ESTIMATION OF ENERGY CONSUMPTION FOR AIR-CONDITIONING OF RESIDENCES

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ABSTRACT

Simplified equations are established to estimate the energy consumption for the heating and cooling of residences, with the coefficients like air-conditioning area rate, air-conditioning-hour rate, etc.. To determine these coefficients, a detached house model is supposed. The air-conditioning load of the house in different regions is calculated with a thermal performance simulation program called the PSSP. With the simplified equations, the primary energy consumption in the future is estimated. The energy consumption for the heating and cooling of residences will increase further in the next century with the increases of floor area of residences, the percentage of air-conditioned floor area, and the air-conditioning hours.

INTRODUCTION

Energy consumption in the sectors of industry and transportation has been stabilized in Japan, but energy consumption in the residential sector is still growing with the improvement of living standards. Therefore it is important to forecast the energy consumption in order to estimate the total energy demand of Japan.

Energy consumption in the residential sector in Japan has been investigated in some studies. Sawachi et al. investigated energy consumption in the residential sector in eight regions of Japan, and established regression equations with parameters like degree-days (T. Sawachi et al, 1994). Ishida investigated energy consumption of detached houses in eight regions of Japan in 1997, and developed some equations to estimate energy consumption for heating, cooling, cooking, lighting and hot water supply using the method of multivariate analyses (K. Ishida, 1997). Miura tried to calculate energy consumption for residences by using the data from surveys on the family budget (S.Miura, 1998). On the other hand, Matsuo et al. developed a simplified method to estimate annual air-conditioning load called the Expanded Degree-Day Method, in which solar radiation and long wave radiation are considered as part of the expanded degree-days (Y. Matsuo, 1979). The Expanded Degree-Day Method is based on the supposition of continuous air-conditioning; nevertheless, most of the residential houses are air-conditioned discontinuously.

In this paper, we are trying to establish some equations to estimate the annual energy consumption for the heating and cooling of residential houses, in which the concepts of degree-hours and air-conditioning-hour rate are introduced, considering the discontinuous air-conditioning in residences. The influence of orientation of buildings, and errors caused by the simplification are also discussed.

THE METHOD OF SIMULATION

A two-storied model house (Fig.1) is considered for the simulations in this study referring to Udagawa's model house (M.Udagawa,1978). The floor area of the house is about 125 m^2, with a four-member-family living in the house. In this study, the house is supposed to be made of wood, considering that most detached houses in Japan are wood-made. A simulation program called PSSP (T. Hayashi et al., 1987) is used in simulating the thermal performance of the house. The program consists of an unsteady heater transfer algorithm and ventilation among rooms in a multi-room system. Twelve cities shown in Table 1 are selected as the representatives to discuss the regional characteristics of energy consumption. Weather data of an average year for these cities are used as the input of the simulations.

ESTIMATION OF ANNUAL LOAD

The thermal performance of the model house is simulated when it is located in the twelve cities shown in Table 1. The word heat loss coefficient is defined as the heat loss per unit floor area when the temperature difference between the indoor and outdoor air is one degree. Another concept to describe the heat gain of the house from solar radiation is solar gain coefficient, which is defined as the solar heat gain per unit floor area to the solar radiation without shading.

To estimate the heating load, some methods based on the degree-days have been used up to now. However, as mentioned in the introduction, the degree-day method is based on continuous heating or cooling, and may cause errors in estimating heating or cooling load on a discontinuous basis. To solve such a problem, the following equation is suggested:

$$Q_h = \varphi_u \varphi_o \{A \bullet (3600 L \bullet DH_h - \mu \bullet I_s) - H - M\} \qquad (1)$$

Degree-hour *DHh* means the accumulated hours multiplying indoor-outdoor temperature difference only when the outdoor temperature is lower than 22C. The relations between daily heating load by Equation (1) and simulations for Tokyo are shown in Fig.2. Regression lines without intercepts are shown in the figure. The coefficient of R^2 is 0.88, therefore the daily heating load can be estimated with Equation (1). The results from Equation (1) also agree with that from simulations quite well for other cities.

In order to verify whether the annual heating load for different cities can be estimated by Equation (1), the relations between the annual heating load from simulations and Equation (1) are examined as shown in Fig.3. At this stage, both φ_o and φ_u are assumed to be 1.0. By the regression equation shown in Fig.3, it is easy to understand that the coefficient φ_u equals 1/0.9796. To determine the coefficient of orientation, simulations are conducted when the orientation of the house is $-90°, -60°, -30°, 0°, 30°, 60°, 90°$. It is found that the annual heating load changes very little with the orientation of the house, therefore it causes no problem to ignore the influence of orientation when the solar gain coefficient is less than 0.05. Using Equation (1), the annual heating load of the 12 regions can be estimated with an error of less than 6% when the air-conditioning is continuous.

Similarly, the cooling load can be estimated with the following equation:

$$Q_c = \varphi'_u \varphi'_o \{A \bullet (3600 L \bullet DH_c + \mu \bullet I_s) + H + M\} \qquad (2)$$

In fact, for heating, degree-hours are almost equal to 24 times of degree-days. For cooling, however, the relation does not always exist because the ambient temperature sometimes drops below the air-conditioned room temperature in summer and cooling is not continuous in most houses. Therefore, the method to estimate cooling load based on degree-days does not always agree with simulations containing an unsteady heat transfer process.

The relationships between the annul cooling load by Equation (2) and simulations are shown in Fig.4, by which one can easily understand that coefficient of unsteady heat transfer for cooling φ'_u is 1/0.968, which is almost equals to that for heating.

The coefficient of house orientation for cooling φ'_o, however, cannot be ignored as heating. The relations between orientation and φ'_o are shown in Fig.5. The orientation coefficient φ'_o changes between 1.0 and 1.14 then the solar gain coefficient is between 0.0225 and 0.042.

EQUATIONS FOR DISCONTINUOUS AIR-CONDITIONING

In Japan, air-conditioning of residences is usually conducted on a discontinuous basis. Furthermore, only the living room and bedrooms are air-conditioned in most regions. Therefore, it is necessary to convert Equations (1) and (2) to equations that can be used to estimate the annual load under discontinuous and partial air-conditioning conditions.

To determine the parameters in the equations for discontinuous and partial air-conditioning, simulations under the conditions of discontinuous cooling and heating are conducted. In summer, the house is cooled during the period of 14:00-21:00 in the living room, and one hour in child’s rooms, two hours for the main bedroom after that period. The house is ventilated naturally during the daytime when air-conditioning is not conducted. As for the winter, all the openings are closed throughout the day.

Two parameters are introduced to Equation (1) as follows:

$$Q_h = \varphi_A \bullet A \bullet (3600 \varphi_t \bullet L \bullet DH_h - \mu \bullet I_s) - H - M \qquad (3)$$

Air-conditioned floor area rate φ_A is expressed in the following equation:

$$\varphi_A = \left(\frac{A_a}{A}\right)^{0.35} \qquad (4)$$

The exponent 0.35 is decided by comparing the results from Equation (3) with that from the simulations. The primary energy consumption for heating can be calculated by multiplying Q_h by energy efficiency or COP of heating machine and conversion coefficient.

Fig.6 shows the comparison of values of energy consumption for heating in Japan from surveys by Sawachi, Ishida and Miura, simulations with the PSSP and Equation (3). The results from Equation (3) agree with not only the simulation results, but also with the survey results.

The load of discontinuous and partial cooling can be calculated by Equation (5):

$$Q_c = \varphi_t' \{ A \bullet \varphi_A' \bullet (3600 L \bullet DH_c + \mu \bullet I_s) + H + M \} \tag{5}$$

where

$$\varphi_A' = \frac{A_a}{A} \tag{6}$$

In these equations, air-conditioned floor area rate φ_A' is simply the percentage of air-conditioned floor area, and air-conditioning-hour rate φ_t' means the percentage of degree-hours when the house is really air-conditioned to the total degree-hours for cooling.

The comparison of primary energy consumption for cooling by surveys, simulations and Equation (5) multiplied by the COP of the cooling devices and conversion coefficient is shown in Fig.7. The values from the three sources agree with one another fairly well, except for that of Fukuoka, where the cooling energy from survey is much smaller than the values from simulations and Equation (5).

FORECAST OF ENERGY CONSUMPTION FOR AIR-CONDITIONING

Using Equations (3) and (5), energy consumption for the heating and cooling of residences can be estimated. According to Sawachi's study, the energy consumption for the cooling of an apartment house is about 0.70 times of that of a detached house in the same city, while the factor is 0.46 for heating. Therefore, in this paper, the energy consumption of apartment houses estimated by multiplying a factor of 0.70 or 0.46 in summer and winter, respectively. The total energy consumption for the heating and cooling of residences is expressed with Equation (7):

$$E_A = \sum_{i=1}^{12} \varepsilon_h Q_{hi} (h_{di} + 0.46 h_{ai}) \bullet c_h + \sum_{i=1}^{12} \varepsilon_c Q_{ci} (h_{di} + 0.7 h_{ai}) \bullet c_c \tag{7}$$

We divide the 47 prefectures of Japan into 12 blocks represented by the 12 cities shown in Table 1. These prefectures are further divided into six regions according to the climate characteristics. The heat loss coefficient of each region will decrease gradually by increasing thermal insulation and air-tightness to save energy in the future. The trend of heat loss coefficients is considered as shown in Fig.8 during the period of 1995-2050.

With the improvement of living standards of Japan, the floor area will increase in the next several decades. The percentage of the floor area to be air-conditioned will also increase for the purposes of thermal comfort and health. The fluctuation in floor area and air-conditioning floor rate is supposed as Fig.9. According to the supposition, the floor area of a detached house will grow to 150 m^2, and the air-conditioning floor area will grow to 80% of the total floor area in 2050.

As shown in Fig.10, the energy consumption for the air-conditioning of residences will be doubled to 30 Mtoe in 2030, and keeping on growing after that. This means that even if the houses become more energy-saving, the energy consumption will grow significantly with the improvement of living standards, especially the increases of floor area, air-conditioned floor rate and air-conditioning-hour rate.

CONCLUTIONS

1. Annual loads of continuous air-conditioning of a wood-made house can be estimated with simplified equations based on the concept of degree-hours.

2. Equations for annual load of discontinuous and partial air-conditioning are developed in this paper.

3. Ever if residences become more energy-saving, the energy consumption for air-conditioning will grow significantly in the next century with the improvement of living standards, especially the increases of floor area, air-conditioned floor rate and air-conditioning hours.

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NEMANCLATURE

A : floor area, m^2

Aa : the air-conditioned floor area

C_c : constant of secondary-primary energy conversion for cooling devices

C_h : constant of secondary-primary energy conversion for heating devices

DH_c: degree-hours for cooling (the room temperature is $25°C$ in this case)

DH_h: degree-hours for heating (in this paper, it is supposed that the room temperature is kept at $22°C$ in winter, and heating begins when the average ambient temperature drops to $10°C$)

E_A: energy consumption for heating and cooling, J or Toe

H: heat generated by domestic electric devices, cooking and lighting etc., J

Ha_i: number of apartment houses in Block i

Hd_i: number of detached houses in Block I

Is: solar radiation, J

L: heat loss coefficient, W/m^{2}K

M: heat generation of human bodies, J

Q_{hi},Q_{ci}: heating and cooling loads for Block i, respectively

ε_c : energy efficiency of cooling devices

ε_h : energy efficiency of heating devices solar

μ : gain coefficient

φ_o : coefficient of orientation (it equals 1.0 when the house faces south)

φ_u : coefficient of unsteady heat transfer

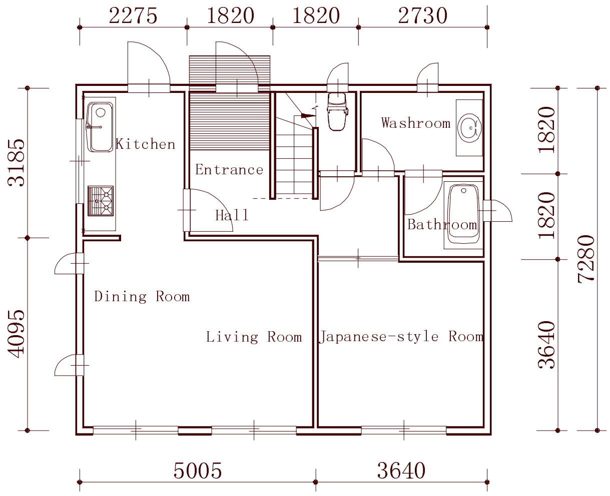
φ'_u : coefficient of unsteady heat transfer for cooling

φ'_o : coefficient of house orientation for cooling

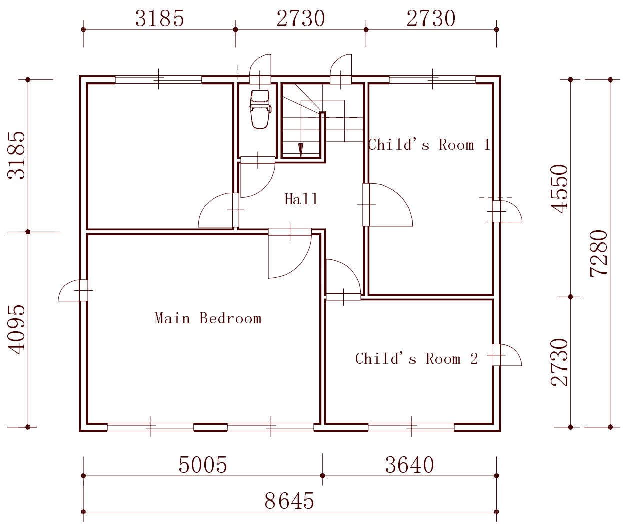
φ_t : air-conditioning-hour rate, which means the ratio of air-conditioning degree-hours to the total degree-hours for heating

Table 1 Cities to be selected as the locations of the model house

City	Location	Degree-hours		Prefectures to be represented	Climate region
		Heating	Cooling		
Sapporo	$43°03'N,141°20'E$	99531	-	Hokkaido	1
Akita	$39°43'N,140°06'E$	76078	1005	Akita, Aomori,Iwate	2
Sendai	$38°16'N,140°54'E$	69102	443	Miyagi, Yamagata	3
Niigata	$37°55'N,139°03'E$	62437	2172	Niigata, Fukushima, Ibaraki, Ishikawa, Toyama, Tichigi, Nagano, Gumma, Yamanashi,Fukui,Shiga, Gifu	3
Tokyo	$35°41'N,139°46'E$	42633	2571	Tokyo, Saitama, Chiba, Kanagawa	4
Nagoya	$35°10'N,136°58'E$	51237	3452	Aichi, Shizuoka, Mie	4
Osaka	$34°41'N,135°31'E$	44202	5335	Osaka, Kyoto, Hyogo, Tottori, Nara, Okayama, Shimane, Hiroshima, Yamaguchi, Wakayama	4
Kochi	$33°34'N,133°33'E$	39174	4058	Kochi, Kagawa, Tokushima, Ehime	4
Fukuoka	$33°35'N,130°23'E$	39893	4987	Fukuoka, Saga, Nagasaki	4
Kumamoto	$32°49'N,130°43'E$	43573	4664	Kumamoto, Oita	4
Kagashima	$31°33'N,130°33'E$	31019	5092	Kagoshima, Miyazaki	5
Naha	$26°12'N,127°41'E$	-	6778	Okinawa	6



(a) 1F Plan



(b) 2F Plan

F1g.1 Plans of the house model for simulations

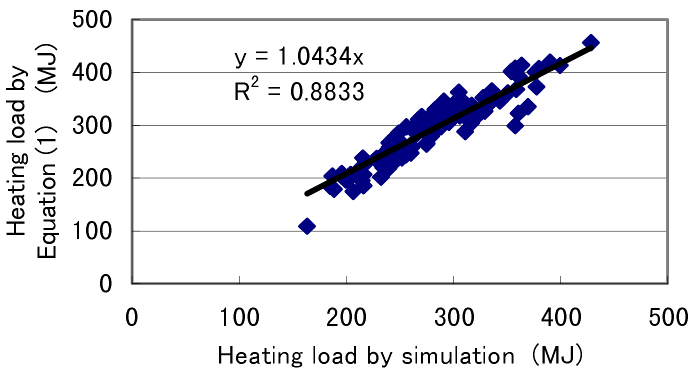


Fig.2 Corelations between heating load by Equation (1) and simulations (Tokyo,L=2.02)

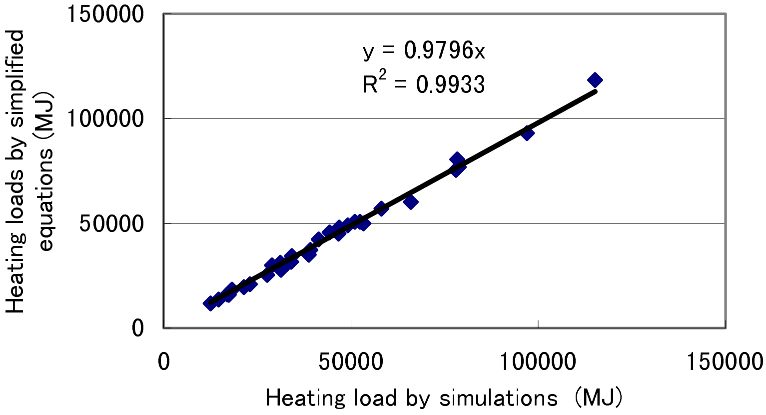


Fig.3 Corelations between heating loads by simplified equations and simulations(L=1.5,2.02,2.84)

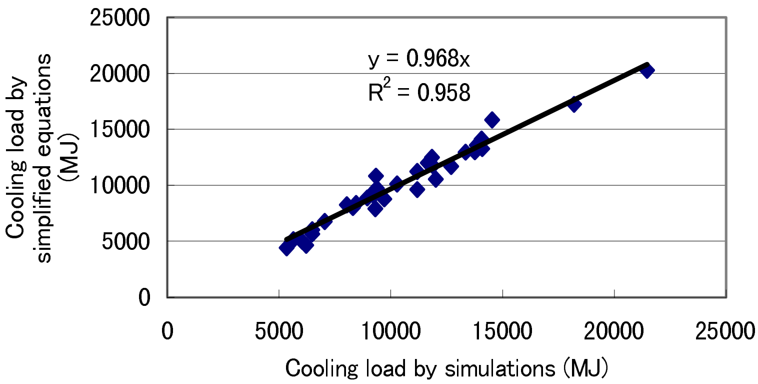


Fig.4 Corelations between annual cooling load values from simulations and simplified eqations(L=1.5,2.02,2.84)

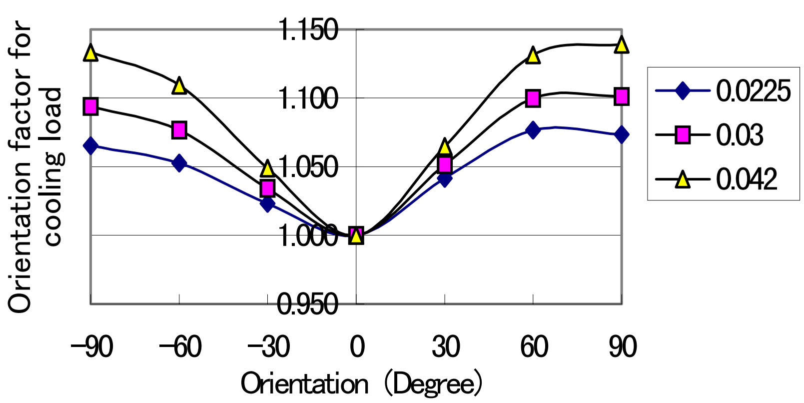


Fig.5 Relation between orientation and cooling load(L=2.9)

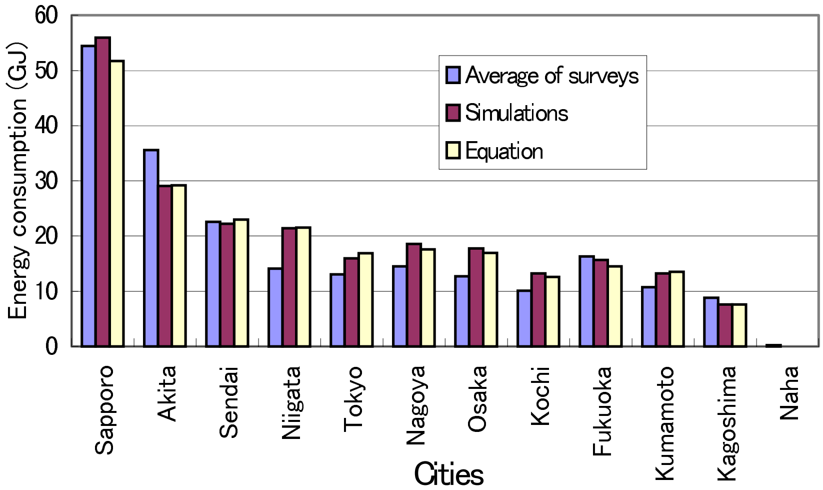


Fig..6 Comparison among primary energy consumption for heating by surveys, simulations and simplified equation

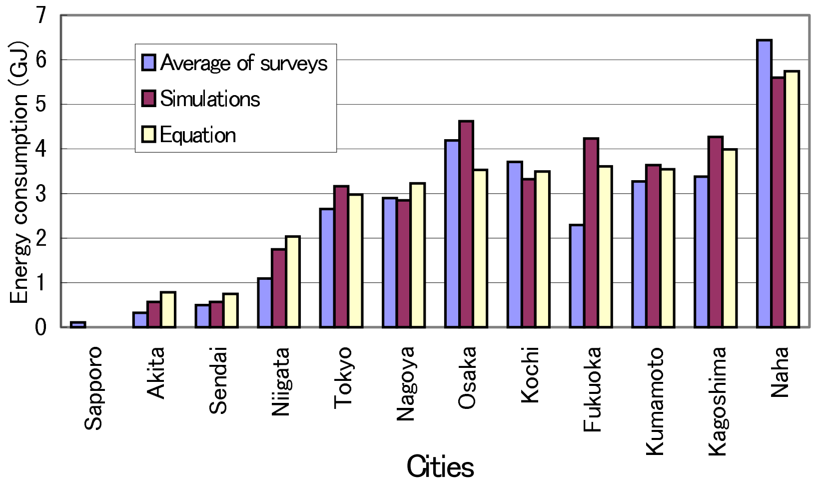


Fig.7 Comperison among primary energy consumption for cooling by surveys, simulations and simplified equation

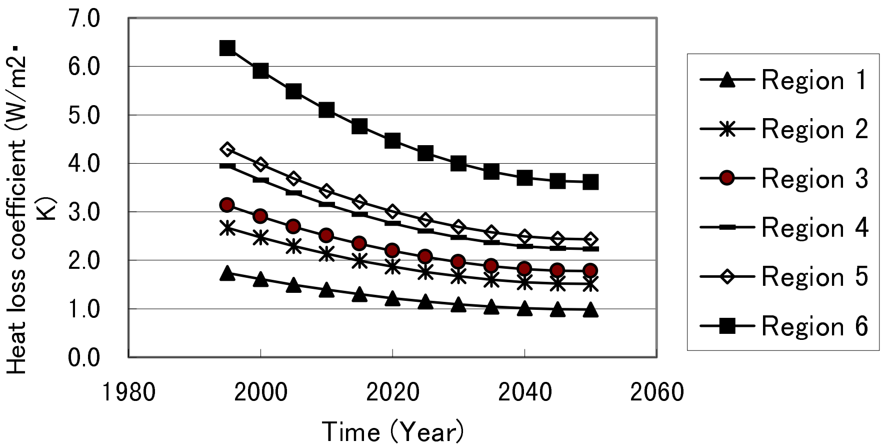


Fig.8 Heat loss coefficients of different ragions

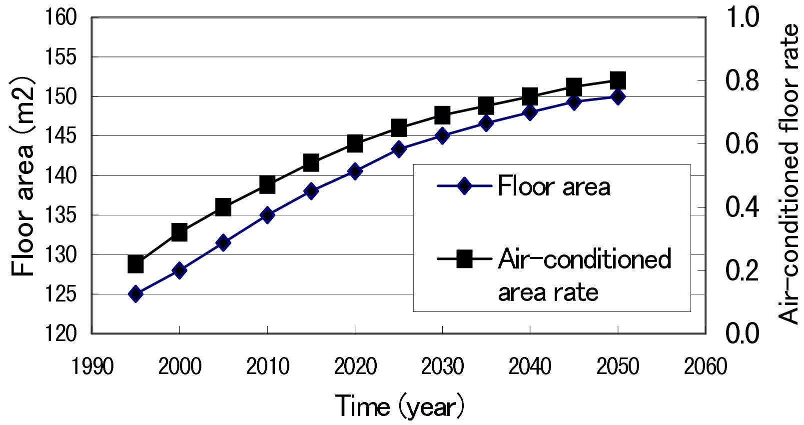


Fig.9 Prediction of floor area and air-conditioned area rate

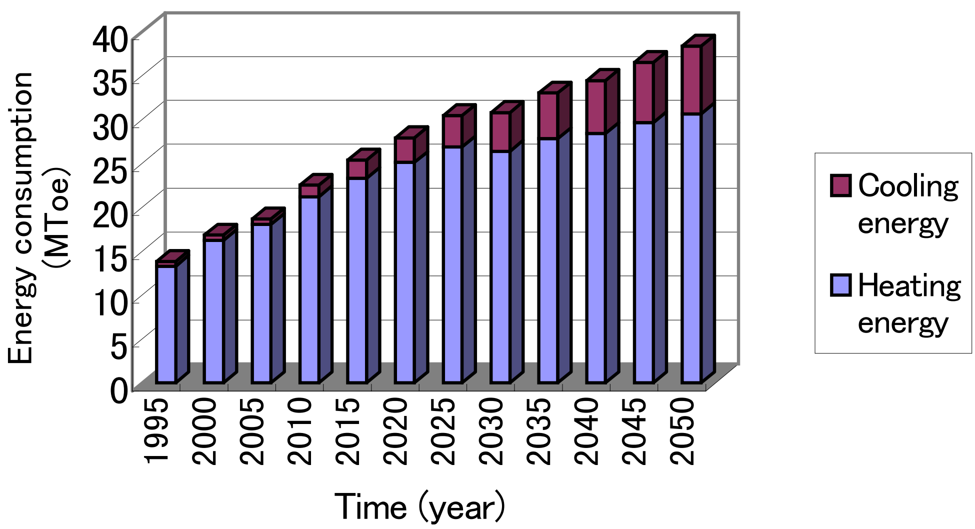


Fig.10 Forecast of primary energy consumption for air-conditioning