 37.8% and 47.5%, respectively, as compared to the 2005 levels in step 5, in which all energy-saving measures were implemented without affecting the quality of life. Then, in step 7, in which all measures were implemented, the annual energy consumption and CO_2 emissions reduced by 41.1% and 50.5%, respectively, as compared to the 2005 levels.

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