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Two-level mathematical programming for analyzing subsidy options to reduce greenhouse-gas emissions

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Foreword

This paper summarizes the results of research conducted by Go Hibino (a coauthor of this paper) who participated in IIASA's 1996 Young Scientists Summer Program (YSSP) in the Methodology of Decision Analysis (MDA) project. This research is part of an ongoing collaboration between the National Institute of Environmental Studies (Tsukuba, Japan) and the MDA project, and began when Mikiko Kainuma (another coauthor) was a staff member of the MDA project.

The research performed at IIASA during the summer of 1996 contributed to a large-scale research program that is aimed at developing an end-use energy model for assessing policy options to reduce greenhouse-gas emissions. The model can evaluate effects of introducing a carbon tax on various carbon-emitting technologies and the resulting reductions of CO_2 emissions. One policy option is to combine the carbon tax with subsidies for technologies that are costly but result in lower emissions of CO_2, so-called subsidy problem.

The subsidy problem has been examined by Hibino, and the solution methods and preliminary results are presented in this paper.

Abstract

In this paper we develop the end-use energy model for assessing policy options to reduce greenhouse-gas emissions. This model evaluates the effects of imposing a carbon tax on various carbon-emitting technologies for reducing CO_2 emissions. It also estimates the effect of combining a carbon tax with other countermeasure policies, such as the introduction of subsidies. The problem can be formulated as two-level mathematical programming. Solution methods for the problem are discussed, and an algorithm to solve the subsidy problem is presented. The conditions under which the conservation technologies would be selected are analyzed with the different carbon tax rates and subsidies. The reduction of CO_2 emissions is calculated based on the introduction of these conservation technologies. Finally, we evaluate the effects of combining a carbon tax with subsidies using the recycled revenues from such a tax.

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

Contents

Two-level mathematical programming for analyzing subsidy options to reduce greenhouse-gas emissions

*Go Hibino**, *Mikiko Kainuma***,
*Yuzuru Matsuoka****, *Tsuneyuki Morita***

1 Introduction

The global-warming problem has been recognized as one of the most important policy problems to be solved for preserving the global environment. To promote adoption of countermeasures, the amount and type of various greenhouse-gas emissions must be precisely predicted and the effects of available countermeasures must be accurately evaluated.

An end-use model has been developed to forecast anthropogenic greenhouse-gas emissions. This model is part of the Asian-Pacific Integrated Model (AIM) and is a tool for estimating end-use energy consumption to assess policy options to reduce greenhouse-gas emissions (Matsuoka *et al.*, 1995). The model takes into accounts final energy consumption based on actual energy use and the performance of energy services. It evaluates the effects of introducing a carbon tax on various carbon-emitting technologies and the amount of CO_2 emission reductions. It also estimates the effects of combining the carbon tax with other countermeasures such as the introduction of subsidies.

This work is an extension of the AIM/end-use model developed by Kainuma *et al.* (1995). The model for analyzing effective subsidies is formulated as a bilevel mathematical programming problem. The bilevel programming is a static Stackelberg game in which two players try to maximize their individual objectives. (Bard and Moore, 1990; Bialas and Karwan, 1984; Kornai and Lipták, 1965; Lai, 1996; Mallozzi and Morgan, 1995; Simaan, 1977). The master problem comprises other constraints that represent the second level mathematical program. Decisions are made in a hierarchical order. A decision maker has no direct control over or influence upon the decisions of the others, but actions taken by one decision maker affects the choice set of and/or returns to the other decision makers (Őnal, 1993). When master-level decision-making situations require inclusion of zero-one variables representing yes-no decisions, the problem is formulated as mixed-integer bilevel programming (Wen and Huang, 1996). The greatest barrier to the effective use of these concepts is the lack of efficient algorithmic procedures to solve the resulting mathematical-programming problems (Wen and Bialas, 1986).

The original problem can be transformed into a one-level problem by using the Kuhn-Tucker conditions. Penalty methods can be used to solve the problem (Aiyoshi and

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Shimizu, 1984; Shimizu and Ishizuka, 1985; Shimizu and Lu, 1995; Őnal, 1993). Branch and bound methods are also applied to the Stackelberg problem (Bard and Moore, 1990; Karlof and Wang, 1996). Edmunds and Bard (1991) proposed a hybrid branch and bound scheme and a method based on objective function cuts. Júdice and Faustino (1992) proposed a hybrid enumerative method. However, an effective algorithm for solving large-scale systems is not known because of its complicated characteristics.

The problem that we address in this paper has two types of players: policy makers and private individuals or consumers. Policy makers want to minimize CO_2 emissions. They have access to economic instruments such as carbon taxes and subsidies. The private individuals or consumers want to minimize the costs for satisfying their service demand. The government's problem is a master problem, and the consumers' problem is a subproblem. After the government determines a strategy, the consumers' problem can be formulated as a linear programming problem.

Three formulations are presented and discussed to solve this problem. A practical algorithm is proposed and applied to cases in Japan. The effects of carbon taxes and subsidies on the future CO_2 emissions are analyzed based upon several scenarios on energy-service demands and conservation technologies.

2 Model Structure

The AIM/end-use model determines final energy consumption based on actual energy use and the way energy services are provided by energy devices. Energy consumption is not an objective in itself. Rather, energy is used to provide services such as heating, cooking, lighting, and passenger and goods transport. The system comprises three elements: energy-service demands, energy devices, and energy resources. An energy device provides energy services by consuming energy. The problem is to select energy devices (or technologies) to meet the energy-service demand. Energy consumption is then calculated based on the energy technologies selected.

Several constraints must be considered in the calculations. For example, energy devices should supply sufficient energy service to meet the demands of consumers. There are, however, limitations on energy resources and available energy technologies.

Several criteria must be examined before introducing energy technologies. One criterion is to select energy technologies that minimize total costs for meeting the energy-service demand. Another criterion is to reduce CO_2 emissions contributing to global warming.

Decision are made by the two players −government and consumers. The government wants to minimize CO_2 emissions by using economic instruments such as carbon taxes and subsidies. Consumers want to minimize costs for satisfying their service demand. A solution of the consumers' linear programming problem depends on parameters which are decided by the government. This end-use problem can be formulated as the following two-stage minimization problem:

$$f_1(\boldsymbol{\alpha}^s, \boldsymbol{z}^s, \boldsymbol{\beta}^s, \hat{\boldsymbol{x}}(\boldsymbol{\alpha}^s, \boldsymbol{z}^s, \boldsymbol{\beta}^s)) = \min_{\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta}} \left(\boldsymbol{d}^{\mathrm{T}} \hat{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta}) + \varepsilon \sum_{i=1}^{n} z_i \right) \tag{1.a}$$

$$\text{subj. to } \sum_{i=1}^{n} z_i \leq B(\boldsymbol{\alpha}, \hat{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta})) \tag{1.b}$$

$$f_2(\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta}, \hat{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta})) = \min_{\boldsymbol{x}} \sum_{i=1}^{n} c_i \cdot (1 - \beta_i) \cdot x_i \tag{1.c}$$

$$\text{subj. to } \mathbf{o} \leq \boldsymbol{\beta} \leq \boldsymbol{\beta}^U \tag{1.d}$$

$$c_i \cdot \beta_i \cdot x_i \leq z_i, \quad i = 1, \cdots, n \tag{1.e}$$

$$A\boldsymbol{x} \geq \boldsymbol{b} \tag{1.f}$$

$$\boldsymbol{x} \geq \mathbf{o}, \ \boldsymbol{z} \geq \mathbf{o}, \ \boldsymbol{\alpha} \geq \mathbf{o}, \tag{1.g}$$

where

$\boldsymbol{\alpha} = (\alpha_1, \cdots, \alpha_k)^{\mathrm{T}}$ denotes carbon tax rates;

$\boldsymbol{z} = (z_1, \cdots, z_n)^{\mathrm{T}}$ denotes amounts of subsidies for service devices determined by the government and $\boldsymbol{z}^s$ is an optimal strategy of the government;

$\boldsymbol{\beta} = (\beta_1, \cdots, \beta_n)^{\mathrm{T}}$ denotes subsidy rates of service devices determined by the government, $\boldsymbol{\beta}^s$ is an optimal strategy of the government, and $\boldsymbol{\beta}^U$ is an upper bound of $\boldsymbol{\beta}$;

$\boldsymbol{x} = (x_1, \cdots, x_n)^{\mathrm{T}}$ denotes the number of the energy devices used by the consumers and $\hat{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{z}, \boldsymbol{\beta})$ is an optimal strategy of consumers when $\boldsymbol{\alpha}$, $\boldsymbol{z}$, and $\boldsymbol{\beta}$ are given;

$\boldsymbol{d} = (d_1, \cdots, d_n)^{\mathrm{T}}$ denotes CO_2 emissions from a unit energy device;

$B(\boldsymbol{\alpha}, \boldsymbol{x})$ denotes the total budget for the subsidy;

$\boldsymbol{c} = (c_1, \cdots, c_n)^{\mathrm{T}}$ denotes costs of service devices without a subsidy;

A denotes a $m \cdot n$ coefficient matrix;

$\boldsymbol{b} = (b_1, \cdots, b_m)^{\mathrm{T}}$ denotes a constraint vector (there are several constraints such as budget constraints, fulfillment of energy demand, energy constraints, and technological constraints);

k denotes the number of energy resources;

m denotes the number of constraints;

n denotes the number of variables; and

ε denotes a small positive number.

This nonlinear programming problem has two levels of optimization. An important part of the model is the consumers' problem, that is, to select energy technologies that minimize costs for fulfilling their demands under several conditions. This corresponds to formula (1.c)–(1.g).

3 Model Formulations

Three formulations are given for solving the problem. The first two have the same type of structure; they are based on linear bilevel programming. The third formulation takes a new approach.

General cases are difficult to solve; however, several algorithms are given for linear bilevel programming. Assuming fixed subsidy rates, the original problem can be converted into a linear bilevel programming problem. The third formulation gives a solution based on a fixed budget.

In the following discussion, the total budget for subsidies and the carbon tax rates are assumed to be set in advance.

3.1 Linear bilevel programming with the same price of the same type of device

The consumers' objective is to minimize total costs. Subsidies are not considered in their objective function. Consumers select the cheapest energy technologies. However, consumers have to select technologies if the government decides to provide subsidies. The formulation is given as follows:

$$\min_{\boldsymbol{z}} \left(\boldsymbol{d}^{\mathrm{T}} \hat{\boldsymbol{x}} + \varepsilon \sum_{i=1}^{n} z_i \right) \tag{2.a}$$

$$\text{subj. to} \quad \sum_{i=1}^{n} z_i \leq TS_{given} \tag{2.b}$$

$$\min_{\boldsymbol{x}} \ \boldsymbol{c}^{\mathrm{T}} \boldsymbol{x} \tag{2.c}$$

$$\text{subj. to} \quad c_i \cdot \beta_i \cdot x_i \geq z_i, \quad i = 1, \cdots, n \tag{2.d}$$

$$A\,\boldsymbol{x} \geq \boldsymbol{b} \tag{2.e}$$

$$\boldsymbol{x} \geq \mathbf{o}, \ \boldsymbol{z} \geq \mathbf{o}, \tag{2.f}$$

where TS_{given} is the total fixed subsidy ($= B(\alpha, \hat{\boldsymbol{x}})$). The subsidy rate $\boldsymbol{\beta}$ is given in advance.

This is a linear two-level problem and can be solved by an appropriate algorithm. The algorithm given by Anandalingam and White (1990) is an example of a solution method for the linear static Stackelberg problem. However, applying this algorithm to large scale systems is very difficult because of its complicated nonlinear characteristics. First, the multilevel program may fail to produce a solution even when the decision variables are defined over a compact set (Bard and Falk, 1982). Second, even though all the functions are linear, local optima can exit in bilevel programming (Candler and Townsley, 1982) and the solution procedure is not usually guaranteed to give global optimality (Edmunds and Bard, 1991). Third, if starting points are not selected adequately, solution procedures sometimes do not converge.

The implication of this formulation is that when the subsidy of a certain device is given, the subsidy must be used even when consumers find the cost are high for introducing the devices. When the subsidy rate $\boldsymbol{\beta}$ is very small, the resulting solution can be unreasonable. The government distributes the subsidy to each conservation technology to try to minimize total CO_2 emissions.

3.2 Linear bilevel programming with different costs of the same type of device

Another formulation with fixed subsidy rate $\boldsymbol{\beta}$ is given as follows:

$$\min_{\boldsymbol{z}} \{ \boldsymbol{d}^{\mathrm{T}} (\hat{\boldsymbol{x}}_1 + \hat{\boldsymbol{x}}_2) + \varepsilon \sum_{i=1}^{n} z_i \} \tag{3.a}$$

$$\text{subj. to } \sum_{i=1}^{n} z_i \leq TS_{given}, \tag{3.b}$$

$$\min_{\boldsymbol{x}_1, \boldsymbol{x}_2} \{ \boldsymbol{c}^{\mathrm{T}} \boldsymbol{x}_1 + \sum_{i=1}^{n} c_i \cdot (1 - \beta_i) \cdot x_{i2} \} \tag{3.c}$$

$$\text{subj. to } c_i \cdot \beta_i \cdot x_{i2} \leq z_i, \quad i = 1, \cdots, n \tag{3.d}$$

$$A(\boldsymbol{x}_1 + \boldsymbol{x}_2) \geq \boldsymbol{b} \tag{3.e}$$

$$\boldsymbol{x}_1 \geq \mathbf{o}, \ \boldsymbol{x}_2 \geq \mathbf{o}, \ \boldsymbol{z} \geq \mathbf{o}, \tag{3.f}$$

where $\boldsymbol{x}_1 = (x_{11}, \cdots, x_{1n})^{\mathrm{T}}$ denotes the number of energy devices used without the subsidy and $\boldsymbol{x}_2 = (x_{21}, \cdots, x_{2n})^{\mathrm{T}}$ is the number of energy devices used with the subsidy.

This formulation is similar to formulation (1.a)–(1.g) except that the same type of device is classified into two categories. The price of the variable $\boldsymbol{x}_1$ does not change and that of the $\boldsymbol{x}_2$ changes with the subsidy rates. In formulation (1.a)–(1.g), the variable $\boldsymbol{x}_1$ is not considered. If the subsidy rate $\boldsymbol{\beta}$ is fixed, the problem may not be feasible because the feasible region of formulation (1.a)–(1.g) is small. The subsidy $c_i \cdot \beta_i \cdot x_i$ is necessary to introduce x_i $(i = 1, \cdots, n)$. If a technology is not allocated enough subsidy, it cannot be introduced. It can be proved that at the optimal point of problem (3.a)–(3.f), either $\boldsymbol{x}_1 = \mathbf{o}$ or $\boldsymbol{x}_2 = \mathbf{o}$. However, $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ must be considered in the procedure to obtain a solution with fixed subsidy rates.

The problem with this model is that when subsidy rate $\boldsymbol{\beta}$ is very large, the amount of subsidy necessary to introduce an energy-conservation technology is larger than that with the marginal subsidy rate. The marginal subsidy rate corresponds to the lowest amount of subsidy needed to introduce an energy-conservation technology. Consequently, the number of technology devices introduced with subsidy rate $\boldsymbol{\beta}$ is smaller than that introduced with the marginal subsidy rate if the subsidy is the same. Subsidy rate $\boldsymbol{\beta}$ is important, but very difficult to determine. In the following section, we propose an optimal strategy for a fixed total budget.

3.3 Optimal strategy under a fixed budget

When the total cost for introducing energy-service technologies is given, an optimal strategy is determined to minimize total CO_2 emissions. The subsidy is then set so that the method of minimizing total CO_2 emissions also solves the consumers' problem. These procedures are given in the following way:

$$\min_{\boldsymbol{x}} \ \boldsymbol{d}^{\mathrm{T}} \boldsymbol{x} \tag{4.a}$$

$$\text{subj. to} \quad A\,\boldsymbol{x} \ \geq \ \boldsymbol{b} \tag{4.b}$$

$$\boldsymbol{c}^{\mathrm{T}} \boldsymbol{x} \ \leq \ TP_{allow} \tag{4.c}$$

$$\boldsymbol{x} \geq \mathbf{o}\,, \tag{4.d}$$

where TP_{allow} is an allowable total cost. The constraint (4.c) is added to solve the subsidy problem. The optimal solution $\boldsymbol{x}^*$ should also solve the consumers' problem, that is, it should satisfy the following problem:

$$\min_{\boldsymbol{x}} \sum_{i=1}^{n} c_i \cdot (1-\beta_i) \cdot x_i \tag{5.a}$$

$$\text{subj. to} \quad A\,\boldsymbol{x} \geq \boldsymbol{b} \tag{5.b}$$

$$\boldsymbol{x} \geq \mathbf{o}\,. \tag{5.c}$$

Subsidy rate $\boldsymbol{\beta}$ is determined so that the solution to problem (5.a)–(5.c) becomes $\boldsymbol{x}^*$. The dual problem of (5.a)–(5.c) is as follows:

$$\max_{\boldsymbol{u}} \ \boldsymbol{b}^{\mathrm{T}} \boldsymbol{u} \tag{6.a}$$

$$\text{subj. to} \quad \sum_{j=1}^{m} a_{j,i} \cdot u_j \ \leq \ c_i \cdot (1-\beta_i), \ \ i = 1, \cdots, n \tag{6.b}$$

$$\boldsymbol{u} \geq \mathbf{o}\,, \tag{6.c}$$

where $\boldsymbol{u}$ is a dual vector of problem (5.a)–(5.c). The optimal solutions of the problems (5.a)–(5.c) and (6.a)–(6.c) should satisfy the following condition:

$$\boldsymbol{b}^{\mathrm{T}} \boldsymbol{u}^* \ = \ \sum_{i=1}^{n} c_i \cdot (1-\beta_i) \cdot x_i^*\,, \tag{7}$$

where $\boldsymbol{u}^*$ is the solution of problem (6.a)–(6.c).

Subsidy rate $\boldsymbol{\beta}$ is determined by the following problem so that consumers select solution $\boldsymbol{x}^*$ (here, the total subsidy is minimized):

$$\min_{\boldsymbol{\beta}, \boldsymbol{u}} \ \sum_{i=1}^{n} c_i \cdot \beta_i \cdot x_i^* \tag{8.a}$$

$$\text{subj. to} \quad \sum_{j=1}^{m} a_{j,i} \cdot u_j \ \leq \ c_i \cdot (1-\beta_i), \ \ i = 1, \cdots, n \tag{8.b}$$

$$\boldsymbol{b}^{\mathrm{T}} \boldsymbol{u} \ = \ \sum_{i=1}^{n} c_i \cdot (1-\beta_i) \cdot x_i^* \tag{8.c}$$

$$\boldsymbol{\beta} \geq \mathbf{o}\,, \ \ \boldsymbol{u} \geq \mathbf{o}\,. \tag{8.d}$$

The required subsidy is given as

$$TS_{required} = \sum_{i=1}^{n} c_i \cdot \beta_i^* \cdot x_i^* , \tag{9}$$

where $TS_{required}$ is the subsidy required and $\boldsymbol{\beta}^*$ is an optimal solution of problem (8.a)−(8.d). The condition

$$TS_{required} \leq TS_{given} \tag{10}$$

must be satisfied when the final solution is obtained. The objective of problem (4.a)−(4.d) is to consider the government's part in minimizing CO_2 emissions, while that of problem (5.a)−(5.c) is to show consumers which technologies have the lowest cost, and that of problem (8.a)−(8.d) is to determine the subsidy rate. The procedures to find solutions to problems (4.a)−(4.d) and (8.a)−(8.d) are iterated by changing TP_{allow} until the largest TP_{allow} is found that gives a corresponding $TS_{required}$ that is less than TS_{given}. This algorithm is given in Section 4. In this formulation, subsidy rate $\boldsymbol{\beta}$ is determined automatically, so the subsidy can be used effectively.

4 An Algorithm for an Optimal Strategy under a Fixed Budget

An algorithm for solving the subsidy problem is given as follows:

Step 1: Problem (5.a)−(5.c) is solved in the case of $\boldsymbol{\beta} = \mathbf{o}$. Its optimal solution is defined as $\boldsymbol{x}_0$; the total cost, as TP_0; and total CO_2 emissions, as TCO_0. TCO_0 is the worst case for the government.

Step 2: The CO_2 minimization problem with enough subsidy − that is, (4.a), (4.b), and (4.d) − is solved. Its optimal solution is defined as $\boldsymbol{x}_1^*$; the total cost, as TP_1; and total CO_2 emissions, as TCO_1. TCO_1 is the best solution for the government.

Step 3: The optimal subsidy rate $\boldsymbol{\beta}^*$ is obtained by problem (8.a)−(8.d). The total required subsidy, $TS_{required}$, is calculated by equation (9).

Step 4: If $TS_{required}$ is less than the total amount of usable subsidy TS_{given},

$$TS_{required} \leq TS_{given},$$

$\boldsymbol{x}^*$ and $\boldsymbol{\beta}^*$ are the final solutions.

Step 5: The search interval of an optimal solution is set on the TP_{allow} axis (the total cost axis). The left side of the interval, TP_{left}, is set to be TP_0 and the right side, TP_{right}, is set to be TP_1.

Step 6: The total required subsidy, $TS_{required}$, in the case $TP_{allow} = TP_{left}$ is less than TS_{given}, and that in the case $TP_{allow} = TP_{right}$ is greater than TS_{given}. Therefore TP_{allow}, which corresponds to the final solution, is between $[TP_{left}, TP_{right}]$.

If the range of $[TP_{left}, TP_{right}]$ is smaller than a certain amount, say δP, TP_{allow} is set to be TP_{left}, and the corresponding solutions $\boldsymbol{x}^*$ and $\boldsymbol{\beta}^*$ are the final solutions. Also, if the number of the iterations arrives at a given number, the $\boldsymbol{x}^*$ and $\boldsymbol{\beta}^*$ of TP_{left} are the final solutions.

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

Sector	Field
Industry	Iron and steel
	Cement
	Petrochemistry
	Paper & pulp
	Other industries
Residence	Air conditioning
	Hot water
	Lighting
	Cooking
	Electrical appliances
Commerce	Air conditioning
	Hot water
	Lighting
	Cooking
	Electrical appliances
Transport	Passengers
	Freight
Power geneation	Thermal plant
	Hydro plant
	Nuclear plant
	New energy systems

Step 7: A new TP_{allow} is set as follows:

$$TP_{allow} = (TP_{left} + TP_{right})/2.$$

The CO_2 minimization problem, (4.a)−(4.d), is solved with a new TP_{allow}, and a new solution $\boldsymbol{x}^*$ is obtained.

Step 8: The subsidy minimization problem, (8.a)−(8.d), is solved with $\boldsymbol{x}^*$ obtained in Step 7. A new $\boldsymbol{\beta}^*$ and $TS_{required}$ are obtained.

Step 9: If $TS_{required} = TS_{given}$, $\boldsymbol{x}^*$ and $\boldsymbol{\beta}^*$ are the final solutions.

If $TS_{required} \leq TS_{given}$, set TP_{left} to be TP_{allow} and return to Step 6.

If $TS_{required} \geq TS_{given}$, set TP_{right} to be TP_{allow} and then return to Step 6.

5 Case Studies in Japan

CO_2 emissions in Japan were analyzed by Kainuma *et al.* (1995) using the AIM/end-use model. In this paper we extend that model and propose a new practical algorithm for solving the subsidy problem. Several cases are studied using recent information on Japan's economic growth, in addition to updated data on service technologies.

5.1 Input data and conditions

Sector and Fields of the AIM/End-use Model

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-service demand; this selection results in estimation of energy consumption and CO_2 emissions. Thus, basic data such as socio-economic indicators and measurements of past energy consumption in each sector and field are prepared for estimating energy-service demand.

Service Technologies

Data of service technologies have been studied for each production step in each sector. *Table 2* lists more than 100 kinds of energy technologies. The following features of these

Table 2: Service technologies examined.

Industrial Sector

- Steel Industry
  - Coke oven
  - Coke wet adjustment equipment
  - Next generation coke oven
  - Coke wet-type quenching
  - Coke dry-type quenching
  - Blast furnace
  - Wet-top pressure recovery turbines
  - Dry-top pressure recovery turbines
  - Basic oxygen furnace
  - Direct iron ore smelting reduction furnace
  - Ingot-making
  - Continuous caster
  - Reheating furnace
  - Hot charge rolling
  - Hot direct rolling
  - Scrap preheater
  - Alternating current electric arc furnace
  - Direct current electric arc furnace
  - Conventional annealing lines
  - Continuous annealing lines
  - Industrial-owned power generation
  - Combined cycle generation
  - Advanced combined cycle generation
- Cement Industry
  - Tube mill
  - Vertical mill
  - Pre-grinder
  - Other than NSP/SP
  - NSP/SP kiln
  - Baking oven
  - High efficiency clinker cooler
  - Industrial-owned power generation
  - Combined cycle generation
  - Advanced combined cycle generation
  - Power by waste heat
- Pulp/Paper Industry
  - Caustification
  - Conventional cooking device
  - Pre-filtration continuos cooking device
  - Conventional pulp washing device
  - High performance pulp washing device
  - Conventional delignification device
  - Oxygen delignification device
  - Drum bleaching device

Industrial Sector

- Pulp/Paper Industry
  - Defuser bleaching device
  - Conventional vapor drum
  - High-performance vapor drum
  - Waste pulp-manufacturing device
  - Semi chemical pulp-manufacturing device
  - Mechanical pulp manufacturing device
  - Sulfite pulp manufacturing device
  - Conventional dryer hood device
  - High-performance dryer hood device
  - Conventional-size press device
  - High-performance-size press device
  - Conventional-bearing dehydration device
  - High-performance-bearing dehydration device
  - Industrial-owned power generation
  - Combined cycle generation
  - Advanced combined cycle generation
  - Coke boiler
  - Oil boiler
  - Gas boiler
  - Boiler combustion control
- Petrochemical Industry
  - Naphtha-cracking device
  - High-performance naphtha cracking device
  - Low-density polyethlene manufacturing device
  - High-performance LDPE manufacturing device
  - High-density polyethlene manufacturing device
  - Ethylene-oxide-manufacturing device
  - Styrene-monomer-manufacturing device
  - Acetaldehyde manufacturing device
  - Polypropylene manufacturing device
  - High performance PP manufacturing device
  - Acrylonitrile manufacturing device
  - Propylene oxide manufacturing device
  - BTX manufacturing device
  - Other petrochemistry products manufacturing device
  - Coke boiler
  - Oil boiler
  - Gas boiler
  - Boiler combustion control
  - Industrial-owned power generation
  - Combined cycle generation
  - Advanced combined cycle generation
  - Gas co-generation

technologies were examined: initial price, amount of service, energy consumption, life time, year first produced, year last produced, share in the past, potential share in future, and payback time.

Fuel Characteristics

Fuel prices and CO_2 emission factors are shown in *Table 3*. Although limestone is not used as a fuel, it is included in the analysis because it is a source of CO_2 emissions when used as a raw material in the cement industry and to remove impurities in the steel-manufacturing process.

Scenarios on Energy-service Demand

Tables 4–7 present major input assumptions for estimating energy-service demands. Technology selection, energy consumption, and CO_2 emissions are calculated based on these energy demands for each year from 1990 to 2010.

All scenarios assume that Japan's economic growth will be 3.0% from 1994 to 2000

Table 2: Continued.

Residential Sector
- Air conditioning (cool:electricity)
- Air conditioner (cool:electricity, warm:electricity)
- High performance air conditioning (cool:electricity, warm:electricity)
- Air conditioning (cool:electricity, warm:gas)
- Air conditioner (cool:electricity, warm:oil)
- Oil stove
- Oil fan heater
- Forced draft balanced fuel-type oil fan heater
- Gas stove
- Gas fan heater
- Forced draft balanced fule type gas fan heater
- Electric stove
- Electric ceramic fan heater
- Electric Gas heat pump
- Oil engine heat pump
- Adiabatic material (glass wool 50mm)
- Adiabatic material (glass wool 100mm)
- Adiabatic material (polyethylene 100mm)
- Pair glass
- Oil water heater
- Gas water heater
- Electric water heater
- Latent heat recovery type water heater
- Solar thermal water heater
- Solar system
- Incandescent lamp
- Fluorescent light of Incadescent type
- Fluorescent light
- Inverter light
- Television
- Refrigeration
- Washing machine
- Vacuum cleaner
- Microwave oven
- Photovoltaic power generation

Commercial Sector
- Gas engine co-generation
- Gas turbine co-generation
- Oil engine co-generation
- Oil turbine co-generation
- Electric air conditioner (cool)
- Electric heating
- Oil heating
- Gas heating
- Oil boiler water heater
- Gas boiler water heater
- Solar thermal water heater
- Latent heat recovery type water heater
- Gas heat pump
- Fluorescent light
- Hf inverter
- Lighting equipment with sensor
- Conventional fire-exit light
- Bright fire-exit light
- Duplication
- Calculation
- Elevator
- Cooking (gas)
- Cooking (coal)
- Photovoltaic power generation

Transportation Sector
- Passenger Transport
  - Light-duty vehicle (gasoline/stock)
  - Light-duty vehicle (gasoline/new)
  - Light-duty vehicle (electricity)
  - Small vehicle (gasoline/stock)
  - Small vehicle (diesel/stock)
  - Small vehicle (gasoline/new)
  - Small vehicle (gasoline/direct injection)
  - Small vehicle (gasoline/electricity)
  - Small vehicle (CNG)
  - Mid-size vehicle (LPG/stock)
  - Mid-size vehicle (gasoline/stock)
  - Mid-size vehicle (diesel/stock)
  - Mid-size vehicle (gasoline/new)
  - Mid-size vehicle (gasoline/direct injection)
  - Mid-size vehicle (electricity)
  - Mid-size vehicle(CNG)
  - Private bus (gasoline/stock)
  - Private bus (diesel/stock)
  - Commercial bus (diesel/stock)
  - Commercial bus (HIMR)
- Railroad transport
- Coastal shipping
- Air transport

Electric Generation Sector
- Hydroelectric electric power generation
- Coal-fired thermal power generation (stock)
- Coal-fired thermal power generation (new)
- Pressurized fluidized bed combined cycle power generation
- Ultra Supercritical power generation
- Oil-fired thermal power generation
- LNG-fired thermal power generation (stock)
- LNG-fired thermal power generation (new)
- Advanced combined cycle power generation
- Geothermal generation
- Wind power generation
- Photovoltaic power generation
- Fuel cell
- Waste power generation
- Biomass generation
- Nuclear power generation
- Nuclear power generation (double standard)
- Nuclear power generation (shortening of regular inspection)
- Nuclear power generation (extension of continuous operation)

and 2.0% from 2000 to 2010.

How to Estimate Energy Consumption and CO_2 Emissions

Based on these assumptions and data, the AIM/end-use model estimates energy consumption and CO_2 emissions in the following way:

I. The amount of energy-service demand (e.g., for production, trips, and air-conditioning) is estimated using scenarios and models.

Table 3: Classification of fuels and their emission factors.

Code	Fuel type	CO_2 emission factor	Price (1994)	Price[A] (2010) no carbon tax	Price[B] (2010) 30,000 yen/tC	[B]/[A] (2010)
		(1.0^{-10}tC/kcal)	(yen/kcal)	(yen/kcal)	(yen/kcal)	
100	Coal	1006.2	0.65	0.77	3.79	4.93
200	Coke	1230.0	0.34	0.31	–	–
310	Coke oven gas	460.0	0.0	0.0	0.0	–
320	Blast furnace gas	2999.0	0.0	0.0	0.0	–
330	Basic oxygen furnace gas	2092.0	0.0	0.0	0.0	–
400	Crude oil	781.1	1.11	1.41	3.75	2.66
410	Gasoline	765.8	12.97	13.83	16.12	1.17
420	Naphtha	760.5	1.58	2.00	4.28	2.14
430	Jet fuel	766.5	–	–	–	–
440	Kerosene	774.8	4.94	5.49	7.82	1.42
450	Diesel oil	783.9	7.83	8.70	11.05	1.27
461	A heavy oil	791.1	3.14	3.74	6.11	1.64
462	B heavy oil	804.7	–	–	–	–
463	C heavy oil	818.0	1.59	1.62	1.88	2.30
470	Liquefied petroleum gas	683.3	22.29	26.94	28.99	1.08
710	Natural gas	563.9	1.23	1.31	3.00	2.29
720	Urban gas	583.5	9.20	9.84	11.59	1.18
800	Solar	0.0	0.0	0.0	0.0	–
900	Black liquor	1075.1	0.0	0.0	0.0	–
1010	Electricity (residence)	1197.2	27.34	28.40	31.26	1.10
1020	Electricity (commerce)	1197.2	18.98	19.72	22.58	1.15
1030	Electricity (industry)	1197.2	14.37	14.43	14.93	1.19
9910	Limestone	0.12	–	–	–	–

Sources: Agency of Natural Resources and Energy, 1994;
Energy Data and Modeling Center, 1993;
Japan Environment Agency, 1992;
Japan Environment Agency, 1994.

Table 4: Input assumptions in the industrial sector.

Field	Service	Unit	1990	2000	2010
Steel	Hot steel products	10^4t	7,209	5,779	5,432
	Cool steel products	10^4t	3,465	2,778	2,611
	Steel products	10^4t	11,171	8,955	8,415
	Electric furnace share	%	31.8	35.0	40.0
Cement	Portland cement	10^4t	7,118	6,676	6,540
	Blast furnace cement	10^4t	1,488	2,214	2,169
	Fry ash cement	10^4t	79	81	81
	Mixture cement share	%	18.0	24.9	24.9
Petro-chemical	Ethylene	10^4t	581	551	520
	Low-density polyethylene	10^4t	178	148	140
	High-density polyethylene	10^4t	110	102	96
	Ethylene oxide	10^4t	67	78	74
	Styrene monomer	10^4t	22	24	22
	Acetaldehyde	10^4t	38	33	31
	Polypropylene	10^4t	194	202	191
	Acrylonitrile	10^4t	59	55	52
	Propylene oxide	10^4t	34	28	27
	Benzene, toluene, and xylene	10^4t	650	975	921
Paper	Paper	10^4t	1,643	1,799	1,857
	Paperboard	10^4t	1,166	1,292	1,333
	Used paper share	%	51.6	56	60

Table 5: Input assumptions in the residential sector.

Service	**1990***	**2000**	**2010**
Cooling	100	188	343
Heating	100	135	177
Hot water	100	126	154
Lighting	100	118	133
Television	100	167	266
Refrigerator	100	136	178
Washing machine	100	116	129
Vacuum cleaner	100	122	142
Microwave oven	100	148	211
Other appliances	100	164	259

* Energy service equals 100 in 1990.

Table 6: Input assumptions in the commercial sector.

Service	**1990***	**2000**	**2010**
Cooling	100	120	137
Warming	100	120	137
Hot water	100	120	137
Duplication	100	116	173
Calculator	100	155	209
Kitchen	100	120	137
Elevator	100	129	179
Lighting	100	120	137
Emergency light	100	120	137
Other appliance	100	120	137

* Energy service equals 100 in 1990.

II. Service-production technologies are selected to meet this amount of service demand.

III. The amount of energy necessary to operate these technologies is calculated.

IV. Total CO_2 emissions are estimated based on energy consumption by fuel type and the CO_2 emission factors given in *Table 3*.

5.2 Simulation cases

The mixture of power sources and the introduction of high efficiency thermal technologies influence the amount of CO_2 emissions from electricity generation. A CO_2 emission factor of electricity generation has a great influence on total CO_2 emissions. Two scenarios are considered for setting CO_2 emission factors of electricity generation *Table 8*.

Scenario A: Scenario A is the business-as-usual case. This scenario includes improvements in heat efficiencies by new electric power plants. For coal, the efficiency of new plant is 40% while the average efficiency of the old stock is 38.95%. For liquefied natural gas (LNG), the efficiency of new plants is 48% while the average efficiency of the old stock is 39.35%.

Scenario B: Scenario B includes the following countermeasures for mitigating CO_2 emissions:

Table 7: Input assumptions in the transportation sector.

Sector	**Service**	**Unit**	**1990**	**2000**	**2010**
Passenger	Private vehicle	10^9passenger-km	727	869	953
	Commercial vehicle	10^9passenger-km	16	17	17
	Bus	10^9passenger-km	110	111	122
	Rail	10^9passenger-km	387	440	483
	Internal navigation	10^9passenger-km	6	7	7
	Air	10^9passenger-km	52	68	75
Freight	Private vehicle	10^9t-km	72	63	66
	Commercial vehicle	10^9t-km	175	184	190
	Special vehicle	10^9t-km	27	35	36
	Rail	10^9t-km	27	25	26
	Internal navigation	10^9t-km	245	240	248
	Air	10^9t-km	1	1	1

Table 8: Share of power sources and CO_2 emissions from electricity generation.

Power Plant	**Actual**	**Scenario A**		**Scenario B**	
	1993	2000	2010	2000	2010
Hydro (%)	12.3	10.1	12.4	10.1	12.4
Coal (%)	12.0	15.9	16.1	14.3	14.1
(PFBC)		(0.0)	(0.0)	(0.5)	(4.5)
Oil (%)	22.1	16.0	10.8	14.9	10.8
LNG (%)	22.2	24.9	22.8	26.0	22.8
(ACC)		(0.0)	(0.0)	(2.8)	(3.4)
Geothermal(%)	0.2	0.5	2.0	0.5	2.0
Nuclear(%)	31.2	32.6	35.9	34.2	37.9
CO_2 (1.0^{-10}tC/kcal)	1197.2	1151.5	992.2	1096.0	935.3

- Pressurized fluidized bed combined cycles are introduced as new coal electric power plants. By 2000 1,000MW plants are introduced, and by 2010 12,400MW plants have been installed.

- Advanced combined cycles are introduced as new LNG electric power plants. By 2000 680MW plants are operating, and 970MW plants are operating by 2010.

- The capacity of nuclear power plants is improved. The output standard will be changed and the duration of regular inspection will be shortened at all nuclear power plants from 2000. The period of continuous operation will be is extended from less than 12~13 months to 15~18 months at 21,680MW plants by 2000 and at all plants by 2010. The increased amount of energy generated by nuclear power is used to replace coal power plants.

- LNG power plants, which emit fewer CO_2 emissions than other fossil fuel plants, are given higher priority than oil plants. In 2000, a total of 10.06TW is generated by LNG plants.

Simulations are performed for the following cases:

Case I (No Change of Technologies): Current technologies continue to be selected because of a lack of understanding and/or for social reasons, even though there are economic benefits in changing the technologies. No countermeasures such as carbon taxes or subsidies are assumed.

- Case I-1 : Without countermeasures for electric power plants (Scenario A in *Table 8*)
- Case I-2 : With countermeasures for electric power plants (Scenario B in *Table 8*)

Case II (Base Case): Technology selection is based solely on a reasonable policy of economic efficiency. There are neither countermeasures for power plants nor subsidies.

Case III (Carbon Tax Case): In this case a carbon tax is introduced beginning in 1997. No subsidy is assumed, but countermeasures are assumed for electric power plants.

- Case III-1 : No carbon tax.
- Case III-2 : Y 3,000 /tC.
- Case III-3 : Y 10,000 /tC.
- Case III-4 : Y 30,000 /tC.
- Case III-5 : Y 100,000 /tC.

Case IV (Subsidy Option): A carbon tax is introduced, and the tax revenue is used to subsidize energy-conservation technologies. Subsidies are assigned to technologies that lower total CO_2 emissions.

- Case IV-1 : A carbon tax of Y 3,000 /tC is introduced, and the tax revenue is used to subsidize the introduction of energy-conservation technologies. In this case, tax revenue cannot be transferred between sectors.
- Case IV-2 : In addition to Case IV-1, tax revenue may be transferred between sectors. This case is expected to reduce more CO_2 emission than Case IV-1, as the subsidy is assigned to the sector in which it will be most effective.
- Case IV-3 : The subsidy of Y 1 trillion is assigned to the sector in which it will be most effective. The amount of the subsidy is almost equal to the revenue generated from the Y 3,000 /tC tax. This case is not expected to reduce more CO_2 emission than Case IV-2, since fuel prices do not rise.
- Case IV-4 : In addition to the terms in Case IV-2, the payback period is extended to 10 years.

5.3 Simulation results

Table 9 shows the simulation results by case and sector.

Table 9: Simulation results by case and sector.

Case		Year	Industry	Residence	Commerce	Transport	Total
Case I	1	1990	153.8	38.0	33.6	58.5	320.0
		2000	146.6 (-4.7%)	48.7 (28.2%)	38.6 (14.9%)	64.1 (9.6%)	334.1 (4.4%)
		2005	147.6 (-4.0%)	54.0 (42.0%)	40.1 (19.3%)	66.3 (13.3%)	344.1 (7.5%)
		2010	148.1 (-3.7%)	58.3 (53.3%)	41.6 (23.8%)	68.4 (17.0%)	352.5 (10.2%)
	2	1990	153.8	38.0	33.6	58.5	320.0
		2000	144.7 (-5.9%)	46.8 (23.0%)	37.2 (10.8%)	64.0 (9.3%)	328.8 (2.7%)
		2005	145.9 (-5.1%)	51.5 (35.4%)	38.6 (14.9%)	66.1 (13.0%)	338.2 (5.7%)
		2010	145.9 (-5.2%)	55.2 (45.3%)	40.0 (18.9%)	68.3 (16.7%)	345.4 (7.9%)
Case II		1990	153.8	38.0	33.6	58.5	320.0
		2000	149.5 (-2.8%)	44.6 (17.4%)	37.0 (10.2%)	61.6 (5.4%)	328.9 (2.8%)
		2005	147.8 (-3.9%)	47.0 (23.7%)	37.0 (10.1%)	62.9 (7.6%)	330.8 (3.4%)
		2010	145.5 (-5.4%)	46.6 (22.6%)	36.0 (7.1%)	62.9 (7.5%)	327.1 (2.2%)
Case III	1	1990	153.8	38.0	33.6	58.5	320.0
		2000	148.3 (-3.6%)	43.6 (14.8%)	36.2 (7.7%)	61.5 (5.2%)	325.8 (1.8%)
		2005	146.6 (-4.7%)	45.8 (20.6%)	36.1 (7.4%)	62.8 (7.4%)	327.4 (2.3%)
		2010	144.2 (-6.3%)	45.2 (18.9%)	35.1 (4.6%)	62.8 (7.3%)	323.3 (1.0%)
	2	1990	153.8	38.0	33.6	58.5	320.0
		2000	147.7 (-4.0%)	43.6 (14.7%)	36.2 (7.7%)	61.5 (5.1%)	325.2 (1.6%)
		2005	145.8 (-5.2%)	45.8 (20.5%)	36.1 (7.4%)	62.8 (7.4%)	326.7 (2.1%)
		2010	143.6 (-6.6%)	44.4 (16.8%)	35.1 (4.5%)	62.5 (6.8%)	321.7 (0.5%)
	3	1990	153.8	38.0	33.6	58.5	320.0
		2000	147.2 (-4.3%)	43.6 (14.7%)	36.2 (7.7%)	60.3 (3.1%)	323.4 (1.1%)
		2005	143.7 (-6.6%)	43.3 (13.9%)	36.1 (7.4%)	61.0 (4.3%)	320.3 (0.1%)
		2010	141.8 (-7.8%)	42.8 (12.6%)	35.1 (4.5%)	61.9 (5.8%)	317.7 (-0.7%)
	4	1990	153.8	38.0	33.6	58.5	320.0
		2000	145.6 (-5.3%)	42.0 (10.5%)	36.2 (7.7%)	60.3 (3.1%)	320.2 (0.1%)
		2005	141.2 (-8.2%)	41.8 (10.0%)	36.1 (7.4%)	61.0 (4.3%)	316.1 (-1.2%)
		2010	139.0 (-9.6%)	42.7 (12.4%)	35.1 (4.5%)	61.9 (5.8%)	314.8 (-1.6%)
	5	1990	153.8	38.0	33.6	58.5	320.0
		2000	136.5 (-11.2%)	40.8 (7.4%)	35.8 (6.5%)	60.1 (2.7%)	309.2 (-3.4%)
		2005	132.5 (-13.8%)	40.1 (5.5%)	35.1 (4.5%)	60.8 (3.9%)	304.6 (-4.8%)
		2010	130.4 (-15.2%)	41.5 (9.2%)	33.1 (-1.5%)	61.7 (5.5%)	302.8 (-5.4%)
Case IV	1	1990	153.8	38.0	33.6	58.5	320.0
		2000	144.8 (-5.9%)	43.4 (13.9%)	36.2 (7.7%)	60.9 (4.1%)	321.3 (0.4%)
		2005	143.1 (-7.0%)	45.6 (20.0%)	36.1 (7.4%)	60.8 (3.9%)	321.7 (0.5%)
		2010	138.2 (-10.1%)	43.4 (14.2%)	35.1 (4.5%)	60.5 (3.4%)	313.3 (-2.1%)
	2	1990	153.8	38.0	33.6	58.5	320.0
		2000	144.8 (-5.9%)	42.6 (12.1%)	36.2 (7.7%)	60.2 (2.9%)	319.8 (-0.2%)
		2005	143.1 (-7.0%)	42.8 (12.6%)	36.1 (7.4%)	59.4 (1.5%)	317.5 (-0.8%)
		2010	138.2 (-10.1%)	41.8 (10.0%)	35.1 (4.5%)	59.5 (1.7%)	310.8 (-2.9%)
	3	1990	153.8	38.0	33.6	58.5	320.0
		2000	144.8 (-5.9%)	42.6 (12.1%)	36.2 (7.7%)	60.2 (2.9%)	319.9 (-0.0%)
		2005	143.6 (-6.6%)	43.0 (13.2%)	36.1 (7.4%)	59.5 (1.7%)	318.2 (-0.6%)
		2010	138.7 (-9.8%)	43.0 (13.2%)	35.1 (4.5%)	59.5 (1.7%)	312.4 (-2.4%)
	4	1990	153.8	38.0	33.6	58.5	320.0
		2000	144.8 (-5.9%)	41.9 (10.3%)	35.7 (6.3%)	60.2 (2.9%)	318.6 (-0.4%)
		2005	143.1 (-7.0%)	39.4 (3.7%)	34.8 (3.6%)	59.4 (1.5%)	312.8 (-2.3%)
		2010	138.2 (-10.1%)	37.9 (-0.3%)	32.5 (-3.3%)	59.5 (1.7%)	304.4 (-4.9%)

Case I (No Change of Technologies): In this case, current technologies continue to be used even if there are economic benefits in changing technologies. Energy consumption per unit of energy-service demand is constant.

CO_2 emissions increase steadily in proportion to the increase of service demand. In the case without countermeasures for electric power plants, Case I-1, emissions increase by 4.4% between 1990 and 2000 and by 10.2% between 1990 and 2010. In the case with countermeasures, Case I-2, emissions increase by 2.7% between 1990 and 2000 and by 7.9% between 1990 and 2010. The difference in CO_2 emissions between the two cases is due to the emission factor of electricity (see *Table 8*).

In the industrial sector, energy-service requirements for steel, cement, and petrochemical industries decrease, while those for the paper and pulp industry increase slightly. Thus, CO_2 emissions in the industrial sector decrease by 4.7% between 1990 and 2000 and by 3.7% between 1990 and 2010 in Case I-1.

Case II (Base Case): In this case, it is assumed that technology selection is based on a reasonable policy of economic efficiency. On the one hand, some energy-conservation technologies, such as electric furnaces in the industrial sector, fluorescent lights of incandescent type in the residential sector, Hf-inverter lights in the commercial sector, and cars with energy efficient engines in the transportation sector, are selected for economical reasons. On the other hand, some heavily emitting technologies are also selected for economical reasons. The CO_2 emission factor of an independent electric power plant is larger than that of purchased electricity, nevertheless the independent electric power plants are selected because they are more economical.

Clearly less CO_2 is emitted in Case II than in Case I. CO_2 emissions in Case II are 1.6% and 7.2% lower than emissions in Case I-1 in 2000 and 2010, respectively. Thus, if each decision maker in each sector behaves according to economic principles, CO_2 emission will be mitigated as efficient energy-conservation technologies are introduced into the market.

Total CO_2 emission levels will begin to decrease only after 2005 in Case II. It will be difficult to lower CO_2 emissions in 2000 to the 1990 level because emissions will increase considerably in the residential and transportation sectors.

Case III (Carbon Tax Case): The results from Case II show that a reasonable selection policy will be effective in mitigating CO_2 emissions; nevertheless, a reduction of emissions to the 1990 level will be difficult to achieve by 2000. Thus, in Case III, a carbon tax is imposed as a countermeasure for mitigating emissions.

Figure 1 shows CO_2 emission levels with different catbon taxes: Y 3,000, Y 10,000, Y 30,000, Y 100,000 per metric ton of carbon. To stablize the CO_2 emissions after 2000 at the 1990 level, the introduction of a carbon tax of Y 30,000 /tC in 2000, Y 10,000 /tC in 2005, and Y 5,000 /tC in 2010 is required. The figure shows that emission may stabilize with a carbon tax that begins at a high rate and is gradually reduced over a 10-year period.

It is difficult to stablize CO_2 emissions with a low carbon tax, such as Y 3,000 /tC. CO_2 emissions increase by 1.6% between 1990 and 2000 at this tax rate. Therefore, additional measures are necessary if a low carbon tax rate is introduced to stabilize emissions.

Case IV (Subsidy Option): Case III shows that the introduction of low carbon tax is not enough to stabilize CO_2 emissions. In Case IV, it is assumed that a low carbon tax is imposed and the tax revenue is used to subsidize the introduction of energy-conservation technologies.

If tax revenues are not transferred between sectors (Case IV-1), then total CO_2 emissions almost stabilize at the 1990 level in 2000; emissions increase by 0.4%. By 2010, total emissions are 2.1% below the 1990 level.

If tax revenues are transferred between sectors (Case IV-2), then total emissions are 0.2% below the 1990 level in 2000 and 2.9% below that level in 2010. Case IV-2 is more effective in mitigating CO_2 emissions than Case IV-1, since subsidies are assigned to sectors that will benefit the most. In this case tax revenues would be

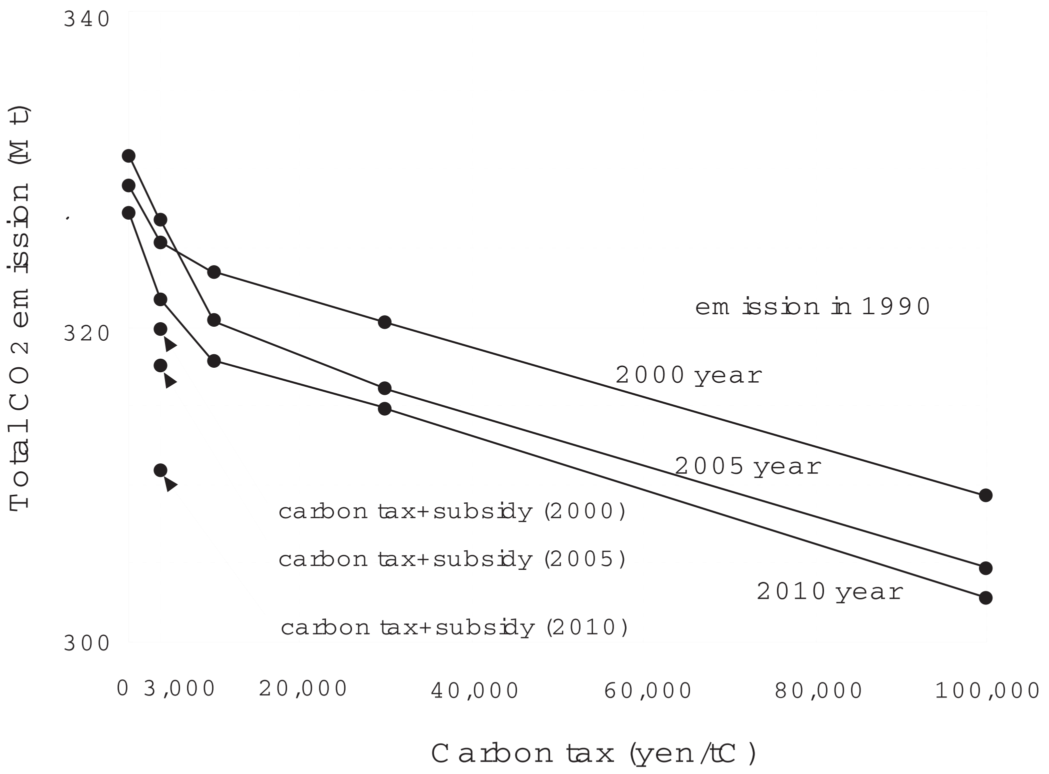

Figure 1: Total CO_2 emissions with different carbon taxes.

allocated as follows in 2000: 15% to the industrial sector, 43% to the residential sector, 0% to the commercial sector, and 41% to the transportation sector.

In Case IV-3, the Y 1 trillion subsidy is assigned to the sector in which it will be most effective; Case IV-3 and Case IV-1 show similar results. Case IV-3 is less effective than Case IV-2, because fuel prices do not increase without the carbon tax.

Moreover, if the payback period is extented to 10 years in the residential and commercial sectors (Case IV-4), the CO_2 emissions decrease considerably. The decrease in the emission is 0.4% between 1990 and 2000 and 4.9% between 1990 and 2010. The behavior in the residential and commercial sectors is different from that in the industrial sector where investment is aimed at the profit, so the extension of the payback period is realistic in these sectors. Our investigations on the extension of the payback time in the residential sector show that the payback time expands as the economic efficiency of the energy-conservation technologies becomes widely accepted. For example, the payback period of adiabatic material and pair glass would expand by about seven years after users understand the technology and how it works.

Summary: Several conclusions can be drawn from the simulation results.

- If the Japanese are presented with the economic benefits of energy conservation, then they will accept the introduction of energy-conservation technologies and mitigation of CO_2 emissions will be promoted without special taxes or subsidies. However, it would be impossible to stabilize the nation's total emission because of increases in emissions in the residential, commercial, and transportation sectors.

- A carbon tax would promote the introduction of energy-conservation technologies. In the case of Y 30,000 /tC, total CO_2 emissions would stablize at the 1990 level in 2000 and fall below the 1990 level in 2010. As emissions stabilize after 2000, the tax rate would gradually be reduced.

  A high CO_2 tax, e.g., Y 30,000 /tC, would be difficult to impose. The introduction of carbon tax rate at Y 30,000 /tC is nearly equal to a tax increase of Y 10 trillion. Consumers would probably resist this high tax. However, a low carbon tax would not be sufficient to stabilize the emission.

- The introduction of a low carbon tax alone cannot stabilize total CO_2 emission. Revenues from the tax must be used as subsidies for the introduction of energy-conservation technologies. If tax revenues are not transferred between sectors, emissions would remain close to the 1990 level in 2000, and would be below the 1990 level in 2010. Futher, some sectors would have a surplus of subsidies after 2000. Thus, revenue transfer between sectors should be permitted. In this case, total emissions could fall below the 1990 level after 2000.

- To lower total CO_2 emissions below the 1990 level, additional options are necessary. If payback periods in the residential and commercial sectors were extended and tax revenues were used as subsidies, then total emissions would fall by 5% below the 1990 level in 2010.

- In summary, one countermeasure to stabilize CO_2 emissions in Japan is the introduction of the carbon tax of more than Y 30,000 /tC by 2000. If the introduction of a high carbon proves difficult, the imposition of a lower carbon tax and the use of tax revenues as subsidies may be effective options. Moreover, the extension of the payback period, in addition to the subsidy option, would help to reduce CO_2 emissions below the 1990 level.

6 Conclusions

Several tasks must still be performed to improve this model:

- The algorithm proposed for the subsidy problem is an approximate method to solve the nonlinear problem. In some cases, an optimal solution of the original problem is not equal to that given by the proposed algorithm. Even so, the proposed method gives a good estimate of a real system. Other methods for handling this problem should be compared with this method. These procedures would improve the solution method.

- In the commercial sector, a subsidy has limited effect. One of the reasons is that there are not enough effective energy-conservation technologies . New energy conservation technologies should be developed.

- Soft technologies, such as recycling systems and daylight saving time, should be evaluated using an additional module.

- Examination of the relationship between the market share of a technology and its cost will provide good motivation for introducing energy-conservation technologies.
- Sectors that have not been modeled, such as agriculture, construction, and food, should be included in the near future.
- Other greenhouse gases can easily be estimated using this model. This must also be done in the near future.
- The AIM/end-use model will be linked to a top-down macro-economic model for analyzing the international market .

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