

Energy Demand Model of Residential and Commercial Sectors of Cities: A Case Study of Tokyo

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1. Introduction

In 1996, approximately 46% of the world's population live in cities. According to economic levels, the urban population accounts for about 40% of the total population in developing countries, 30% in East Asia, and 76% in developed countries. Since rapid urbanization is anticipated especially in developing countries, urban activities will greatly affect the problem of global warming. Above all, energy consumption in the residential/commercial sector of Asian mega-cities will be the key because the synergistic effect of urbanization and economic growth is anticipated to significantly increase energy consumption.

The purpose of this study is to construct a model for the prediction of energy consumption in the residential/commercial sectors of Asian mega-cities. This paper reports on a prediction model of energy consumption in the residential/commercial sectors of Tokyo. The model developed here can be applied to the study of Asian mega-cities and will facilitate international comparisons.

2. Basic concept and model structure

Asian cities should be studied with consideration of two points. One is data acquisition. Considering this, 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 permitted.

The other is to keep up with the varying rates of growth in the region. Economic growth and its accompanying change 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 emission in the residential/commercial sector in 2020.

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3. Target City

A prediction model will be constructed for Tokyo and will be applicable to other Asian mega-cities.

4. Construction of energy demand model for residential sector

4.1. Analytical procedure

Figure 1 shows the analytical method of a model for predicting the home energy demand. As this 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 heating, cooling, hot-water supply, and lighting, driving, and other uses. The energy demand for each use is expressed as the following identity with intermediate terms:

$$ENE.D = HS \times \frac{FL}{HS} \times \frac{ENE.D}{FL}$$

(1)

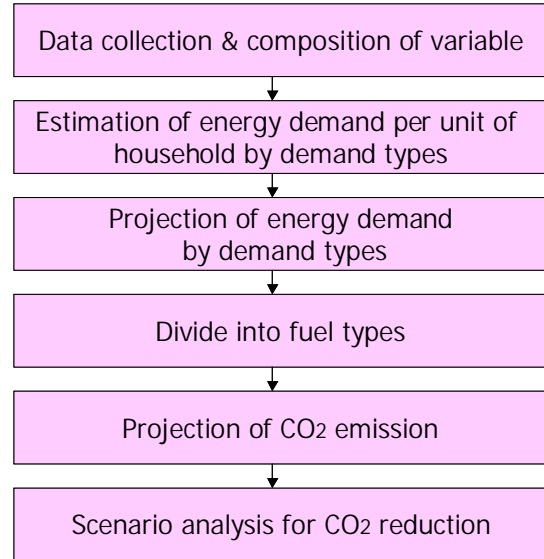


Figure 1. Analytical flow of residential sector.

where $ENE.D$ is energy consumption by demand type, HS is number of household, FL is floor space. The second intermediate term represents the floor space per household and the third intermediate term represents the energy demand per unit floor space.

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

$$ENE.D = HS \times \frac{ENE.D}{HS}$$

(2)

The second intermediate term represents the energy demand per household. The procedure up to the construction of the prediction model is outlined below.

STEP1

When necessary, synthesize the explanatory variables of energy demand per unit floor space, more specifically, energy price, equipment possession 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.

STEP2

To estimate the second and third intermediate terms of Formula (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.

STEP3

Prepare predictive values for the explanatory variables of the model formulated in STEP2. Thus, the model is used to calculate predictive values of the energy demand by uses until 2020.

STEP4

Decompose the values estimated in STEP3 by fuel type (electricity, kerosene, city gas, and LPG). To do so, an energy demand matrix for each fuel type by use should be prepared. Estimate the matrices of electricity, kerosene, and gas (city gas + LPG) by use from the trends of the past 25 years. With regard to the breakdown of gases, city gas consumption was predicted with the estimated future diffusion of city gas as an explanatory variable. The remainder is LPG.

STEP5

Estimate the energy demand by fuel type and multiply the energy demand by the unit requirement of carbon dioxide emission to predict the carbon dioxide emission until 2020.

4.2. Energy demand for heating

Figure 2 shows the method for estimating the 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 formula obtained this way was adopted as a prediction model.

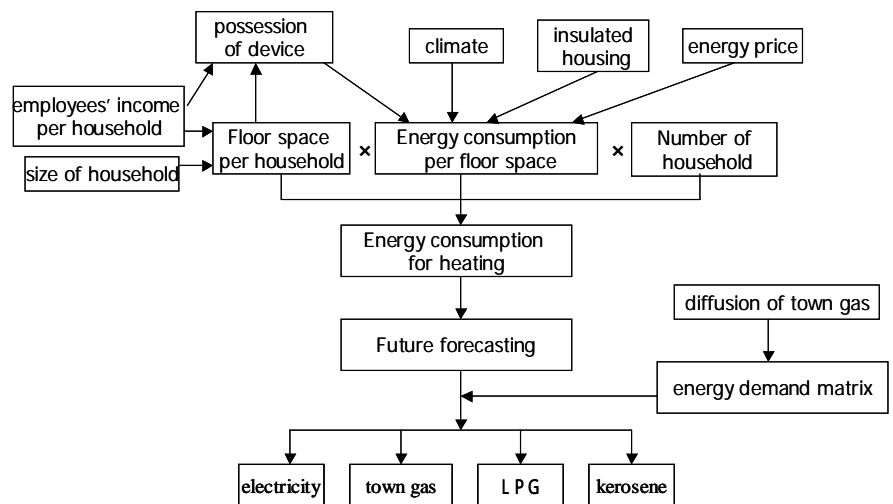


Figure 2. Estimation of energy consumption for heating.

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, an formula 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 for prediction. 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.

By multiplying the energy consumption per unit floor space, the floor space per household, and the number of households estimated according to Formula (1), the predictive value of energy consumption was calculated for heating. The calculation method depends on the fuel type as explained in STEP4 of 4.1.

4.3. Energy demand for cooling

Figure 3 shows the method for estimating the energy demand for cooling.

To estimate the unit requirement of energy consumption per unit floor space, variable factors were 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 formula 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 Formula (1), the predictive value of energy consumption for cooling was calculated. The energy for cooling is electricity only and needs not be decomposed by fuel type.

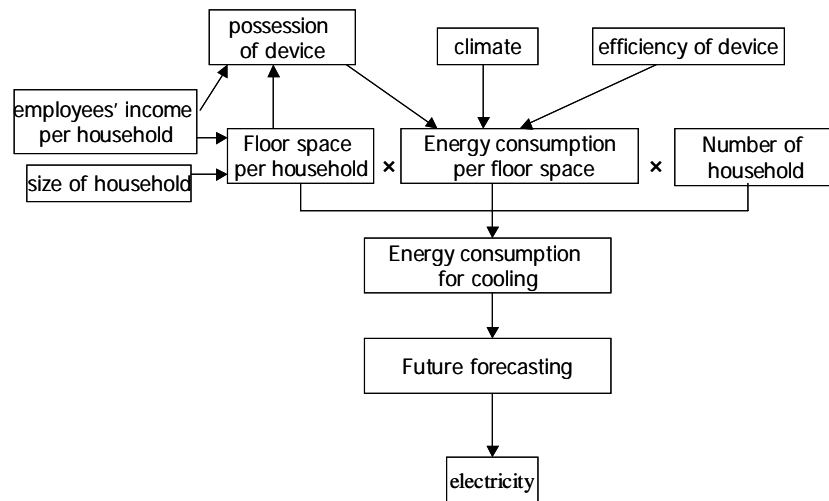


Figure 3. Estimation of energy consumption for cooling.

4.4. Energy demand for hot-water supply

Figure 4 shows the method for estimating the energy demand for hot-water. The energy demand for hot-water supply was calculated using Formula (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 of new household diffusion. The regression formula 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 predictive value of energy consumption for hot-water supply was calculated and decomposed by fuel type according to STEP4 of 4.1.

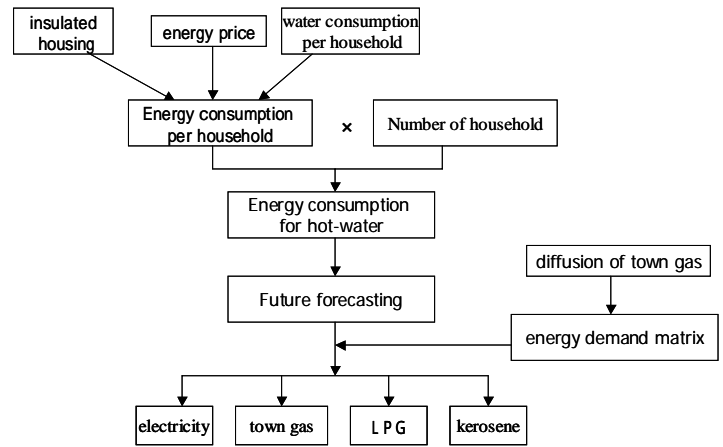


Figure 4. Estimation of energy consumption for hot-water supply.

4.5. Energy demand for lighting, driving, and other uses

Figure 5 shows the method for calculating the energy demand for lighting, driving, 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, driving, 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. The energy price was adopted the mean value of 9 years in the past as well as another. With regard to equipment efficiency, the future value was estimated as a time-dependent logistic function.

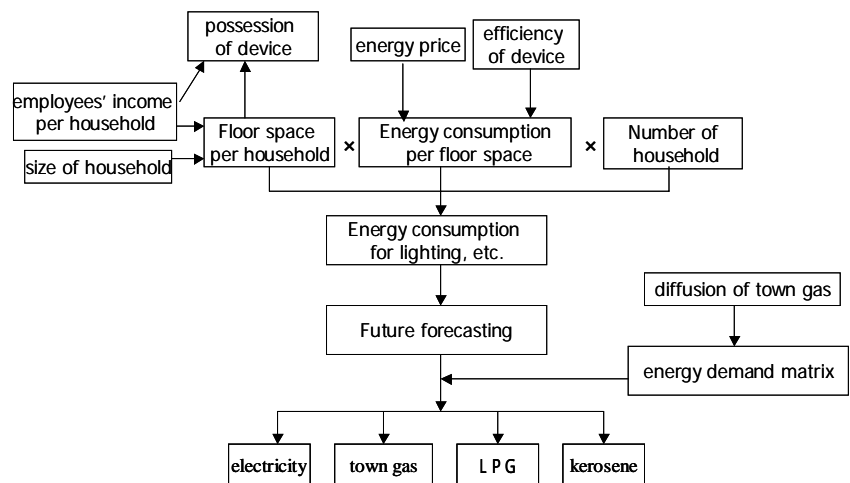


Figure 5. Estimation of energy consumption for lighting, etc.

By multiplying the energy consumption per unit floor space, the floor space per household, and the number of households estimated according to Formula (1), the predictive value of energy consumption for lighting, driving, and other uses was calculated and decomposed by fuel type according to STEP4 of 4.1.

4.6. Prediction of carbon dioxide emission and discussion

Figure 6 shows the transition of energy consumption by uses. Consequently, the energy consumption for heating shows a slightly decreasing tendency while those for other uses show slightly increasing tendencies. The energy consumption for heating is decreases because the number of households is not increasing and the house insulation factor is improving. In total, the energy consumption will increase until 2015 but then start to decrease.

The energy consumption by use and fuel type was multiplied by the unit requirement of carbon dioxide emission to calculate the carbon dioxide emission until 2020 (Figure 7). The unit requirement released by the Japanese Ministry of Environment in 1999 was applied. The consumption of kerosene and LPG will continue to decrease and those of electricity and city gas will start to decrease after 2016. The total consumption will reach its peak in 2013. The value in 2020 will be about 17% higher than that in 1990.

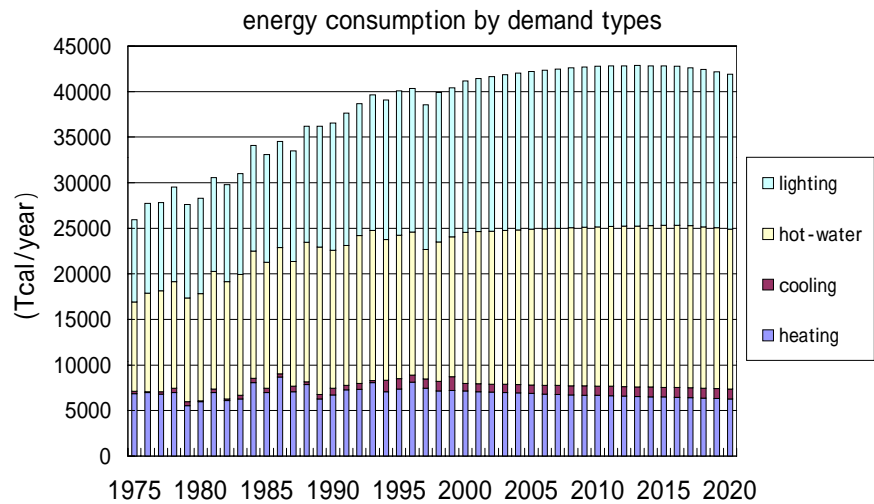


Figure 6. Energy consumption by demand type in residential sector

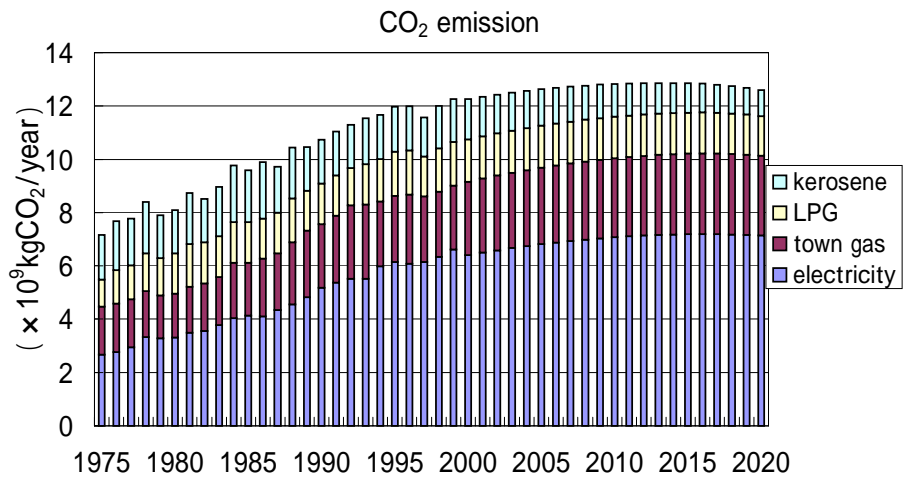


Figure 7. CO₂ emission by fuel type in residential sector

5. Construction of energy demand model for commercial sector

5.1. Analytical procedure

Figure 8 shows the model for predicting the business energy demand. For model construction, business data is generally more difficult to obtain than home data. The unit requirement of energy consumption by building type and use is obtained and multiplied by the predicted floor space. Buildings are classified into four types (two profit-making types and two nonprofit-making types). The identity can be expressed as shown below.

$$ENE.BD = FL \times \frac{ENE.BD}{FL} \quad (3)$$

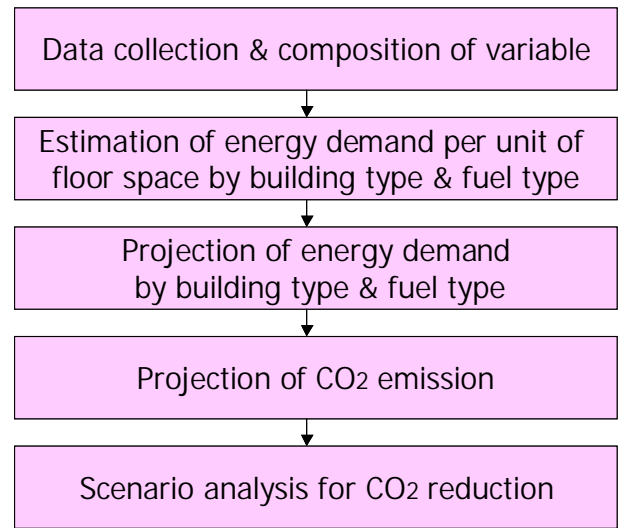


Figure 7. Analytical flow of commercial sector.

where *ENE.BD* is energy consumption by building type and demand type. The second intermediate term denotes the energy demand per unit floor space by building and fuel type per household. The procedure until the construction of a prediction model is outlined below.

STEP1

When necessary, synthesize the explanatory variables of the energy demand per unit floor space by building type and fuel type.

STEP2

To estimate the second intermediate term of Formula (3), evaluate the variable factors by multiple regression analysis. From the results, formulate a model for estimating the energy demand per unit floor space by building type and fuel type.

STEP3

Prepare predictive values for the explanatory variables of the model formulated in STEP2. Thus, the model is used to calculate predictive values of energy demand by building type and fuel type until 2020.

STEP4

The energy demand by building type and fuel type is multiplied by the unit requirement of carbon dioxide emission to predict the carbon dioxide emission until 2020.

5.2. Prediction of carbon dioxide emission and discussion

Partial regression coefficient in multiple regression analysis for commercial sector was established in Table 1. Then the future values of explanation valuables were needed to establish. The energy price and climate factors were adopted the mean value of the past. The GRP of tertiary industry was assumed to be an expansion by 0.5% in the annual rate.

With regard to floor space, the future value was estimated as a time-dependent logistic function. By multiplying the energy consumption per unit floor space and the floor space of commercial sector according to Formula (3), the predictive value of energy consumption by energy type was calculated.

Figure 8 shows the transition and prediction of electricity consumption by building type. Figure 9 shows the transition and prediction of the carbon dioxide emission by fuel type until 2020. The total energy consumption and CO₂ emission will reach these peaks in 2015. Most kinds of the fuel consumption except city gas will start to decrease after 2015. The value in 2020 will be about 39% higher than that in 1990.

Table 1. Result of partial regression coefficient in the multiple regression analysis for commercial sector

	building type	fuel type	explanation variable				constant	notes	
			climate		energy price	activities			computer per floor space
			heating degree	cooling degree					
profit sector	office	electricity	-101.21	-16.22	-1457.41	-778.12	72.06	activity: Real GRP of Tertiary Industry / floor space	
		town gas	13.08	8.68	-2647.52	-180.83	***		
		LPG	0.10	***	15.22	3.00	***		
		A heavy oil	-9.21	***	1192.69	***	***		
		B·C heavy oil	***	***	***	***	***		
		kerosene	-7.03	***	626.91	6.53	***		
	other	electricity	71.18	74.61	1638.37	111.49	***	activity: Real GRP of Tertiary Industry / floor space	
		town gas	200.63	90.74	-14969.33	66.41	***		
		LPG	-1.70	***	53.73	-2.51	***		
		A heavy oil	30.73	***	2875.39	18.36	***		
		B·C heavy oil	***	***	***	***	***		
		kerosene	6.36	***	365.73	3.30	***		
non-profit sector	hospital	electricity	-273.12	-26.29	***	-59.54	***	activity: number of patient / floor space	
		town gas	-53.77	***	-3394.05	-22.44	***		
		LPG	1.67	***	***	0.54	***		
		A heavy oil	-82.94	***	7790.82	0.00	***		
		B·C heavy oil	***	***	0.00	0.00	***		
		kerosene	-55.65	***	4299.19	0.00	***		
	school	electricity	-23.59	-6.22	-602.22	-221.92	***	activity: number of student/ floor space	
		town gas	13.43	8.76	-3492.11	-217.35	***		
		LPG	0.09	***	22.57	3.71	***		
		A heavy oil	-17.31	***	1603.89	***	***		
		B·C heavy oil	0.00	***	***	***	***		
		kerosene	-1.32	***	94.56	1.68	***		

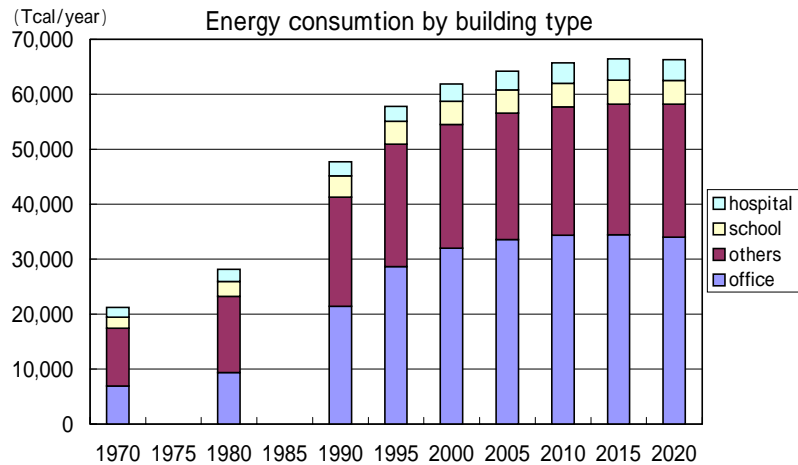


Figure 8. Energy consumption by building type in commercial sector

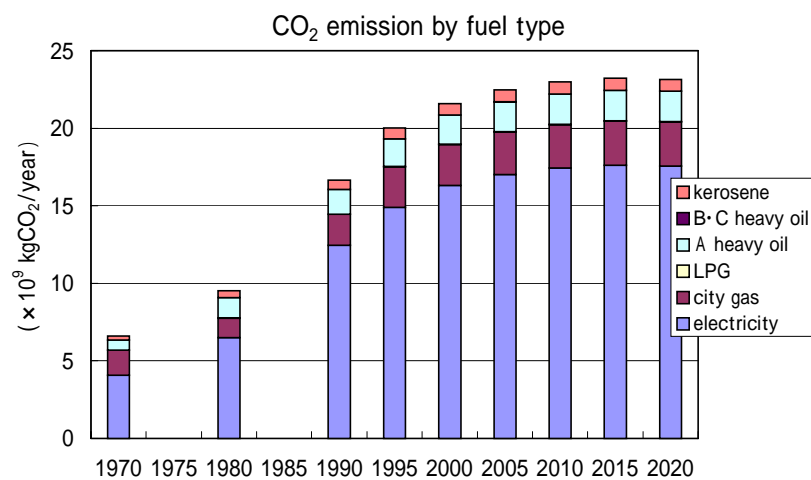


Figure 9. CO₂ emission by fuel type in commercial sector

6. Subjects for scenario analysis

For application to Asian mega-cities, the authors developed a model for predicting the energy demand in the residential/commercial sectors of Tokyo. The analysis so far enabled for the prediction of a so-called trend case. The next step is to estimate the effects of various measures and the influence of social trend changes using the model.

The subjects in the home division can be classified mainly into household and lifestyle factors, household factors, and energy equipment factor. For trial calculation, the influence of these scenarios on the unit requirements of energy consumption (per unit floor space and per household) calculated in Chapters 4 and 5 were analyzed. As to , the influence of household property changes can be experimentally calculated if the energy consumption characteristics by household can be gained through questionnaire surveys. The change in the time spent at home due to changes of work patterns may be another factor that can be experimentally calculated as a change from the assumed trend case in the same way.

An appendix lists necessary data for application to Asian mega-cities. However, the model structure can be handled flexibly according to the possibility of data acquisition because it is based on the decomposition of the energy

consumption structure by intermediate terms and the regression analysis of each term. Analysis in several cities will enable for a study of international comparisons.

Appendix I: List of data used in energy demand model for residential sector

	Inputs	detail
Overall	economic indicators	households income population
	energy demand	energy demand by energy type by demand type (matrix)
Service unit	number of households	
Energy Intensity per unit of Service	household property	number of people
	housing property	type (detached / apartment) insulated rate floor space
	number of service device	possession rate of equipment water consumption per household
	energy efficiency factor	energy demand * by equipment COP(coefficient of performance) by equipment
	energy price	energy price by energy types *
	climate factor	cooling degree heating degree

*: coal, kerosene, LPG, town gas, electricity, solar heat

Appendix II: List of data used in energy demand model for commercial sector

	Inputs	detail
Overall	economic indicators	production by category of business
	energy demand	energy demand by energy type by demand type (matrix)
Service unit	floor space	floor space by business type (if available)
Energy Intensity per unit of Service	business activity	production value (or sales value) by business type * performance ** by business type
	energy price	energy price by energy types ***
	climate factor	cooling degree heating degree

*: office, small shop, department store, supermarket, hotel, entertainment, school, hospital, others (public facility, etc.)

** : labor force, number of bed (hospital), number of student (school), number of guest (hotel, entertainment)

***: coal, kerosene, heavy oil, town gas, electricity, solar heat

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