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Full Paper

RESIDENTIAL ENERGY DEMAND AND CO_2 EMISSION IN THE ASIAN MEGA-CITIES: ESTIMATION OF FUTURE TRENDS AND POLICY IMPLICATIONS

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Abstract

In this paper, future trends of residential energy demand and CO_2 emissions are estimated for the four Asian mega-cities of Tokyo, Seoul, Beijing and Shanghai based on the development of models for residential energy demand. In addition, for CO_2 emission reduction, effects of measures on fuel type factor, energy-related appliances, housing and lifestyle factors are assessed by a scenario approach. It is shown that Beijing has a large percentage increase in total energy demand, and will become the second largest energy consuming mega-city after Seoul in 2005. Due to less efficiency in electricity generation and heat supply and faster population growth, Beijing will be positioned above Seoul and Shanghai will be positioned above Tokyo in CO_2 emission by 2020. Among the five scenarios for CO_2 emission reduction, the comprehensive factor improvement scenario including all the measures has the highest CO_2 reduction rate, and the fuel-type factor imporveemnt scenario has the lowest. In 2020, by improving the comprehensive factor, CO_2 reduction amounts could reach 8.6 million tons in Beijing, 4.8 million tons in Shanghai, 4.6 million tons in Tokyo, and 4.4 tons in Seoul.

KEYWORDS: *energy demand model, residential sector, CO_2 emission, Asian mega-cities, scenario approach*

1. Introduction

According to an estimate by the United Nations in 2001, the urban population ratio in Asia in 1996 was 47.7%; however, the number is expected to grow to 60.2% in 2030. Urbanization in Asia has the distinct characteristic of taking place in large-scale urban areas. In terms of mega-cities that have a population of over 10 million, it is expected that 21 of them will come into existence on the planet by 2015, and 13 of that estimated number will be in Asia.

As a synergistic effect of the further expansion of Asian mega-cities and an increase in peoples' income, energy consumption in residential sectors will drastically increase. Not even considering air pollution issues in urban areas, urban activities hold an important position for determining future global warming issues also.

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Table 1. Comparison of the four mega-cities on population, area and population density.

	Tokyo			Seoul			Beijing			Shanghai		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
Population	11,618	11,856	12,059	8,364	10,613	10,373	9,043	11,035	12,780	11,465	12,834	13,216
Area (km^2)	2,183	2,183	2,187	607	605	606	16,808	16,808	16,808	6,186	6,341	6,341
Population density (person/km^2)	5,322	5,431	5,514	13,779	17,542	17,132	538	657	760	1,853	2,024	2,084

Data source: data for 2000 is from Tokyo Statistical Yearbook 2001, Statistical Yearbook Seoul 2001, Statistical Yearbook of Beijing 2001, Statistical Yearbook of Shanghai 2001; other data refers to Kaneko et al. (2001).

In this report, we will take a closer look at energy consumption in residential sectors in the Asian mega-cities. Prediction models of residential energy consumption were developed for Tokyo, Seoul, Beijing, and Shanghai until 2020.

Table 1 explains the general conditions in the four cities for population, area and population density. First, we need to clearly define the term "urban." In order to accumulate data at the urban level to the greatest degree possible, the term must include metropolitan areas and districts in Japan, metropolitan areas and cities in Korea, and also "greater regions," which include urban and rural areas in China. As the table shows in its comparison of the metropolitan scales of the Tokyo metropolis, the Seoul metropolis, and the greater Beijing region, Beijing has a distinctly larger area than the other two, but the population is on a similar scale.

During the past few decades, the three cities other than Tokyo have experienced many changes in their residential energy consumption patterns both in quantitative and qualitative respects. From 1980 to 2000, Seoul has the highest increase in both total residential energy consumption and residential energy consumption per household. Tokyo has a slightly increasing trend for total energy consumption and an almost unchanged trend of energy consumption per household. On the other hand, in Beijing and Shanghai, energy consumption per household increased slightly, but total energy consumption increased dramatically. As to energy consumption composition, Seoul shows a quite evident decline in coal use from 52% to 2% and an increased diffusion of town gas from 7% to 61% during the period 1990-2000. Even though coal use has been declining in both Beijing and Shanghai, Beijing has a drastically increased consumption rate of natural gas from 1% to 25% during the same period.

The changes in residential energy consumption can be explained by population growth, demographic changes such as the changes in household size, and increased income, which resulted in a more energy-intensive lifestyle. Figure 1 shows the floor space per household, and Figure 2 shows the size of households. In all of the four urban areas, the floor space per household is becoming larger, and the number of persons per household is becoming smaller. Both trends are general factors in energy consumption increase per person. Figure 3 indicates diffusion rates for refrigerators and air conditioners in Tokyo, Shanghai, and Beijing. In Beijing and Shanghai, the diffusion rate for refrigerators is almost 100% in urban areas and approximately 80% in rural areas. Secondly, diffusion rates for air conditioners are 160% in Tokyo, approximately 90% in urban areas of Shanghai, and approximately 60% in urban areas of Beijing. Even in terms of color TVs and microwave ovens, urban areas in Shanghai and Beijing show numbers that are reaching very close to the standard of Tokyo.

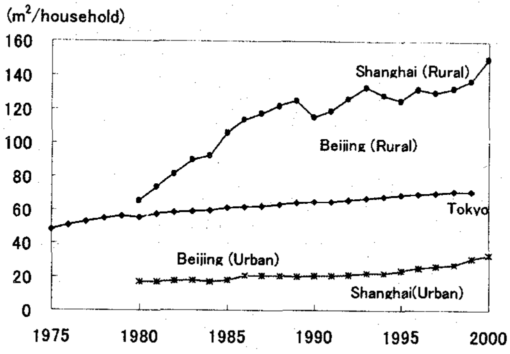


Figure 1. Trends in floor space per household.

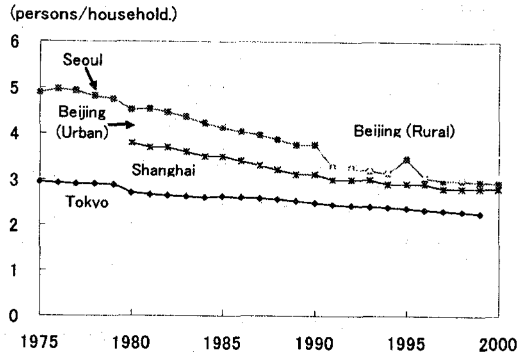


Figure 2. Trends in size of household.

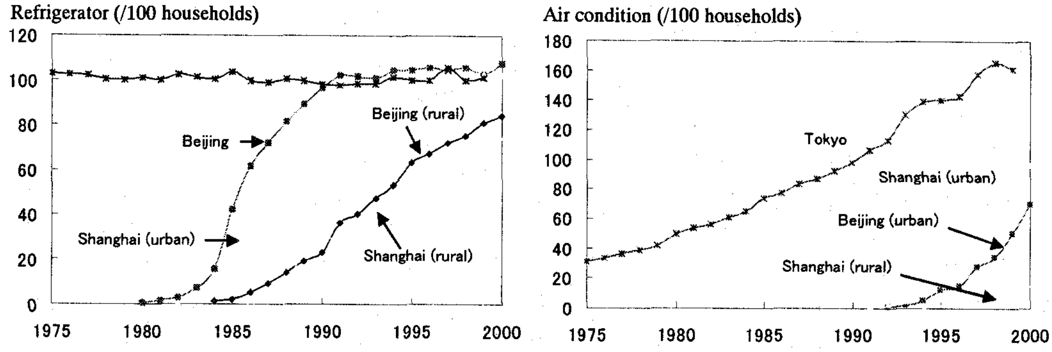


Figure 3. Ownership rates for major home electric appliances.

2. Methodology

Basic Concepts: Asian cities should be studied with particular consideration of two points. One is data acquisition. Considering this factor, the refinement of the structure of a model appears limited. In particular, more data is available for Tokyo than for any other city, but model construction based on Tokyo is not suitable. The other concern is to keep up with the varying rates of growth in the region. Economic growth and its accompanying changes in living standards or enhancement of technical standards means that not many parameters can be handled as fixed values. This makes it necessary to ensure that the structural parameters of a model structure are variable. Therefore, the authors will develop a model satisfying these two points and predict the energy consumption and carbon dioxide discharge in the residential sector until 2020.

Framework: The analytical flow of this paper is shown in Figure 4. The "BaU (Business as Usual)" part of this figure demonstrates the analytical flows of energy demand in projection models for the residential sectors of Tokyo, Seoul, Beijing, and Shanghai, due mainly to the availability of energy consumption data by use types. Since data regarding energy consumption by use type and fuel type in Tokyo was available, energy consumption per fixed floor space or household by use type has been estimated, and then this estimated value of energy consumption by use type was divided by fuel

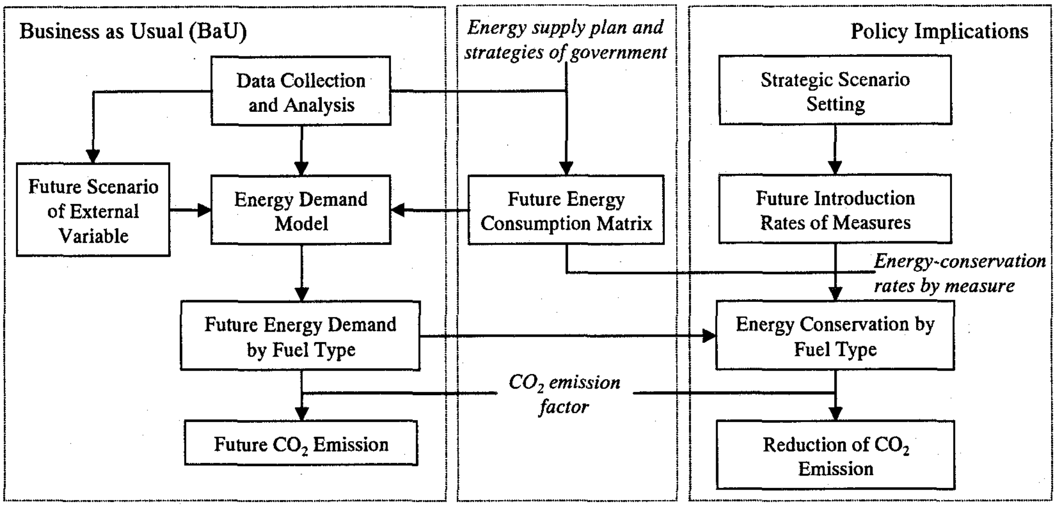


Figure 4. Analytical flow chart.

types. For estimating the amount of energy consumption by use types, multiple regression analysis with explanatory variables was utilized. For the other three mega-cities, since statistics for the amounts of energy consumption by use type and fuel type were unavailable, only the amounts by fuel types were estimated. Beijing has a widely diffused district heating system (DHS), so heat is estimated separately. Further, the urban areas and rural areas have quite different energy consumption structures, which are estimated separately for Beijing.

For CO_2 emission reduction in the residential sector, policy implications are analyzed by a scenario approach. The "policy implications" part of Figure 4 shows the estimation structure used in this analysis. First, after setting up scenarios, the introduction rate of the strategic cases and the energy consumption rate by usage in those cases are defined. By multiplying them by the energy consumption of the BaU case, an energy consumption amount based on usage is calculated. Next, based on the energy demand matrix, the energy consumption amount based on usage is divided into the energy consumption amount based on fuel type. Further, by multiplying the estimated energy consumption amount based on fuel type by the basic unit of CO_2 emissions, a reduction of CO_2 emissions, impacted by the measures to be conducted by 2020, is projected. Then, by subtracting the amount of the estimated value from the BaU case, the amount of CO_2 emissions is estimated.

As the above figure shows, the energy demand for each use is estimated and decomposed by usage and fuel types. The uses of energy in each division were classified into ① heating, ② cooling, ③ hot water supply, and ④ lighting, driving, and other uses. The residential energy demand by usage and fuel types and total CO_2 emission amount is expressed in the following equation.

$$T_{CO_2} = \sum_j \left(\lambda_j \sum_i E_{ij} \right) = \sum_j \left[\lambda_j \sum_i \left(\gamma_{ij} g_i fH_i \right) \right]$$

(1)

where

T_{CO2}: Total CO_2 emission amount from residential energy consumption

λ_j: CO_2 emission factor of fuel j

E_{ij}: Residential energy consumption of fuel j for energy use i

γ_{ij}: Share of fuel j in residential energy use i

g_i : Residential energy consumption for energy use i per unit floor space

f : Floor space per household

H_i: Number of households with residential energy use i

If floor space data is not available or the future floor space is directly available, the equation below is appropriate. The equation will also be used to predict the energy demand for heating not dependent on floor space.

$$T_{CO_2} = \sum_j \left(\lambda_j \sum_i E_{ij} \right) = \sum_j \lambda_j \left[\sum_i \left(\gamma_{ij} e_i H_i \right) \right] \tag{2}$$

where

e_i: Residential energy consumption for energy use i per household

The CO_2 emission factors used in the models are shown in Table 2. Except for electricity and heat, Models for Korea and China adopt the same factors as Japan.

The procedure up to the construction of the prediction model is outlined below.

Table 2. CO_2 emission factors (t-CO_2/TOE) for 2000.

Country	Energy type	Emission factor	Country	Energy type	Emission factor
Japan[1)]	General coal	2.64	Japan[1)]	Kerosene	2.82
	Town gas	2.15		Heavy oil	2.94
	Natural gas	2.13		Electricity	4.15
	LPG	2.45	Korea	Electricity	4.74
	Coal gas	1.69		Heat	5.83
	Gasoline	2.90	China	Electricity	9.26
	Diesel	2.03		Heat	4.24

1) The emission factors except for electricity are adopted in the models for Korea and China

Step 1: When necessary, synthesize the explanatory variables of energy demand per unit floor space, more specifically, energy price, equipment ownership rate, and equipment energy efficiency. These variables are unique to the equipment or energy type. For use as explanatory variables of energy demand per unit floor space by uses, synthesize the variables into the average value for each use.

Step 2: To estimate the floor space per household of Equation (1), evaluate the variable factors by multiple regression analysis. From the results, formulate a model for predicting the floor space per household and the energy demand per unit floor space.

Step 3: Prepare predictive values for the explanatory variables of the model formulated in step 2. Thus, the model is used to calculate predictive values for the energy demand by uses until 2020.

Step 4: Decompose the values estimated in Step 3 by fuel type (electricity, kerosene, town gas, and LPG). To do so, an energy demand matrix for each fuel type by use should be prepared. Estimate the matrices for electricity, kerosene, and gas (town gas + LPG) by use from the trends of the past 25 years. With regard to the breakdown of gases, town gas consumption was predicted with the estimated future diffusion of town gas as an explanatory variable. The remainder is LPG.

Step 5: Estimate the energy demand by fuel type and multiply the energy demand by the CO_2 emission factor to predict the carbon dioxide discharge until 2020.

3. Development Trends in Residential Energy Demand and CO_2 Emission

3.1 Energy demand model

(1) Tokyo

Figure 5 shows models for estimating the residential energy demand for heating, cooling, hot water, lighting, power, and other uses in Tokyo.

Energy Demand for Heating: To estimate the requirement of energy consumption per unit area, variable factors were evaluated by multiple regression analysis. Consequently, the heating degree day, the heating energy price, the house insulation factor, and the amount of heating equipment per unit floor space were adopted as four variables. The regression equation obtained this way was adopted as a prediction model.

As an explanatory variable, the amount of heating equipment differs greatly depending on the equipment type (air conditioner, kerosene stove, or fan-forced heater) and also between single and multiple occupancy households. Therefore, the amounts of heating equipment by equipment and household type were synthesized from the energy efficiency of each model and the number of households by household type.

To estimate the floor space per household, a equation was created from the number of persons in a household and the compensation of employees per household. This also applies to the energy demands for cooling and hot water supply.

The above explains the past energy consumption for heating but future parameter settings are necessary to predict. As to the house insulation factor, the time series trend of the slowdown of growth was predicted by using an exponential curve. The equipment diffusion per unit floor space was predicted from the compensation of employees per household. The energy price and the heating degree day were adopted from past averaged data. With regard to the number of households and the number of persons per household, values estimated by the National Institute of Population and Social Security Research were used. Table 3 shows the ways of determining value settings for the external variables in the future scenario.

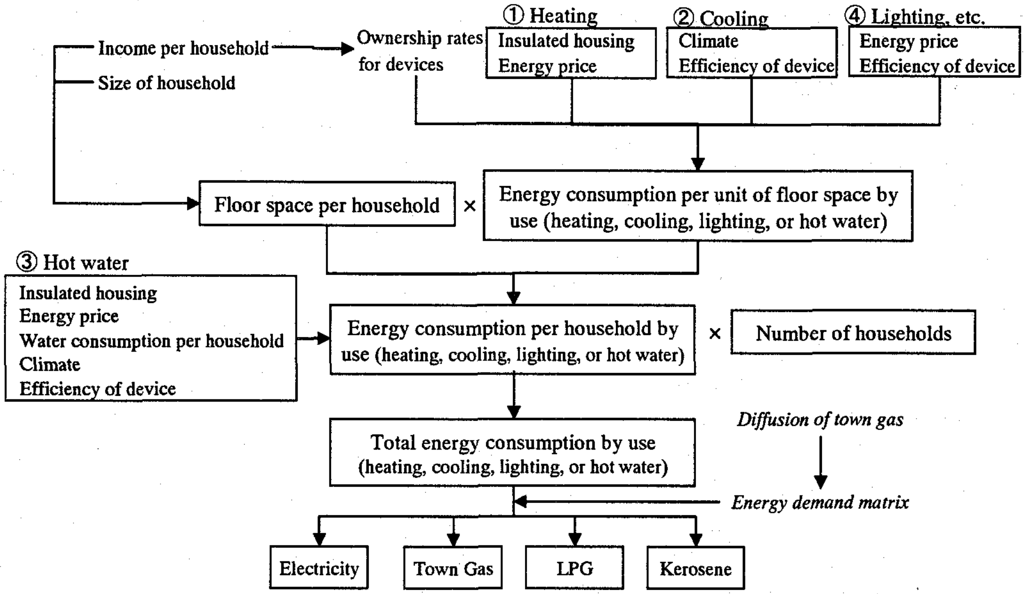


Figure 5. Model structure for Tokyo.

Table 3. Future scenario of external variables - Tokyo.

External variables	Future scenario
No.of households	as estimated by the National Institute of Population an Social Security Research
No of persons per household	as estimated by the National Institute of Population an Social Security Research
Compensation of employees per household	Assuming the average figure for the increase rate of the employment income per head during 1989-1998 to be constant in the future, calculate the prospective employment income per head. Multiply the figure achieved by the estimated value of the number of household members, and set this as the prospective employment income per household.
Cooling degree day (CDD) Heating degree day (HDD)	Averrage values for 1975-1999
Energy price	Average value for 1991-1999
Water consumption per household	the water consumption per capita during the period 1975-1999 was linearly approximated and anticipated to increase at the same rate. Multiplying this by the assumed number of people per household and put this as the prospective amount of water per household.

By multiplying the energy consumption per unit floor space, the floor space per household, and the number of households estimated according to Equation (1), the predicted value for energy consumption was calculated for heating. The calculation method depends on the fuel type as explained in Step 4 of Section 2.

Energy Demand for Cooling: To estimate the unit requirement of energy consumption per unit of floor space, variable factors was evaluated by multiple regression analysis. Consequently, the heating degree-day, cooling coefficient of performance (COP), and the amount of cooling equipment per unit floor space were adopted as variables. As for heating, the cooling energy price, the cooling

COP, and the amount of cooling equipment per unit floor space were weighted with energy consumptions by cooling equipment and averaged as synthesized variables. The regression equation obtained in this manner was adopted in the prediction model. Future values of parameters were established for prediction. The cooling COP was evaluated using a time-dependent logistic function. The amount of cooling equipment per unit floor space was predicted by the floor space per household. For the cooling degree-day, the average value of past data was adopted, as for heating. By multiplying the energy consumption per unit floor space, the floor space per household, and the number of households estimated according to Equation (1), the predicted value for energy consumption for cooling was calculated. The energy for cooling is electricity only and need not be decomposed by fuel type.

Energy Demand for Hot Water Supply: The energy demand for hot water supply was calculated using Equation (2) because it does not depend significantly on the floor space.

To estimate the unit requirement of energy consumption per household, variable factors were evaluated by multiple regression analysis. Consequently, the hot water supply energy price, the household insulation factor, and the water consumption per household were adopted as variables. The energy price is a synthesized variable. The house insulation factor was considered to average the performance of hot water supply equipment as a proxy variable for new household diffusion. The regression equation obtained in this manner was adopted as a prediction model.

As to the future values of parameters, the water consumption per person was obtained by linear regression on the assumption that the tendency of a slight increase in the past 25 years would continue. From the energy consumption and the number of households estimated above, the predicted value for energy consumption for hot water supply was calculated and decomposed by fuel type according to Step 4 in Section 2.

Energy Demand for Lighting, Power and Other Uses: To estimate the unit requirement of energy consumption per unit floor space, variable factors were evaluated by multiple regression analysis. Consequently, the lighting, power, energy price and the refrigerator equipment efficiency were adopted as variables. The energy price is a synthesized variable.

The future values of parameters were then established. With regard to equipment efficiency, the future value was estimated as a time-dependent logistic function.

By multiplying the energy consumption per unit floor space, the floor space per household, and the number of households estimated according to Equation (1), the predictive value of energy consumption for lighting, power, and other uses was calculated and decomposed by fuel type according to Step 4 in Section 2.

(2) Seoul

Outline of Model: The model was constructed by categorizing household energy consumption into three parts; (1) heating systems and hot water supplies, (2) kitchen, and (3) lighting, power, air cooling systems and others. The predicted values for the explanatory variables will be established by using the methods in Table 4.

Energy Demand for Heating and Hot water: Floor space per household was estimated on the basis of the number of persons per household and income per household. The energy consumption rate for heating was 38kwh/m^2/year, which was the estimated value of energy consumption for

Table 4. Future scenario of external variables - Seoul.

External variables	Future scenario
Income per household	The future income per household was calculated by multiplying per capita income by the number of household members. Income per person was estimated by the equation attained from the correlation analysis with respect to GRP per person.
Consumption expenditure per household	The future consumption expenditure per household was calculated by multiplying consumption expenditure per person by the number of household members. Consumption expenditure per person was attained by a correlation analysis with respect to GRP per person.
Energy consumption price index	The future energy consumption price index was predicted by keeping the average value of the 1991-1998 energy expenditure price index.

heating per unit of floor space in 1990 (Ralf, 2003).

According to Ojima (Ojima, 1996), the energy consumption for hot water per unit of floor space in Tokyo varied, ranging from 60.9 (condominium) to 62.3 (private single residence) Mcal/m^2/year, and its average value, 61.6Mcal/m^2/year, was applied to Seoul.

Energy Demand for Cooking: Multiple regression analysis was applied, and explanatory variables for energy consumption per household were consumption expenditure per household, income per household and the number of people per household.

Energy Demand for Lighting, Power, Cooling and Other Uses: The energy cost for lighting, power, cooling and other uses, consumption expenditure per household, and income per household were used as explanatory variables for the energy consumption per household.

Perspectives on the Proportion of the Energy Consumption by Fuel Type: To decompose the previously estimated residential energy use by type of use, proportion of the energy consumption by fuel type is estimated. The proportion of gas consumption was obtained by extrapolating the trend of the 9-year gas consumption data for the period 1991-1998. The prospective value of the proportion of coal consumption was obtained from a correlation equation with respect to past gas consumption, and the remainder was taken as oil consumption. Electricity consumption was assumed to equal the predicted result for lighting, power, cooling and other uses of energy consumption. Moreover, by adopting the past trend, gas was divided into town gas and LPG consumption, oil into kerosene, heavy oil and diesel.

(3) Beijing

Outline of the Model: Due to the unavailability of data on energy consumption by use type in Beijing, it was estimated by fuel type (Beijing Municipal Statistical Bureau, Department of Industry and Transport Statistics, National Bureau of Statistics, P.R. China). For this purpose, it was necessary to consider the matching of uses of energy and fuel type, and appropriate explanatory variables (Beijing Municipal Statistical Bureau). In urban areas of Beijing, district heating systems (DHS) and individual heating using coal are the most widespread methods for heating in winter. Some heat is also generated by electricity and gas; however, due to the small amounts used, these are ignored here.

Gas used for hot water and cooking will be divided into LPG, natural gas and town gas (coal gas) after estimating the total amount of gas consumption. Electricity is estimated on the basis of income per household. In the case of rural areas, only commercial energy was taken into account, on the basis

Table 5. Future scenario of external variables - Beijing.

	External variables	Future scenario
Urban	Floor space per household	Floor space per household was estimated by a linear equation based on a correlation analysis to income per household (1980-2000 data). Future income per household was calculated by multiplying income per person by the number of household members. Income per head was estimated by the correlation equation (logistic curve) determined by correlation analysis with respect to GRP per person.
	No. of households in urban areas	The proportion of the number of households in urban area was predicted by applying the 1988-2000 time-series trends respect to its linear equation. The perspective number of households of the urban area was estimated by multiplying the previously achieved figure by the estimated total number of households.
	Household diffusion rate of district heating system	This was estimated based on the district heating system plan in Beijing until 2010.
	Floor space of DHS user household	This was calculated by multiplying floor space per household by the number of households in urban area and household diffusion rate of regional heating system.
	Conversion coefficient for heating space	The conversion coefficient for heating space was calculated by dividing DHS heating space by floor space of the households with DHS. The average value for the 1995-2000 data remained constant.
	Household diffusion rate of individual heating	Calculated by subtracting household diffusion rate of regional heating from 100%.
	Gas diffusion rate	Future value was set at 100%.
Rural	The number of households in rural areas	Subtracting households in urban areas from the total households number.
	Income per household	Future predicted income per household was calculated by multiplying income per head by the number of household members.

of which the consumption of coal and electricity were estimated.

Heat from DHS and Coal for Individual Heating in Urban Area: Both of these heating categories relate to urban areas. The heat from DHS can be obtained by calculating the heat consumption per unit of heating space by applying the following Equation (3) (Song, X. H. and N. Moriyama), and then multiplying it by the heating area of the DHS. The heating space supplied by the DHS was calculated from the number of households with the DHS, floor space per household and a conversion coefficient from floor space to heating space. The predicted value for explanatory variables was calculated by applying the method noted in Table 5.

$$Q = Z \times 24 \times 3600 \times q \times \left[\frac{t_i - t_p}{t_i - t_w}\right] \times 2.39 \times 10^{-11} \tag{3}$$

where

Q: annual heat consumption per square meter heating area (0.00932 TOE/m^2)

Z: heating days (125)

q: heating design load (50 W/m^2)

ti: indoor design temperature for heating (18℃)

tp: average outside temperature during the period when heating system is in operation (-1.6℃)
tw: outdoor design temperature for heating (-9℃)

As for coal consumption values used for individual heating in urban area, they can be obtained by calculating the coal consumption per unit of heating space by applying Equation (4) (Song, X. H. and N. Moriyama), and then multiplying it by the heating area of individual heating.

$$D = \frac{Q}{\eta_1 \times \eta_2} \tag{4}$$

where
D: annual coal consumption per square meter of heating area (0.0172TOE/m^2)

η_1 : boiler efficiency (0.6)

η_2 : transport efficiency of piping (0.9)

Coal Used in Urban Areas (excluding the part for heating) and Coal Used in Rural Areas: Coal consumption occurs not only for individual heating in urban areas, but also for cooking and hot water supplies by the hobo population without census register in Beijing, concentrated hot water supplies, and communal baths. The estimated figure for 1995-2000, obtained by subtracting coal for individual heating and cooking from coal consumption in urban areas, reveals that it decreased from 790, 000 TOE in 1995 to 350, 000 TOE in 2000. In order to predict a future figure, it was assumed that it decreases at a constant rate from the amount in the year 2000. In addition, it was assumed that the amount of decrease represented conversion to gas.

Regarding coal consumption per household in rural areas, an average value for the period 1995-2000 figures was taken as the coal consumption rate for future prediction. By multiplying the rate by the number of households in the rural area, coal energy consumption was estimated.

Gas: Today, gas is used only in the urban area of Beijing. To obtain the gas consumption per household, multiple regression analysis was used and variable factors were analyzed. As a result, the ownership rate of electric cooking appliances was chosen.

Electricity: Similarly, in order to estimate the electricity consumption per household, multiple regression analysis was used and the variable factors were examined. The results made it necessary to use income per household for urban areas, and in the case of rural areas the number of color televisions owned and income per household were adopted.

(4) Shanghai

Outline of Model: In 2000, about 99 percent of the total population in Shanghai are urban residents, so the investigation was carried out by combining both urban and rural areas. The uses of energy consumption were grouped roughly into (1) cooking and hot water, (2) lighting, power, and air conditioners. Table 6 shows the approaches to prediction of the explanatory variables.

Energy Demand for Cooking and Hot water: The energy consumption for cooking and hot water per household was calculated based on the basis of 1980-2000 data on town gas (coal gas), LPG,

Table 6. Future scenario of external variables - Shanghai.

External variables	Future scenario
Population	Predicted by the logistic curve time-series trend based on the 1980-2000 data.
Persons per household	Predicted with respect to the comparison with the population time-series trends in Tokyo.
GRP	Calculated by assuming the increase rates of GRP to be the same in Shanghai and Beijing.
Income per household	Future income per household was calculated by multiplying income per person by the no. of persons per household. Per capita income was estimated by a correlation equation (logistic curve), determing the correlation analysis with respect to GRP per person.

coal consumption and the number of households, and no notable change was seen in figures for that period of 20 years. Therefore, the average value of the most recent 5 years was used as predictive of energy consumption per household in the future.

Between 1980 and 2000, the proportion of coal consumed decreased sharply from 87 per cent to 43 per cent. However, the proportion of town gas used increased from 12 per cent to 37 per cent, and the LPG use increased from less than 1 per cent in 1980 to 13 per cent in 1995, and since then has been maintained at the level of 15 per cent. In the future, the exploitation of natural gas is expected to increase further due to the realization of the "West-East Natural Gas Transmission Project" to transfer the natural gas in Xinjian Uighur Municipality to Shanghai. Although coal consumption will keep decreasing with the changes in energy consumption structure, it is still used as residential energy for the hobo population, part of the population in rural areas, and fuel for public hot water supply and communal baths.

Energy demand for lighting, power and air conditioning, etc.: By multiple regression analysis, the total number of air conditioners, color televisions and microwaves possessed was adopted as explanatory variable for electricity consumption per household.

3.2 Matrix of energy demand

Energy demand matrices for residential sectors are estimated based on past energy consumption based on fuel type and usage. The estimated results for 1998 are shown in Figure 6. Beijing has a 37.0% rate of coal consumption in relation to the total energy consumption in urban areas, but 93.5% in suburban areas. Shanghai has a 50.5% rate of coal consumption. From these results and government energy plans and policies, it is clear that Beijing and Shanghai are in need of efforts to carry out a fuel conversion from coal to gas in the future.

3.3 Prediction results

Figure 7 shows the estimated results of future residential energy consumption by fuel types in the four mega-cities by 2020. In total energy consumption, Beijing has a large percentage of increase, and will become the second largest energy consuming mega-city after Seoul from 2005; in contrast, Tokyo has a trend from a flat to a declining tendency after 2000.

In Seoul, Beijing, and Shanghai, the amount of coal use is declining, and the amount of town gas and natural gas use is increasing. Even though the percentage of electric energy consumption has not

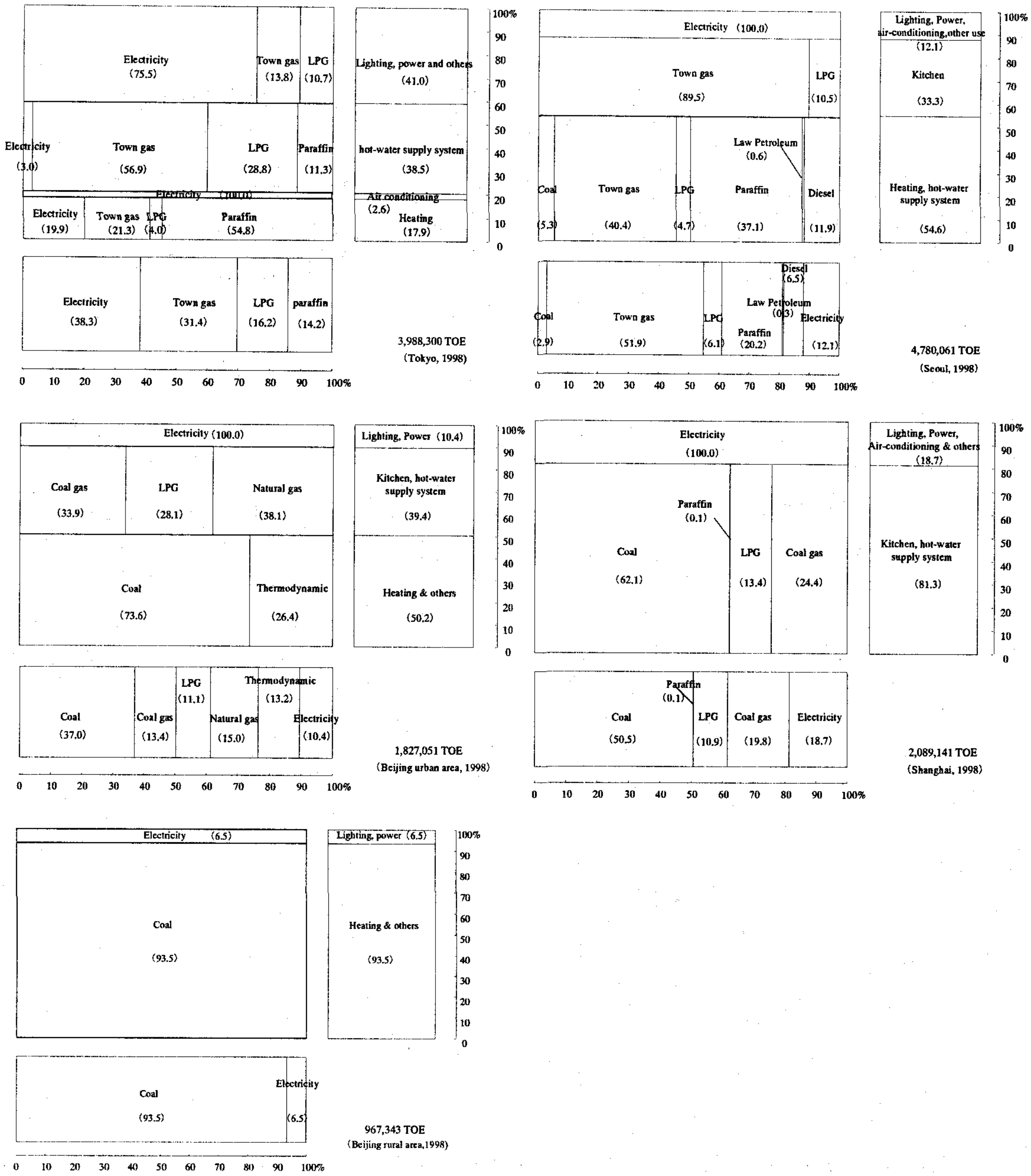


Figure 6. Residential energy consumption matrices for Tokyo, Seoul, Beijing and Shanghai.

changed much, this is due to the fact that the results do not sufficiently express transitions to electric energy consumption for heating, hot water supply, and cooking.

Figure 8 shows future expected results for total CO_2 emission and CO_2 emission per household from energy consumption in residential sectors. One remarkable difference from the expected amount

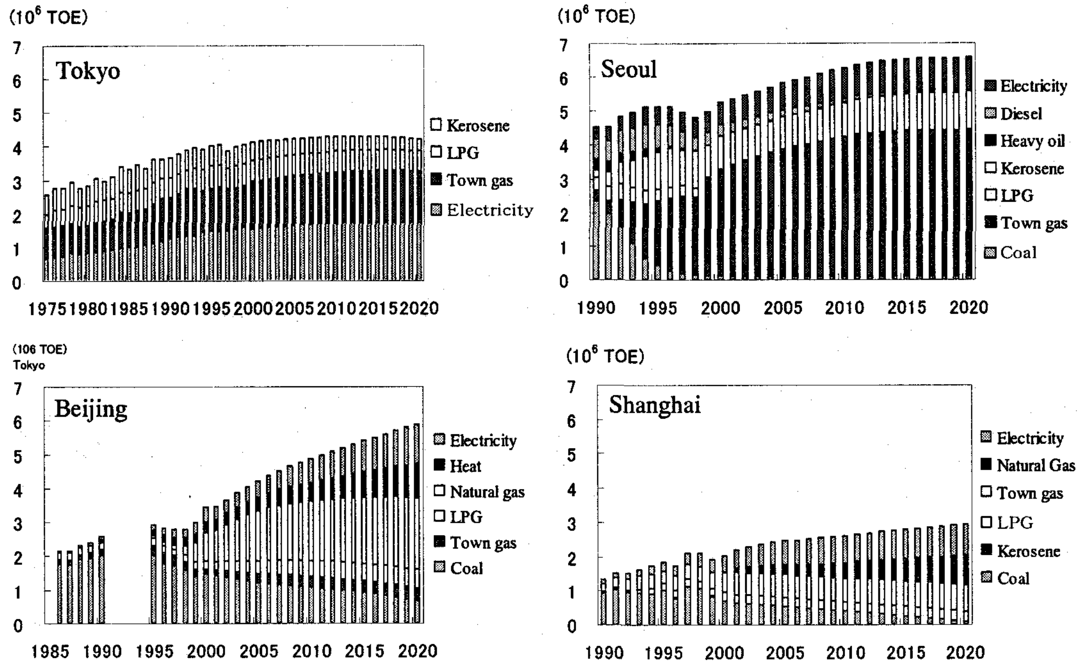
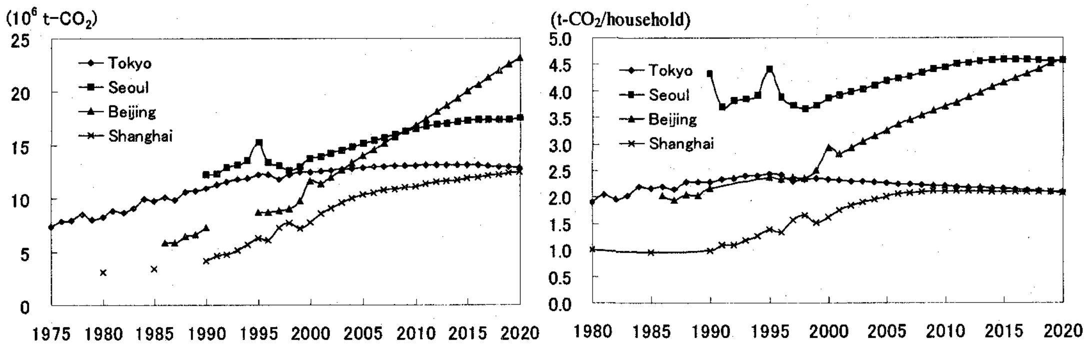


Figure 7. Projection of residential energy consumption by fuel type until 2020. Data for Tokyo and Seoul until 1998 are actual values; data for Beijing and Shanghai until 2000 are actual values.



(a) Total CO_2 emission

(b) CO_2 emission per household

Figure 8. Projection of CO_2 emission from residential energy consumption. Data for Tokyo and Seoul until 1998 are actual values; data for Beijing and Shanghai until 2000 are actual values.

of residential energy consumption is that Beijing will be positioned above Seoul and Shanghai will be positioned above Tokyo in both total CO_2 emission and CO_2 emission per capita by 2020. In addition to faster population growth, less efficient electricity generation and heat supply in China could be considered to account for the countertrend.

Table 7. Outline of measures for CO_2 emission reduction by scenarios.

Scenario	Type	Details	Energy saved 1) (%)
Fuel factors	Fuel	Preference for gas use	20[2]
Appliance factors	Air-conditioner	Efficiency improvement in compressors, improvement of heat exchangers, intelligent controls	44[3]
	Refrigerator	Invertor techniques, conversion of DC motors, use of evacuated insulation, reform of door gaskets	47[3]
	TV	Improvement of electric circuits, light controls, cutting off of power in non-detected signal cases, liquid crystal TVs (permutation from cathode-ray tubes)	45[2]
	Lighting	Fluorescent light (permutation from electric light bulbs), inverting system-fluorescent lights (permutation from the general type), sensored lighting (permutation from the general type)	58[2]
	Standby power, etc	Condenser motive controls, electric controls for each circuit, intermittent movement	10[3]
Housing factors	Residential insulation work	Insulation work on roofs, ceilings, walls, and floors, and double-glazed (double-window)	20[3]
Lifecycle factors	Fundamental attitude survey	Promotion of energy-conservation	16[4]

1) Reduction rate of energy-consumption compared to general household appliances, air-conditioner demand and hot-water supply demand as of 1997; 2) Estimated figure of this study; 3) 2001「Survey Study of House Energy Consumption」Report 2002 March Architectural Institute of Japan; 4) Global Warming Prevention Action Plan (Basic Plan), http://www.city.yokohama.jp/me/cplan/epb/machi/kyogikai/jigyo/3jidata/suanl.html

4. Policy Implications for CO_2 Emission Reduction

4.1 Scenario setting

Table 7 shows an overview of the measures for energy conservation in residential sector. Five scenarios are set: fuel factor improvement scenario, instrumentation factor improvement (devices, machines, etc.) scenario, housing factor improvement scenario, lifestyle factor improvement scenario and comprehensive factor improvement scenario. The comprehensive factor includes the fuel, instrumentation, housing and lifestyle factors. Further, details of each of the measures and energy conservation rates shown in the table are defined.

4.2 Estimation of introduction rate of measures by scenarios

This study assumes that all household appliances (air conditioners, refrigerators, televisions) purchased between 2005 and 2020 will be energy-conserving models, and new houses constructed during this time frame will incorporate energy-conserving lighting systems, standby electricity and housing heat insulation systems. The percentage of houses whose residents are highly aware of energy conservation after 2005 is set to 100%. Furthermore, the transition rate of fuel type from coal to gas in Beijing and Shanghai is assumed to be 50% after 2005.

The introduction rate for energy-conserving household appliances indicates the percentage of the total number of purchases after 2005 in relation to the total number of appliances. The total number

Table 8. Introduction rate of energy–conserving household appliances (%).

Year	Tokyo, Seoul[1)]			Beijing					Shanghai		
	All			Urban			Rural		All		
	Air-condi.	Refri.	TV	Air-condi.	Refri.	TV	Refri.	TV	Air-condi.	Refri.	TV
2005	9.5	9.2	11.1	14.1	8.6	8.6	13.3	6.8	18.1	13.7	16.8
2006	19.0	16.2	19.3	22.1	18.2	18.1	18.6	15.8	34.8	24.8	27.0
2007	35.1	30.3	31.0	33.2	26.6	26.6	25.2	28.1	46.8	38.9	36.6
2008	45.2	35.3	44.5	39.4	34.9	37.9	29.5	36.5	53.8	56.0	46.9
2009	51.1	45.4	50.0	51.2	47.4	58.6	43.8	53.2	65.8	65.2	61.2
2010	57.9	58.7	63.8	61.3	61.1	65.7	55.9	60.1	73.8	71.8	68.6
2011	68.4	67.0	72.5	66.3	71.2	73.3	73.8	69.6	77.7	84.9	75.8
2012	77.2	79.7	81.9	78.7	82.4	82.5	80.1	78.2	84.0	88.9	82.8
2013	90.8	88.6	89.2	89.1	90.3	92.1	89.4	85.6	90.1	96.7	91.7
2014	100	100	100	100	100	100	100	100	100	100	100
2015	100	100	100	100	100	100	100	100	100	100	100
2016	100	100	100	100	100	100	100	100	100	100	100
2017	100	100	100	100	100	100	100	100	100	100	100
2018	100	100	100	100	100	100	100	100	100	100	100
2019	100	100	100	100	100	100	100	100	100	100	100
2020	100	100	100	100	100	100	100	100	100	100	100

1) The number of household appliances in Seoul is assumed to be the same as that of Tokyo due to data limitation.

of appliances is calculated by multiplying the number of appliances per household by the number of households. In order to estimate the number of air conditioners per household and the number of televisions per household, a multiple regression analysis is implemented and the source of variation is analyzed. In this calculation, the floor space per household is utilized. The fixed average value between 1996 and 2000 is used to estimate the number of refrigerators per household. In addition, the average life span of durable appliances is set at 10 years. The increase in the total number of appliances is added to the number of appliances purchased 10 years ago to calculate the number of appliances purchased in a particular year, and then to estimate the total number of appliances purchased after 2005. By dividing this estimation by the total number of appliances, the introduction rate of energy-conserving household appliances can be forecast. The results are shown in Table 8.

In order to discuss the amounts of conserved energy and reduced CO_2 impacted by purchases of energy conserving models of air-conditioning systems, refrigerators and televisions, the energy consumption rates for appliances in households must be clearly understood. Based on the energy consumption rates by appliance in Tokyo as of 1997, the total energy consumption per household is comprised of 22% by air-conditioning systems, 18% by refrigerators, 16% by lighting and 9% by televisions. Even though it is true that energy consumption rates by usage may vary depending on the city and the defined time frame, the energy consumption rate by appliance in Tokyo as of 1997 is applied in this study since the details of usage rates by appliance are very difficult to determine in reality.

The introduction rate (introduction rate of measures related to floor space) of housing heat insulation systems, energy-conserving lighting systems and standby electricity indicate the percentage of the total value of residential floor space newly constructed after 2005 in relation to the total residential floor space. Therefore, it is necessary to estimate the total residential floor space, as well as newly constructed residential floor space. In order to estimate the total residential floor space, a multiple regression analysis is implemented and the source of variation is analyzed. Subsequently,

Table 9. Introduction rate of measures related to floor space (%).

Year	Tokyo	Seoul	Beijing	Shanghai	Year	Tokyo	Seoul	Beijing	Shanghai
2005	3.4	3.4	4.5	6.4	2013	30.3	30.5	39.3	39.8
2006	6.7	6.8	8.9	12.3	2014	33.7	33.8	43.7	42.9
2007	10.1	10.1	13.3	17.8	2015	37.2	37.1	48	45.2
2008	13.4	13.5	17.7	22	2016	40.7	40.5	52.5	47.3
2009	16.8	16.9	22.1	26.6	2017	44.3	43.7	56.8	49.2
2010	20.1	20.3	26.3	30.2	2018	47.9	47	61.3	51
2011	23.5	23.7	30.7	33.5	2019	51.6	50.3	65.8	52.6
2012	26.9	27.1	34.9	37.1	2020	55.4	53.6	70.3	54

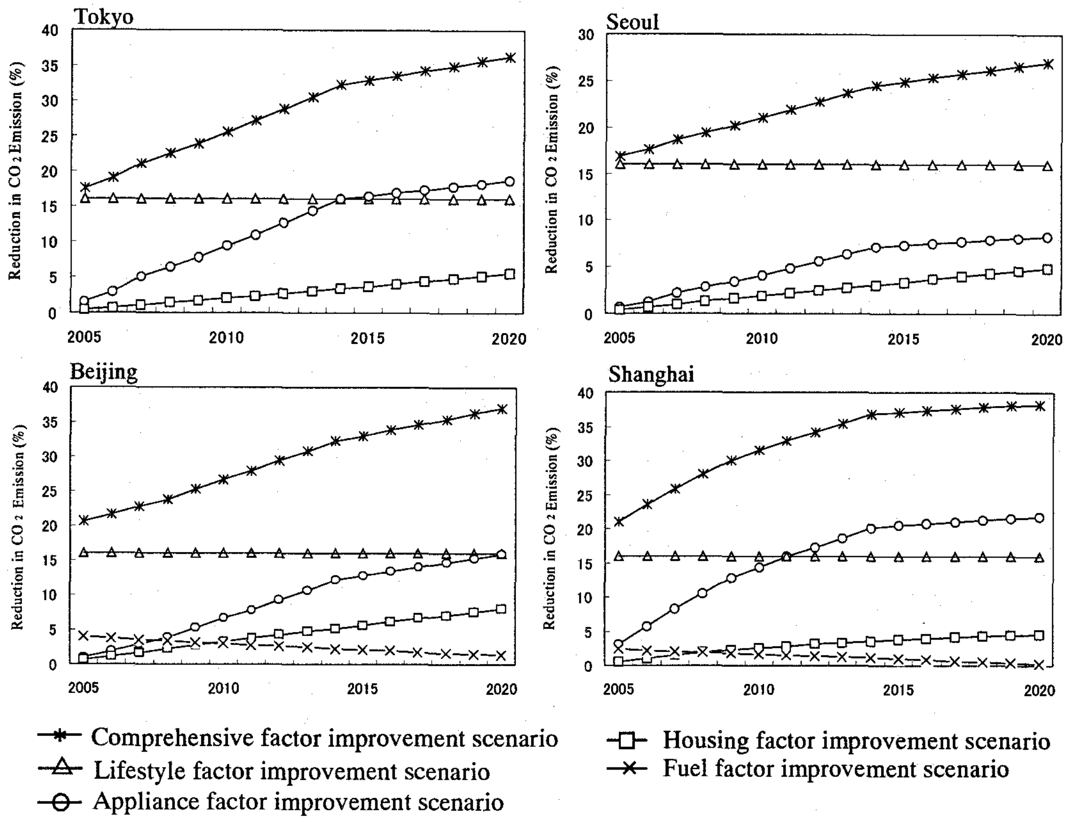


Figure 9. Reduction in CO_2 emission by different scenarios.

Gross Regional Product (GRP) is utilized. For newly constructed floor space, a fixed rate, which is the average rate of newly constructed floor space in relation to the total residential floor space in the last four years (1998-2001) in Tokyo, is utilized.

The fixed rate is multiplied by the current total floor space to estimate newly constructed floor space. For Beijing and Shanghai, a fixed value that indicates demolished floor space in the last 10 years is used, and then the annual increase of floor space is added to this value. By dividing floor space newly constructed after 2005 by the total residential floor space, the introduction rate of

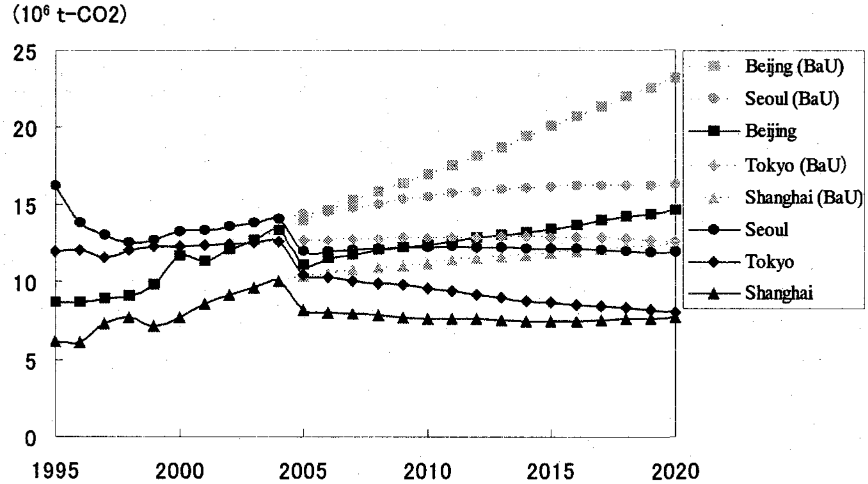


Figure 10. Comparison of CO_2 emission between BaU and comprehensive factor improvement scenario.

housing heat insulation systems, energy-conserving lighting systems and standby electricity into the residential sector can be forecast. Table 9 shows the introduction rates of strategic cases related to floor space.

4.3 Estimated CO_2 emission reduction

Figure 9 indicates estimated CO_2 reduction rates by scenario in the residential sector by 2020. Looking at the CO_2 reduction rate for each factor improvement case, the comprehensive factor improvement case has the highest rate in Beijing, Seoul, Tokyo (prior to 2014) and Shanghai (prior to 2012). These results are followed, in order, by the lifestyle factor improvement case, the instrumentation factor improvement case, and the housing factor improvement case. On the other hand, in Tokyo (after 2014) and Shanghai (after 2012), the comprehensive factor improvement case has the highest reduction rate, followed in order by the instrumentation factor, the lifestyle factor, and the housing factor improvement cases. This result is due to the fact that these cities have a large share of electrical power consumption in the overall energy consumption pattern in residential sectors. As with the energy conservation rate, the fuel type factor improvement case has the lowest CO_2 reduction rates after 2010. As of 2020, the largest CO_2 reduction rates are 36.3% in Tokyo, 37.0% in Beijing, 38.3% in Shanghai and 27.0% in Seoul.

4.4 Comparison between BaU and improvement scenario

Figure 10 shows the CO_2 emissions amount in the BaU case and that in the comprehensive factor improvement case. As of 2020, by improving the comprehensive set of factor, CO_2 reduction amounts are estimated at 8.586 million tons in Beijing, 4.759 million tons in Shanghai, 4.570 million tons in Tokyo and 4.384 million tons in Seoul.

5 Conclusions

In this paper, future trends in residential energy demand and CO_2 emissions are predicted, as well as a scenario approach is used to assess measures for energy conservation and CO_2 emission reduction in four Asian mega-cities: Tokyo, Seoul, Beijing and Shanghai. As for our future research tasks, a detailed delineation of the calculation parameters is needed; this can be achieved through questionnaires and trend forecasts based on diversified scenarios developed from various angles.

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