# Working Paper

# End-use Energy Model for Analysing the Policy Options to Reduce Greenhouse Gas Emissions

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December 1995

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# Abstract

The objective of this work is to develop the end-use energy model for assessing the policy options to reduce greenhouse gas emissions. This model is a part of the integrated model called AIM (the Asian-Pacific Integrated Model). This module evaluates the effect of introducing a carbon tax on various carbon emission countermeasure technologies such as energy conservation technologies, and the size of consequent $CO_2$ emission reductions. It also estimates the increased effect when the carbon tax is combined with other countermeasure policies, such as the introduction of subsidies. This model was applied to the Japanese case. The conditions for which each energy conservation technology menu would be adopted were defined using its relationship with the carbon tax rate and subsidy assuming a certain end-use energy scenario. Then, the relationships between the introduction of these technology menus and reduced $CO_2$ emissions based on various socioeconomic scenarios were analyzed and an evaluation was made of the effects of combining a carbon tax and subsidies using the recycled revenues from such a tax.

**Keywords:** linear programming, end-use energy model, energy technologies, global warming

# Contents

# End-use energy model for analysing the policy options to reduce greenhouse gas emissions

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## 1 Introduction

The problem of global warming is now recognized to be one of the most important factors influencing the future development of the Asia-Pacific region. However, the implementation of appropriate countermeasures will be expensive.

As part of the efforts to reduce the impacts of global warming and their abatement costs in the region, the Global Warming Response Team of Japan's National Institute for Environmental Studies has been developing the 'Asia-Pacific Integrated Model for Evaluating Policy Options to Reduce Greenhouse Gas Emissions and Global Warming Impacts (AIM)' by collaborating with other institutes in the region.

AIM is a simulation model that evaluates the effects of various global warming countermeasures by integrating all the factors involved in the global warming process, such as anthropocentric Greenhouse Gas (GHG) emissions, climate change caused by the increase in the atmospheric concentration of GHGs, and the impacts of climate change on both the natural environment and human societies (Matsuoka et al., 1995).

It is also able to operate at the global and regional levels and, because of the comprehensive structure of the GHG emission model, it can evaluate the effects of individual countermeasures.

This evaluation ability was important for policy assessment to reduce $CO_2$ emissions. For example, Japan's Government decided to stabilize $CO_2$ emissions at the 1990 level after 2000, but the potential countermeasures that would have an impact by 2000 are limited. Efforts will concentrate on those countermeasures that promote energy conservation in the end-use energy sector, so researches will need to determine how rapidly and to what extent the different energy efficient technologies can be introduced. The introduction of such energy conservation technologies will depend greatly on energy prices and the effects of carbon taxes and subsidies.

Thus, the model analyzes the relationships between energy prices, economic phenomena and $CO_2$ emissions, so as to evaluate the available countermeasures and select appropriate energy conservation technologies and tools for the end-use energy consumption sector.

The work described here had two main objectives: 1) to estimate the effects of the introduction of a carbon tax on various carbon emission countermeasure technologies

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and the size of consequent $CO_2$ emission reductions; and, 2) to evaluate the potential to increase this effect by integrating the tax with other countermeasure policies, such as the introduction of subsidies.

To do this, the authors developed the 'End-use (final energy consumption) Model' which simulates the relationships between technology selection, energy efficiency, energy service demand, related socio-economic variables, energy consumption and $CO_2$ emissions. This model was applied to the Japanese cases for describing the conditions for which each energy conservation technology menu would be adopted, for analyzing the relationships between the introduction of these technology menus and reduced $CO_2$ emissions, and for evaluating the effects of combining a carbon tax and subsidies using the recycled revenues from such a tax.

## 2 Summary of the AIM End-use Model and its characteristics

The model developed here is primarily the 'End-use (final consumption of energy) Model' component of the 'AIM:Asian-Pacific Integrated Model for Evaluating Policy Options to Reduce GHG Emissions and Global Warming Impacts'. AIM was originally developed to evaluate greenhouse gas emissions and their counter-measures in the Asian-Pacific region, plus the environmental impacts of the resulting climate change. The End-use Model developed by the authors is a part of this Greenhouse Gas Emission Model which makes detailed assumptions about energy service and its related devices, and then based on those conditions simulates energy conservation mechanisms.

The End-use model is comprised of 3 modules, as shown in Figure 1. The first is an energy service estimate module which estimates various demands that will need to be met using energy (energy service). This module obtains its forward linkages from other models and scenarios that determine socio-economic variables. It estimates energy service demand using a basic unit that reflects lifestyles and the concept of environmental conservation. The second module is an energy efficiency estimate module that calculates the improvements in energy efficiency. It comprises 'the Reference Energy System (RES)' which connects the energy supply from the secondary energy step and energy service demands and links them with technological information about devices using energy. The third module selects various service technologies that define energy efficiency. It evaluates the benefits of service devices with criteria such as economic efficiency and selects the optimal devices for each situation and service. Also included is a module that estimates the optimal solutions for each sector by combining these 3 modules. Their functions are modularized and designed to treat all time periods, all countries and all sectors with a single sub-program and to link them with other models of AIM through the energy macroeconomic linkage.

The AIM model is a Bottom-up, Energy-technology Model. A number of GHG emission models have been developed (Morita et al., 1994). These energy consumption-based Greenhouse Gas Emission Models can be classified into 2 types. Those that are called "Top-down Models" start with an economic model and present the relationships between energy consumption and national products intensively by using prices and elasticities as economic indices. The other types of models, which are called "Bottom-up Models", focus on the activities of the people who deal with energy consumption and production, plus the changes in technologies. Based on detailed descriptions of these items, they calculate the total energy consumption and production from the "bottom-up". Among

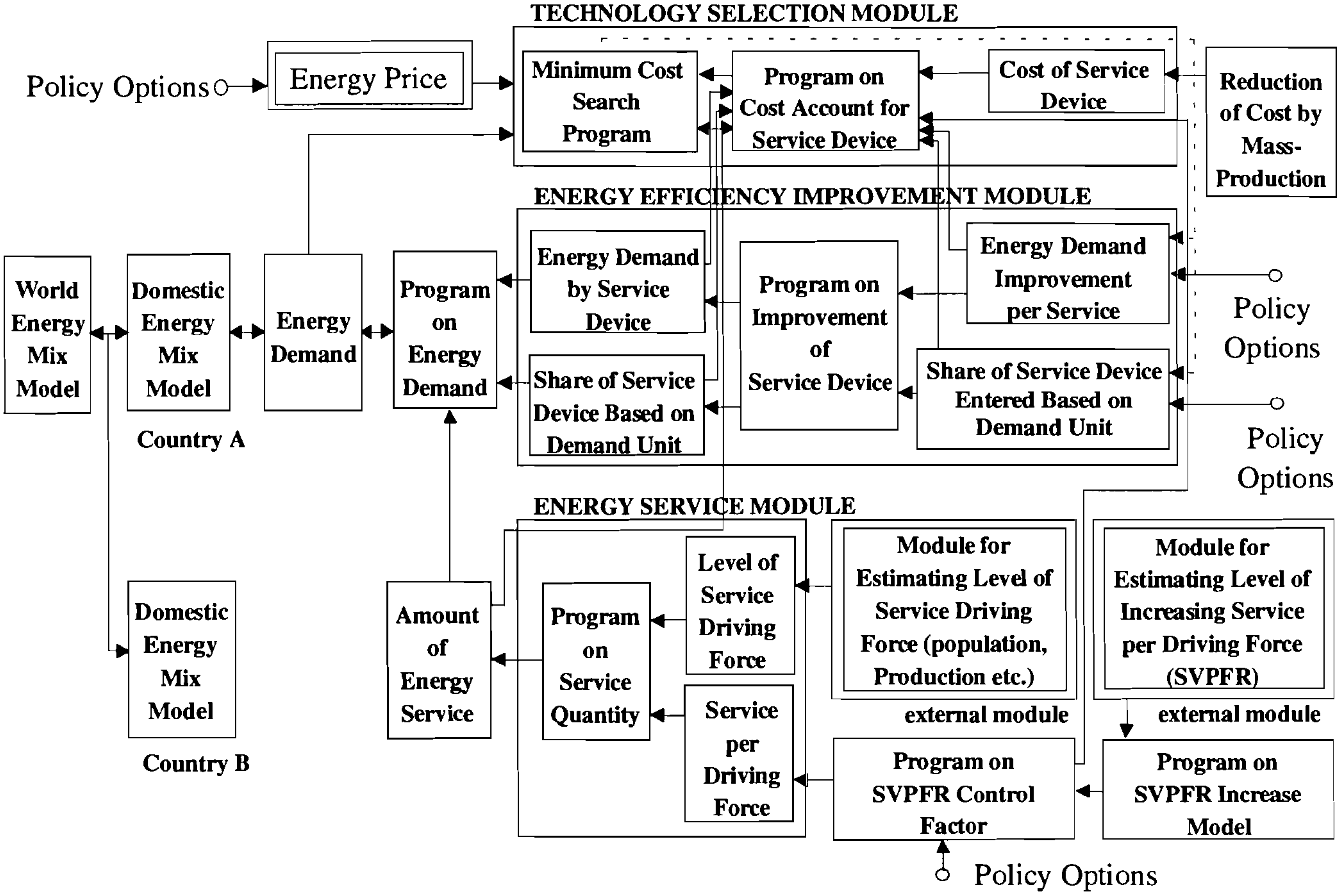

Figure 1: Structure of End-use Energy Demand Model

the many advantages of "Bottom-up Models", the most important is that their results can be interpreted clearly because they are based on detailed descriptions of changes in human activities and technologies. When introducing new policies, these Bottom-up Models, with their tangible results and explainability, are indispensable for explaining the directions and effects of policies to politicians.

Bottom-up Models have been developed in 2 directions. One is for analyzing more efficient technologies and their combinations by focusing on the supply and change of energy. MARKAL (Berger et al., 1987; Fishbone, 1981; Manne, 1992), which was developed primarily by the International Energy Agency, and EFOM, which was developed in France, are representative of this field. The other direction taken is for calculating how changes in the lifestyles of each sector influence energy demand in a bottom-up way, by focusing on energy demand and consumption. These models are usually called 'End-use Models'. Among this type of model, MEDEE (Lapillonne, 1985) developed in France and LEAP from the Stockholm Environmental Institute (Lazarus et al., 1993) are the most notable. However, the development of End-use Energy-technology Models, which analyze more efficient energy technologies and their combinations using energy demand and consumption, has been slow.

To reduce $CO_2$ emissions in Japan, the kind and amount of energy conservation technologies that can be introduced are most important, so the development of an End-use Energy-technology Model was necessary. The AIM End-use Model is exactly this type of model and provides a new direction not available with previous Bottom-up Models. The AIM End-use Model can calculate the changes in energy consumption from technological substitution caused by changes in energy prices, in a bottom-up way. Thus, it is possible to evaluate not only the efficiency of each individual policy, but also the effect when various policies are combined. By linking the technology selection model with the energy demand model, it is possible to estimate energy efficiency improvements based on the actual situation for each technology. Also, because this model can be linked to the AIM World Model which has already been completed, analyses of the effects of international factors and analyses that consider the impacts of the effects of international cooperation will be possible in the future.

However, the End-use Model has some limitations. The first is that so far it is not linked to a Top-down economic model, so energy service demand is provided by scenarios. Thus, it cannot estimate macro-economic losses because it does not take into account direct effects of higher energy prices in controlling energy demand and indirect economic effects through suppression of consumption or reduction of stocks. The second problem is that it does not consider social costs, such as institutional obstacles, while selecting technologies. As such, it might overestimate the reduction in $CO_2$ emissions caused by each technology. The third is that it might underestimate the total reduction of $CO_2$ emissions because subjective technologies are not comprehensive. For example, technologies that are not in practical use now are not the subject of an estimation. Some of these limits arise from the limits of the Energy-technology model, while others are because this model is not yet complete. Thus, it is necessary to consider these points when interpreting the results of this research. However, even with these limitations, the tangibility of these results and their ability to support policy development is very high.

# 3 Model structure

## 3.1 Model formulation

The AIM/end-use model accounts for final consumption of energy based on actual energy use and the way energy services are performed by energy devices. Energy consumption is not an objective in itself. Rather, energy is used to provide energy services such as heating, cooking, lighting, and passenger and goods transport. The system comprises three elements; energy service demand, energy device units and energy sources. A service device performs energy service by consuming energy. The problem is to select energy devices (or technologies) for supplying energy service demand under several constraints. Then energy consumption is calculated based on the selected energy technologies.

There are several constraints to be considered. For example, energy devices should supply sufficient energy service to meet their demand by consumers. There are limitations on energy sources and available energy technologies.

There are several criteria for introducing energy technologies. One criterion is to use energy technologies so as to minimize the total cost for supplying their energy service demand. Another criterion is to reduce $CO_2$ emissions from the points of global warming.

The two types of players; a government and consumers are assumed to make the decision. The government wants to minimize $CO_2$ emissions. His economic instruments are carbon tax and subsidy. The consumers want to minimize costs for supplying their service demand. Then the end-use problem can be described as a two-stage minimization problem in the following way:

$$f_1(\alpha^s, \boldsymbol{\beta}^s, \hat{\boldsymbol{x}}(\alpha^s, \boldsymbol{\beta}^s)) = \min_{\alpha, \boldsymbol{\beta}} \{(\boldsymbol{d}^{\mathrm{T}}\, \hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta}) + \varepsilon\, \boldsymbol{\beta}^{\mathrm{T}} R\, \hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta})\} \tag{1.a}$$

$$\text{subj. to} \quad \boldsymbol{\beta}^{\mathrm{T}} R\, \hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta}) \ \leq\ B(\alpha, \hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta})) \tag{1.b}$$

$$0 \leq \boldsymbol{\beta} \leq \boldsymbol{\beta}^U \tag{1.c}$$

$$f_2(\alpha, \boldsymbol{\beta}, \hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta})) = \min_{\boldsymbol{x}} \{(\boldsymbol{c}_1^{\mathrm{T}} + \boldsymbol{c}_2^{\mathrm{T}}(\alpha))\, \boldsymbol{x} - \boldsymbol{\beta}^{\mathrm{T}} R\, \boldsymbol{x}\} \tag{1.d}$$

$$\text{subj. to} \quad A_1 \boldsymbol{x} \geq \boldsymbol{b}^1 \tag{1.e}$$

$$A_2 \boldsymbol{x} = \boldsymbol{b}^2 \tag{1.f}$$

$$\boldsymbol{x} \geq 0 \tag{1.g}$$

where,

$\boldsymbol{\beta}^{\mathrm{T}} R\, \boldsymbol{x}$: total amount of subsidy

$\alpha$: a carbon tax

$\boldsymbol{\beta} = (\beta_{N1V+1}, \cdots, \beta_{N3V})^{\mathrm{T}}$ : subsidy rates of service technologies determined by the government. $\boldsymbol{\beta}^s$ is an optimal strategy of the government. $\boldsymbol{\beta}^U$ is an upper bound of $\boldsymbol{\beta}$.

$\boldsymbol{x} = (x_1, \cdots, x_{N5V})^{\mathrm{T}}$ : number of the energy technologies used by the consumers. $\hat{\boldsymbol{x}}(\alpha, \boldsymbol{\beta})$ is an optimal strategy of the consumers when $\alpha$ and $\boldsymbol{\beta}$ are given. $\hat{\boldsymbol{x}}(\alpha^s, \boldsymbol{\beta}^s)$ corresponds to their optimal strategy when optimal strategies of the government, $\alpha^s$ and $\boldsymbol{\beta}^s$, are given. There are five types of variables. $x_i$ $(i = 1, \cdots, N1V)$ is a variable representing the number of machines that have already been introduced. $x_i$ $(i = N1V + 1, \cdots, N2V)$ is a variable representing the number of reformed stocks at the present time period. $x_i$ $(i = N2V + 1, \cdots, N3V)$ is a variable of newly introduced stocks. $x_i$ $(i = N3V + 1, \cdots, N4V)$ is a variable of direct energy sources. $x_i$ $(i = N4V + 1, \cdots, N5V)$ is a variable of direct services. Direct energy sources/services are distinguished from intermediate energy sources/services. Direct energy sources are ones that are determined from outside. Direct services are ones that are final energy services. Intermediate energy sources are ones that are generated by some energy devices and used by other devices. Outputs from the energy devices used by other devices are called intermediate energy services.

$\boldsymbol{d} = (d_1, \cdots, d_{N3V})^{\mathrm{T}}$ : $CO_2$ emission from unit energy technologies.

$B(\alpha, \boldsymbol{x})$ : the total budget for the subsidy of energy technologies.

$\boldsymbol{c}_1 = (c_{1,1}, \cdots, c_{1,N3V})^{\mathrm{T}}$: fixed costs of service technologies without subsidy,

$\boldsymbol{c}_2(\alpha) = (c_{2,1}, \cdots, c_{2,N3V})^{\mathrm{T}}$ : running costs of service technologies. The running cost depends on the energy costs which is a function of a carbon tax.

$R$ : $((N3V - N1V) \times N3V)$ matrix whose $(i, N1V + i)$ component is $c_{1,N1V+i}$ and others are zero. A fixed cost for the $i$ th technology is $c_{1,i}$ $(i = 1, \cdots, N1V)$, and $c_{1,i} \times (1 - \beta_{i-(N1V)})$ $(i = N1V + 1, \cdots, N3V)$, respectively.

$A_1$ and $A_2$ : $(m_1 \times N5V)$ and $(m_2 \times N5V)$ coefficient matrices.

$\boldsymbol{b}^1 = (b_{1,1}, \cdots, b_{1,m_1})^{\mathrm{T}}$ and $\boldsymbol{b}^2 = (b_{2,1}, \cdots, b_{2,m_2})^{\mathrm{T}}$ : $m_1$ and $m_2$ vectors. There are several constraints such as total amounts of old stocks, reform stocks and recruit stocks, supplying the demand of energy services, and limitation of energy resources.

$\varepsilon$: a small positive number

The problem is a nonlinear programming problem that has two levels of optimization. Nonlinear elements, $\beta_i \cdot x_{N1V+i}$ $(i = 1, \cdots, N3V - N1V)$, make the problem difficult.

The important aspect of this formulation is the consumers problem, that is, to select energy technologies so as to minimize costs under several conditions for supplying their demands. This corresponds to the formula (1.d)-(1.f). Some criteria for selecting energy technologies are written in the following section.

## 3.2 Economic criteria of technology selection

The most important judgment made in the end use model is that of selecting service production technologies. The criteria used for technology selection depend on whether the technology then in use is to be replaced at that time or not.

**Case 1: The technology is to be replaced**

If a current device has reached its scheduled replacement time, a decision is needed whether to introduce an older technology to supply the service demand or a more expensive energy conserving technology. Thus, taking into account both the difference in the purchase prices and the cost of fuel that can be saved leads to choosing the more economic technology.

Also, where current devices are not sufficient and new devices are needed because of an increase in demand, the decision whether to introduce previous devices or energy conservation devices is made in the same way.

If $(F_A + E_A) < (F_B + E_B) \rightarrow$ Select technology A
If $(F_A + E_A) \geq (F_B + E_B) \rightarrow$ Select technology B

where F: Fixed annual cost
E: Annual fuel cost
A: Technology A (previous device)
B: Technology B (energy conservation device)

**Case 2: Technologies that have not yet reached their replacement time**

The method for selecting technologies in this situation depends on the types of substitutive technologies available, i.e. whether they are:

- Technologies of a different kind (devices that need to be completely replaced), or
- Technologies in a different stage (devices that need to be partly replaced)

If a current technology is to be replaced at a particular time, it is replaced and/or upgraded only when the total cost of replacement and improvement is less than the cost of fuel saved by energy conservation.

i) Technologies of a different kind

A comparison is made between the fuel cost of the current technology and the sum of the replacement cost and the fuel cost of the substitutive technology, and the current technology will be totally replaced if the substitutive technology is more economic.

If $E_A \leq (F_B + E_B) \rightarrow$ Current technology is not replaced
If $E_A > (F_B + E_B) \rightarrow$ Current technology is replaced with a new technology

where F: Fixed annual cost,
E: Annual fuel cost
A: Technology A (current equipment)
B: Technology B (substitutive equipment)

ii) Technologies at a different stage

A comparison is made of the fuel cost of the current technology and the total increased cost for upgrading current equipment (improvement cost) and the fuel cost. The current technology will be partly replaced if the upgraded technology is more economic.

Even if the technology is improved, the improvement will not lengthen the assumed lifetime of the current technology.

If $E_A \leq (\Delta F_B + E_B) \rightarrow$ Current technology is not improved
If $E_A > (\Delta F_B + E_B) \rightarrow$ Current technology is improved

where F: Fixed annual cost
E: Annual fuel cost
A: Technology A (current equipment)
B: Technology B (upgraded equipment)
$\Delta$ F: Improvement cost

Because these decision-making processes are included in the model, different technologies will be selected if a carbon tax or subsidies are introduced. As a result, energy consumption and $CO_2$ emissions vary. For example, if a carbon tax is introduced, the price of energy will rise and the cost of fuel saved by energy conservation will increase. This will make possible the introduction of comparatively expensive energy conservation technologies. The introduction of subsidies will reduce the purchase price of energy conservation technologies, and this in turn will also promote their introduction.

In both the residential and commercial sectors, there are service devices that can provide several kinds of services simultaneously. Also, there are some energy conservation devices in the industrial sector that can be used for different processes. In these cases, the selection of alternative technologies does not always guarantee the most favorable combination of devices. Thus, an optimal technology-selection submodule was developed that uses linear programming to decide the best combination of technologies to allow several kinds of service technologies to provide the most efficient services. The simulations for both the residential and commercial sectors, which are described later, are performed using this optimal selection submodule.

## 3.3 Some problems with the criteria

As was described above, this model evaluates the selection of service production technologies by comparing the annual net value of the purchase cost of devices, the fuel cost and a carbon tax, and then deciding the most favorable combination given the condition that the service demand is met. Although the criteria for this technology selection are simple, there are still some important points to be examined and abstracted.

Firstly, it is difficult to describe the suitability of residential devices only by the amount of service. Current selection using several criteria does not always agree with the selections made by this model.

Secondly, when the beneficiaries of the service are not the ones who pay the cost, selection using economic efficiency criteria cannot be relied upon. In rented houses for example, there is no trade-off relationship for the people who bear the expense of the fuel for heating and those who pay for the insulation.

Thirdly, even when the beneficiaries are the ones who pay the cost and the selection criteria are only based on economic efficiency, there are still many barriers to implementation. For example, incomplete information on technology selection, ambiguities in future energy prices and the expectation of technological innovations increase the future discount rate for technology selection. This leads to the selection of devices with lower energy efficiency. Matsuhashi et al. (1991) estimated a high future discount rate for investment in energy conservation equipment by the industrial sector in Japan, such as 2 years, using an index for the pay-back year. Such trends are also seen in Europe and America, and the pay-back period for energy intensive industries in the U.S. is estimated to be less than 2 years (ASE, 1983). Research done by the IEA estimated it to be 1 $\sim$ 5 years (IEA, 1987). The use of such 'internal' future discount rates in selecting technologies depends greatly upon the energy consuming sector and the energy production sector. In the residential sector, it is influenced by the consumer's socioeconomic position and objective technologies (Train, 1985) which are all much greater than the market opportunity cost rate. Such differences between the 'internal' discount rate and the opportunity cost rate, and the difference between the discount rates of the energy production and consumption sectors greatly distort the economic rationality of actual energy consuming/producing activities (Jochem et al., 1990). Recently, proposals and measures to remove such barriers to action using social and systematic inducement have been promoted (for example, Geller, 1991) and, countermeasures have been implemented in some regions (for example, Nadel, 1992).

The economic efficiency criteria for selecting technologies adopted in this model are thus in some ways impractical. Although some are the result of basic defects in the criteria, many result from the estrangement caused by the irrational institutional and behavioral practices of actual energy consumption/production systems. The former problem can be reduced by expanding the range of criteria and analyzing the characteristics of economic criteria in the actual situation. Also, in relation to the latter point, some of the main objectives of this model are to search for parameters that can reproduce actual situations and generate normative models that identify institutional and behavioral barriers preventing the creation of energy efficient societies.

## 3.4 Constraints

The model is composed of variables of energy service demands, energy service devices and energy sources. Service devices use different kinds of energy such as electricity, coal, oil and gas to perform energy services. Energy sources are categorized into two types: direct energy and intermediate energy. Direct energy is supplied by outside the system and intermediate energy is generated in the system and used to produce energy service.

A service device performs more than one energy service by using more than one kind of energy. For example, a gas air conditioner uses electricity for cooling and gas and electricity for space heating. If a service device performs more than two energy services, its main energy service is specified and called the standard service. A unit stock of a service device performs one unit of its standard service. A service device is characterized by its type of service device, its technological level, its remaining life time, its initial cost and its energy consumption per unit stock. A group of service devices that have the same device type, the same technological level and the same remaining lifetime is called a cohort. Each cohort is an element of variables.

In addition to each variable being non-negative, there are several constraints on the stocks of service devices, energy service demand, available energy sources and intermediate services.

## Old stocks of devices

The stocks of the previous time period are equal to or greater than the sum of the reformed and unreformed stocks of the same service devices in the current time period.

$$x_i + x_{i'} \leq x_{0i}, \qquad i = 1, N1V$$

where $x_{0i}$ is the stock of the i-th cohort in the previous time period, $x_i$ is the unreformed stock of the i-th cohort at the current time period, and $x_{i'}$ is the reformed stock of the i′-th cohort. When some of the service devices of the i-th cohort are reformed, a new cohort, the i′-th cohort, is generated whose components are the reformed service devices of the i-th cohort.

## Reformed devices

Suppose $X_{rf,j}$ be the maximum potential of the j-th service device that can be reformed in the current time period, then the following constraints are applied.

$$\sum_{i=N1V}^{N2V} \delta_{sd,j,i} \cdot x_i \leq X_{rf,j}, \qquad j = 1, NSD$$

where, $\delta_{sd,j,i}$ equals 1 when the service device of the i-th cohort is j, and 0 if it is otherwise. $NSD$ is the number of the reformed service devices.

## Newly introduced devices

The stock of the i-th cohort introduced at the current time period can not exceed the number of the newly available service devices.

$$x_i \leq X_{rc,i}, \qquad i = N2V + 1, N3V$$

where, $X_{rc,i}$ is the potential amount of service devices of the i-th cohort that can be introduced.

When the total amount of stocks of the j-th device is given, the following constraint is applied:

$$\sum_{i=1}^{N3V} \delta_{sd,j,i} \cdot x_i \leq X_{rc,j}, \qquad j = 1, NSD$$

where, $X_{rc,j}$ is the maximum potential of the j-th device for introduction.

## Meeting the demands of energy services

The energy services performed by the energy devices should satisfy the following end-use demand specifications:

$$\sum_{i=1}^{N3V} A_{j,i} \cdot x_i + \sum_{i=N4V+1}^{N5V} \delta_{sv,j,i} \cdot x_i \geq S_j, \qquad j = 1, NSV$$

where, $A_{j,i}$ is the amount of the j-th energy service supplied by a unit of the i-th cohort. $S_j$ is the end-use demand of the j-th energy service. $\delta_{sv,j,i}$ equals 1 when the service of the i-the cohort is the j-th energy service, and 0 if it is otherwise. $NSV$ is the number of energy services.

### Direct energy supply

When the supply of direct energy is limited, the following constraint is applied:

$$\sum_{i=1}^{N3V} x_i \cdot E_{i,k} + \sum_{i=N3V+1}^{N4V} x_i \cdot \delta_{eng,i,k'} \leq Q_{k'}, \qquad k' = 1, NENG$$

where, $E_{i,k}$ is the amount of the k-th energy used by a unit of the i-th cohort. $Q_{k'}$ is the maximum potential energy supply of the $k'$-th energy. Energy classes are numbered sequentially. $k'$ is the sequential number excluding unlimited energy, while $k$ is the sequential number including both limited and unlimited energy. $\delta_{eng,i,k'}$ is 1 when the direct energy of the i-th cohort corresponds to the k-th energy, and 0 if it is otherwise. The total number of limited energy is $NENG$.

### Intermediate services

The sum of the services (energy) supplied by the system and energy supplied from outside should not exceed the sum of the energy used by other service devices and the output of the system. The constraints of intermediate services are described as follows:

$$\sum_{i=1}^{N3V} A_{l,i}x_i + \sum_{i=N3V+1}^{N4V} \delta_{sv,l,i}x_i - \sum_{i=1}^{N3V} x_iE_{i,l} - \sum_{i=N4V+1}^{N5V} x_i\delta_{eng,i,l} \geq 0,$$
$$l = 1, INT\_N$$

where, $INT\_N$ is the number of intermediate services.

## 3.5 Objective Functions

There are two objective functions; one is for the government and the other is for the consumers.

The government's objective is to reduce $CO_2$ emissions.

$$\sum_{i=1}^{N3V} d_i \cdot x_i \rightarrow minimum$$

If there are multiple sets $\{x_i, i = 1, \cdots, N5V\}$ that minimize $CO_2$ emissions, the next criteria is taken for minimizing the total subsidies.

The consumer's objective is to find the number of necessary energy devices that minimize the following cost.

$$\sum_{i=1}^{N3V} C_i \cdot x_i \rightarrow minimum$$

where,

$$C_i = \begin{cases} (1-\varepsilon \cdot L_i) \cdot \displaystyle\sum_{k=1}^{NENERGY} E_{i,k} \cdot P_k & \text{if } i = 1, N1V \\ (1-\varepsilon \cdot L_i) \cdot \{(c_i - c_{i'}) \cdot PtoM(PB_i) \cdot (1-\beta_i) + \displaystyle\sum_{k=1}^{NENERGY} E_{i,k} \cdot P_k\} & \\ & \text{if } i = N1V+1, N2V \\ (1-\varepsilon \cdot L_i) \cdot \{c_i \cdot PtoM(PB_i) \cdot (1-\beta_i) + \displaystyle\sum_{k=1}^{NENERGY} E_{i,k} \cdot P_k\} & \\ & \text{if } i = N2V+1, N3V \end{cases}$$

$\varepsilon$ is a small positive number and is used to select the energy devices that have longer lifetime if other conditions are same. $L_i$ is the remaining lifetime of the service device of the i-th cohort. $NENERGY$ is the total number of energy classes. $P_k$ is the energy price of the $k$-th energy class. $c_i$ is the initial cost of the $i$-th cohort. $c_{i'}$ corresponds to an initial cost of a device that has already been installed and may be reformed with higher technological level. The reform cost is the difference between the initial cost with higher technology and that of the installed device. $PtoM(PB)$ is a conversion factor from an initial cost to an annual cost when a pay-back time is $PB$.

# 4 Case studies in Japan

## 4.1 Setting input data and conditions

Table 1 presents the sectors and fields of the AIM End-use Model. Energy service demand is given for each sector and field. Technologies are selected for meeting energy services to estimate energy consumption and $CO_2$ emissions. Thus, basic data such as socio-economic data and past energy consumption for each of these sectors and fields were prepared for estimating energy service demand. Second, research was conducted on the service technology for each production step of these sectors, fields and industrial sector as a whole. More than 100 kinds of energy conservation technologies shown in Table 2 were examined. Next, basic data, such as purchase price, energy consumption per service unit, energy conservation potential, stocks, and pay-back time, for all these technologies were collected and used to create a database.

For each fuel type, an average calorie value, a price, and a $CO_2$ emission factor to be used in this analysis are as shown in Table 3. Although limestone is not used as a fuel, it is included in the analysis because it causes $CO_2$ emissions while being used as a raw material in the cement industry and to remove impurities in the steel manufacturing process.

In the following case studies, the carbon tax is given exogenously. When the subsidies are given, the problem is solved heuristically. Total amount of them is assumed to be less than the total amount of carbon tax income. The service technologies to be subsidized are determined based on the $CO_2$ emissions and the introduction costs per unit services.

Table 1: Sectors and fields of the AIM end-use model

| Sectors | Industrial sector | Residential sector | Commercial sector | Transportation sector |
|---|---|---|---|---|
| Fields | Iron and Steel industry<br>Cement<br>Petrochemical industry<br>Pulp and Paper | Hot Water Supply<br>Cooking<br>Air Conditioning<br>Motor | Hot Water Supply<br>Cooking<br>Air Conditioning<br>Motor | Passenger Transport<br>Goods Transport |

Based on these premises and data, the AIM End-use Model estimates energy consumption and $CO_2$ emissions in the following way. It:

1. estimates the amount of energy service (e.g. the amount of productions, trips and air conditioning demand) using scenarios and models; and,
2. selects service production technologies to meet this amount of service. At this time, more economic technologies replace and/or supplement older technologies in all levels (manufacturing process, transport method). Then it,
3. calculates the amount of energy needed to operate these technologies; and,
4. using the energy consumption by fuel type calculated above, it estimates the amount of $CO_2$ emissions.

Table 4 presents the major scenarios as simulation input assumptions. These determine the level of the energy service demand increase. Based on the assumptions of these scenarios, we calculated the technology selection, energy consumption and $CO_2$ emissions using the size of the energy service for each year from 1985 until 2010.

Simulations were performed for the following 5 cases;

1. No change with technologies

   Current technologies continue to be selected because of a lack of understanding and/or there are social constraints preventing replacement even though there are economic benefits in changing the technologies. No countermeasures such as carbon tax or subsidy are assumed.

2. The base case

   The standard case which assumes that technology selection is based on a reasonable judgment of economic efficiency. No subsidy is assumed.

3. Introduction of a carbon tax

   The introduction of a carbon tax is added to the base case. The tax rate was provisionally fixed at 30,000 yen/tC to test how the model operated and what outcomes might be expected.

4. Introduction of a carbon tax and extension of the subjective pay-back period

   In addition to the introduction of a carbon tax, the subjective pay-back period was, just as an example, extended to a maximum of 20 years. This assumes that the Japanese people come to appreciate the long-term economic benefits of energy conservation.

Table 2: Examined service technologies

| Industrial Sector | |
|---|---|
| **Steel** | continuos annealing furnace for waste heat, high temperature casting slice continuous caster, DC electric water cooling wall-type electric arc furnace, processing heat treatment device at hot rolling mill, thin copperplate form control device, direct use of chrome ore at basic oxygen absorbing furnace, high performance high frequency at blast furnace, high performance sheet metal processing device, dry waste pressure recovery device, materials preheating device for electric furnace, coal moisture control, oxygen combustion device, high performance slag water mill device, high performance copper divest gas device, high efficiency copperplate continuous coating device, total process of manufacture for continuous, coal pre-process device for coke, high heat cooperate direct device, DC electric arc furnace, gas recovery converter, scrap preheating device, high pressure power generation at blast furnace, hot sharge rolling, hot direct rolling |
| **Cement** | roller method energy saving mill, l roll brace device, SP/NSP kiln, preliminary crushing mill, energy saving mill/finishing, energy saving mill/raw materials |
| **Pulp/ paper** | pre-filtration continuous cooking, high performance pulp washing device, deoxidization lignin device, high performance size press, high performance bearing dehydration, high performance dryer hood, high performance waste paper pulp making device |
| **Petro-chemical** | high performance disjointing reaction device, high performance deoxidization reaction device, high performance polypropylene vapor conversion, low pressure defmethane device, high performance polymerization system for basic vinyl resin, high efficiency compression device, reuse device of carbon dioxide, waste gas process device at catalytic combustion method, high performance anhydride maleic acid manufacturing device, high efficiency decarbon dioxide device, two vapor turbines |

| Residential Sector | |
|---|---|
| **Air control** | improvement of heating structure (newly built detached houses), improvement of heating structure (newly built town houses), improvement of heating structure (existing detached houses), improvement of heating structure (existing town hoses), air conditioner(gas, electric, kerosene), stove(electric, kerosene), fan heater(gas, kerosene), electric ceramic fan heater |
| **Hot water supply** | gas hot water supply, kerosene hot water supply, electric hot water supply, solar thermal water heater, solar system |
| **Light** | incandescent electric lamp, fluorescent light, inverter lights |
| **Household electric appliances** | efficiency improvement of TV, efficiency improvement of refrigerators, efficiency improvement of washing machine, efficiency improvement of vacuum cleaner, efficiency improvement of electronic oven, etc. |

| Commercial Sector | |
|---|---|
| **Air control** | adiabatic material+pair glass, gas air conditioner, cogeneration system(gas engine), gas turbine, diesel engine, regional air cooling and heating, afforestation at a housetop |

| Transport Sector | |
|---|---|
| | electric vehicle(midget passenger car), electric vehicle(compact passenger car), electric vehicle(compact cargo vehicle), electric vehicle(light cargo vehicle), hybrid vehicle(compact truck), hybrid vehicle(ordinary truck), hybrid vehicle(bus), natural gas vehicle, methanol vehicle, high efficiency electric locomotive, vessel waste heat boiler, vessel propulsion axis electric power using generation |

Table 3: Classification of fuels and their emission factors

| Code | Fuel types | Average calorie | Price [A] | CO2 emission factors | Price (Carbon tax 30,000 yen/tC) [B] | ([B]/[A] -1)*100 |
|---|---|---|---|---|---|---|
| | | | (yen(1990)) /kcal) | (1.0E-10tC) /kcal) | (yen/kcal) | (%) |
| 1 | Coal | 6,200(kcal/kg) | 0.00116 | 1042.2 | 0.00457 | 3.93 |
| 2 | Coke | 7,200(kcal/kg) | 0.00337 | 1061.2 | 0.00706 | 2.1 |
| 3 | Coke oven gas | 2,000(kcal/m^3) | 0.00337 | 1061.2 | 0.00706 | 2.1 |
| 4 | Gasoline | 8,400(kcal/l) | 0.01321 | 765.8 | 0.01551 | 1.17 |
| 5 | Kerosene | 8,900(kcal/l) | 0.00481 | 777.5 | 0.00713 | 1.48 |
| 6 | Diesel oil | 9,200(kcal/l) | 0.00662 | 783.9 | 0.00897 | 1.36 |
| 7 | Heavy oil | 9,800(kcal/l) | 0.00259 | 818 | 0.00495 | 1.91 |
| 8 | Petroleum products | 10,000(kcal/kg) | 0.01321 | 773.7 | 0.01512 | 1.14 |
| 9 | LPG | 12,000(kcal/kg) | 0.0073 | 688.3 | 0.00935 | 1.28 |
| 10 | Gas | 10,000(kcal/m^3) | 0.01071 | 563.9 | 0.01246 | 1.16 |
| 11 | Solar power | - | 0 | 0 | 0 | 1 |
| 12 | Electricity(household) | 860(kcal/kWh) | 0.02894 | 1212.8 | 0.03257 | 1.13 |
| | Electricity(Service) | | 0.02 | 1212.8 | 0.02363 | 1.18 |
| | Electricity(Industry) | | 0.01538 | 1212.8 | 0.01901 | 1.24 |
| 13 | Steam | 639(kcal/kg) | 0.02758 | - | 0.02758 | 1 |
| 14 | Jet fuel | 8,700(kcal/l) | 0.00777 | 766.5 | 0.01007 | 1.3 |
| 15 | Oil coke | 8,500(kcal/kg) | 0.0022 | 1061.2 | 0.00538 | 2.45 |
| 16 | Naphtha | 8,000(kcal/l) | 0.00289 | 760.5 | 0.00517 | 1.79 |
| 21 | Kraft black liquid | 3,000(kcal/kg) | 0 | 1075.1 | 0.00323 | - |
| 22 | Bark | 4,000(kcal/kg) | 0 | 1075.1 | 0.00242 | - |
| 23 | Crude oil | 9,250(kcal/l) | 0.0022 | 781.1 | 0.00454 | 2.07 |
| 29 | Limestone | - | - | 0.12(tC/t) | - | - |
| 30 | Waste heat | - | 0 | - | - | - |

Sources: Statistical survey of energy and economy (1993) / EDMC
Report on CO2 emissions (1992.5) / the Environment Agency

5. Carbon tax and subsidies

In addition to the base case, a low carbon tax is introduced and part of its tax revenue is used to subsidize the introduction of energy conservation technologies. In this case, subsidies are assigned so as to minimize total $CO_2$ emissions, and no transfer of tax revenue between sectors is assumed. The tax is assumed to be applied to raw materials for energy production, such as imported oil. The tax rate was assumed to have been decided and announced in 1990 and was provisionally fixed at 3,000 yen /tC.

Although the carbon tax is here introduced from 1995, the extension of the pay-back period is assumed to start from 1990 because the effect of the announcement of the tax will start from 1990. Even though the introduction of carbon tax has already been decided, it needs to be remembered that there might be a time-lag in its effects on the results. Also, although the pay-back period for all sectors in the case with no countermeasure is a maximum of 3 years, it was assumed that the pay-back period is extended by a maximum of 10 years in the residential sector and by a maximum of 15 years in the commercial sector based on an extension of the subjective pay-back period if a carbon tax is introduced.

Table 4: Major scenarios for simulation input assumptions

| Sector | Assumption | Source |
|---|---|---|
| Steel | Production of steel decreases from 112 Mt (1990) to 105 Mt (2000) and remains constant afterwards.<br>Share of electric arc furnace increases from 31.6% (1990) to 35.0% (2000). | Statistical yearbook of iron and steel, Assumption by the Environment Agency |
| Cement | Production of cement decreases from 84 Kt (1990) to 80 Kt (2000) and remains constant afterwards.<br>Share of mixing cement increases from 18.2% (1990) to 22% (2000) and remains constant afterwards. | Cement Handbook, Cement Yearbook |
| Petrochemical | Production of ethylene increases from 5.81 Mt (1990) to 6.6 Mt (2000) and remains constant afterwards.<br>Share of polyethylene, polypropylene and BTX does not change. | State of petrochemical industry |
| Pulp/Paper | Production of paper increases from 2,809 Mt (1990) to 3,450 Mt (2000) and 3,810 Mt(2010).<br>Share of recycle pulp increases from 51.4% (1990) to 56.0% (2000) and 60.0% (2010). | Pulp and Paper statistical yearbook |
| Residential | Number of households increases in 0.6%/year by 2000 and then in 0.1%/year.<br>Area of household increases from 46 m2 (1985) to 48.5 m2 (2010).<br>Energy intensity of air conditioning of cooling becomes 2.77 times during 20 years.<br>Energy intensity of air conditioning of heating becomes 1.37 times during 20 years.<br>Energy intensity of hot-water supply and kitchen becomes 1.27 times during 20 years.<br>Energy intensity of light becomes 1.17 times in 20 years.<br>Possession of television increases from 174.7 (1985, /100 households) to 254.0 (2010).<br>size of television becomes 1.8 times during 25 years.<br>Possession of refrigerator increases from 114.3 (1985, /100 households) to 130.1 (1985).<br>Quality index of refrigerator becomes 1.4 times during 25 years.<br>Possession of electric washing machine increases from 106.5 (1985, /100 households) to 113.0 (2010).<br>Possession of vacuum cleaner increases from 124.8 (1985, /100 households) to 149.2 (2010).<br>Possession of electronic oven increases from 46.0 (1985, /100 households) to 89.8 (2010). | The 6th 5 year program of housing,<br>Handbook on energy conservation, JIS,<br>Handbook on global warming abatement,<br>Japan light association,<br>Committee on global warming and economic system,<br>Japanese association of electronic and machine industry |
| Commercial | Area of floors increases in 2.4%/year by 2000 and then in 1.4%/year.<br>Electric energy consumption of duplicating machine becomes 2.2 times during 25 years.<br>Electric energy consumption of computer becomes 3.0 times during 25 years.<br>Share of middle and high building becomes 1.5 times (2000) and 1.8 times (2010) compared with 1985. | Handbook on global warming abatement,<br>Japanese association for promotion of electronic industry |
| Transport | Number of light cars increases in 1.8%/year and that of small and medium size cars increases in 2.5%/year.<br>Number of cars for business uses increases 0.2%/year and that of buses for business increases 1.8%/year.<br>Number of trucks and light trucks increases 1.6%/year.<br>Numbers of small trucks decreases in 1.3%/year.<br>Number of passenger trains and that of freight trains increase in 1.9%/year, 3.5%/year respectively. | Committee of transport policy, etc. |

Table 5: Simulation results by cases and sectors

(MtC)

| Sector | Year | No technological change | No carbon tax | Carbon tax (30,000yen/tC) | Carbon tax + payback time | Carbon tax(3,000 yen/tC) + subsidy |
|---|---|---|---|---|---|---|
| Industry total | 1990 | 150.8 | 150.8 | 150.8 | - | 150.8 |
| | 1995 | 152.9(1.4) | 148.9(-1.3) | 148.5(-1.5) | - | 148.4(-1.6) |
| | 2000 | 153.1(1.5) | 144.9(-3.9) | 144.3(-4.3) | - | 144.1(-4.4) |
| | 2005 | 155.1(2.9) | 145.2(-3.7) | 144.5(-4.2) | - | 144.0(-4.5) |
| | 2010 | 156.8(4.0) | 145.3(-3.6) | 144.7(-4.0) | - | 143.8(-4.6) |
| Residential | 1990 | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 |
| | 1995 | 40.9(7.5) | 41.1(8.2) | 38.8(2.1) | 37.4(-1.6) | 41.6(9.5) |
| | 2000 | 44.8(17.9) | 45.5(19.7) | 39.0(2.6) | 36.1(- 5.0) | 44.1(16.1) |
| | 2005 | 48.6(27.9) | 49.8(31.1) | 42.4(11.5) | 39.3(3.4) | 43.7(15.0) |
| | 2010 | 52.8(38.9) | 50.9(32.9) | 45.9(20.9) | 42.7(12.4) | 46.3(21.8) |
| Commercial | 1990 | 33.6 | 33.6 | 33.6 | 33.6 | 33.6 |
| | 1995 | 37.0(10.1) | 37.7(12.2) | 35.9(6.9) | 34.9(3.9) | 37.7(12.2) |
| | 2000 | 41.1(22.3) | 41.3(22.9) | 37.3(11.0) | 35.3(5.1) | 40.7(21.1) |
| | 2005 | 43.5(29.5) | 42.3(25.9) | 38.9(15.9) | 31.9(-5.1) | 40.1(19.3) |
| | 2010 | 46.2(37.5) | 42.5(26.5) | 38.1(13.4) | 32.5(-3.3) | 38.0(13.1) |
| Transport | 1990 | 58.5 | 58.5 | 58.5 | - | 58.5 |
| | 1995 | 60.7(3.8) | 60.7(3.8) | 60.6(3.6) | - | 60.7(3.8) |
| | 2000 | 67.7(15.7) | 67.3(15.0) | 65.4(11.8) | - | 65.3(11.6) |
| | 2005 | 75.9(29.7) | 75.4(28.9) | 72.3(23.6) | - | 72.0(23.1) |
| | 2010 | 85.8(46.7) | 85.2(45.6) | 81.8(39.8) | - | 81.4(39.1) |
| Total | 1990 | 317.4 | 317.4 | 317.4 | [317.4] | 317.4 |
| | 1995 | 326.2(2.8) | 324.7(2.3) | 320.1(0.9) | [317.7](0.1) | 324.6(2.3) |
| | 2000 | 338.9(6.8) | 335.2(5.6) | 322.1(1.5) | [317.3](0.0) | 330.3(4.1) |
| | 2005 | 353.9(11.5) | 348.8(9.9) | 334.2(5.3) | [324.1](2.1) | 335.9(5.8) |
| | 2010 | 370.7(16.9) | 360(13.4) | 346.5(9.2) | [337.7](6.4) | 345.6(8.9) |

Values in parentheses are increasing percentage from 1990.
Sector total includes CO2 emission in conversions sector.

Such an extension was not assumed for the transport and industrial sectors because the sensitivity of the pay-back period is small within the current technology menu. The range of the extension in the commercial sector's pay-back period is longer than that of the residential sector because it is assumed that there will be rational management of investments under a long-term investment plan when a co-generation system is introduced. However, there is no actual data on which to base such subjective judgments, so they are uncertain. These assumptions will need to be reexamined in future research.

## 4.2 Simulation results

The results of the simulation for each case based on the above assumptions follow. Table 5 presents the simulation results by cases and sectors while the total $CO_2$ emissions at 2000 is shown in Figure 2 and that for 2005 is given in Figure 3.

First, as for the case where there is no rational technology selection, although the increase in $CO_2$ emissions by the industrial sector is small, emissions from the residential sector will increase by 18% between 1990 and 2000. Also, the increase in emissions from the commercial sector is 22% while that for the transport sector is 16%.

In comparison, if the Japanese people select energy devices in a rational manner (here defined as coming to understand the benefits of energy conservation) and there are less obstacles for technology selection because of the relaxation of regulations restricting these introduction, $CO_2$ emissions from the industrial sector will be greatly reduced, as shown

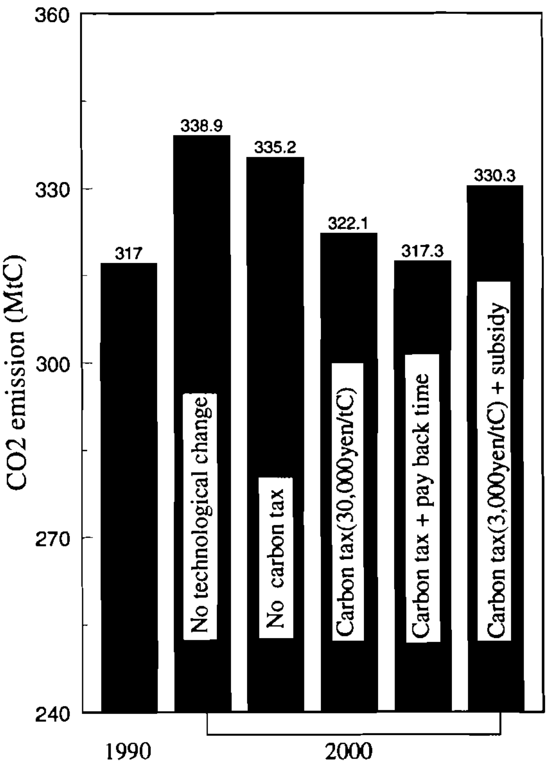

Figure 2: Simulated CO2 emissions at 2000

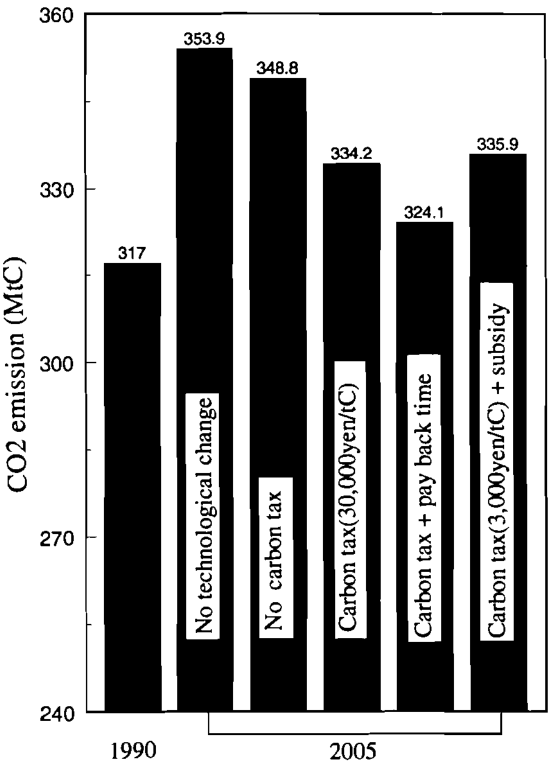

Figure 3: Simulated CO2 emissions at 2005

in the results of the base case. In the industrial sector, it would be possible to stabilize $CO_2$ emissions without introducing a carbon tax because emissions in 2000 will be less than the 1990 level. There is also potential, albeit slight, to restrict the increase in $CO_2$ emissions from the transport sector through the increased use of smaller cars and more fuel efficient trucks. In the residential and commercial sectors, however, $CO_2$ emissions might possibly increase if the major preference for pay-back periods for energy conservation investment is short (such as 3 years). Cheap, energy inefficient products, such as electric light globes would be selected rather than technologies with higher energy efficiencies such as solar-based hot water systems. The pay-back period for the residential and commercial sectors is currently quite short, about 3 years (according to an unpublished survey by the Environment Agency of Japan). If this was extended, it would be possible to reduce $CO_2$ emissions even in the base case.

Next, in the case where a 30,000 yen/tC carbon tax is introduced, $CO_2$ emissions from the industrial sector using technologies from among those listed above will decrease only slightly compared to the base case. However, a 15% reduction is assumed in the residential sector, 10% in the commercial sector and 3% in the transport sector at 2000 compared to the base case. Although it is assumed that total $CO_2$ emissions will be reduced by 4% compared to the base case in 2000, another 2% reduction will be necessary to stabilize them at the 1990 level.

Thus, in addition to the introduction of the 30,000 yen/tC carbon tax, another case is assumed in which the subjective payback period is extended by a maximum of 20 years with people appreciating the economic benefits of energy conservation over the long-term, or people's financial burden is reduced by the use of soft loans. As a result, $CO_2$ emissions in the residential and commercial sectors declined even more, as shown in Table 5, so it might be possible to stabilize $CO_2$ emissions in 2000 at the 1990 level (see Figure 2).

However, it will be difficult to stabilize all emissions after 2000 because of the continuing increase in the transport sector. Thus, specific countermeasures such as a modal shift or a change in consciousness that ensures automobiles are selected for their energy efficiency are essential.

When a carbon tax of 3,000 yen/tC was introduced on top of the base case and the tax revenue recycled as subsidies for the introduction of energy conservation technology, $CO_2$ emissions were reduced in all sectors. Although the overall impact of this alternative is less than that of a carbon tax of 30,000 yen/tC in 2000, it will probably be as effective as a full-scale carbon tax by 2005 (see Figures 2 and 3). Although there are some problems with such subsidies such as an increase in $CO_2$ emissions caused by the 'Polluter Pays Principle', an expansion of the market, and a reduction in the efficiency of the subsidy distribution system, it is considered here that they are worth examination as short-term countermeasures.

The simulations results can be summarized as follows:

1. If the Japanese people come to understand the economic benefits of energy conservation, the introduction of energy conservation technologies will be able to be promoted without any special taxes or subsidies. As a result, it would be possible to stabilize $CO_2$ emissions from the industrial sector, but impossible to stabilize the nation's total emissions because of the rapid increase of emissions from other sectors.

2. If Japan introduces a carbon tax of about 20,000-30,000 yen/tC, the introduction of energy conservation technologies in the residential, commercial and transport sectors would be further promoted. However, this alone might not be sufficient to stabilize total $CO_2$ emissions.

3. To stabilize $CO_2$ emissions in the residential and commercial sectors, additional countermeasures need to be examined. In particular, several things are essential: the promotion of the community's understanding of the role of energy conservation investments, such as the extension of subjective payback periods, reducing the burden of new initial investment through the use of subsidies, promotion of a long-range perspective for energy conservation investment using softloans, public education and an expansion of the range of technologies examined, such as recycling technologies. By combining these countermeasures the stabilization of $CO_2$ emissions will become possible.

4. There has been a rapid growth in energy consumption by the transport sector, and effective energy conservation measures could not be found. Thus, this sector will be the most important obstacle to stabilizing $CO_2$ emissions. Drastic countermeasures, such as a modal shift or changed consumer consciousness towards the selection of automobiles will definitely be needed.

5. Recycling tax revenues as subsidies for initial investments in energy conservation would have a significant effect over the short term. Even a 3,000 yen/tC carbon tax with a recycled subsidy would be as effective as 20,000- 30,000 yen/tC carbon tax under certain conditions. However, problems with the introduction of these subsidies such as conflicts with the "Polluter Pays Principle', an increase in $CO_2$ emissions caused by market expansion and problems with the subsidy distribution system must be considered at the same time.

6. In summary, to stabilize $CO_2$ emissions in Japan, there must be a combination of several countermeasures, for example the combination of a carbon tax and a subsidy would be effective over the short term. Further examination is required of the effects of middle and long-range technology innovations, the announcement effects of taxes and measures to extend the subjective payback period.

# 5 Conclusions

There are several tasks left that need to be performed to improve the applicability of this model. Some of them are listed as follows:

1. Technologies that are not currently in use but will be introduced after the year 2000 should be added to the technology menu of the model;
2. Soft technologies, such as recycling systems and 'daylight saving', should be evaluated using an additional module;
3. Consumer and company behavior should be investigated to test the technology selection criteria used in the model;
4. The relationship between the market share of a technology and its cost needs to be investigated;
5. The remaining unmodeled sectors, such as agriculture, construction and food, should be modeled;
6. Greenhouse Gases other than $CO_2$ should be estimated using the End-use model;
7. The End-use Model should be linked to a top-down macro-economic model, and a start has been made on this work in conjunction with other researchers from Korea and China.

Another point that should be mentioned here is that methodologies for solving the end-use model should be studied further. The problem is now solved for each field and sector to give an optimal solution for that sector that will be modified to treat the whole sector simultaneously.

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