Development of an End-Use Model for Analyzing Policy Options to Reduce Greenhouse Gas Emissions

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abstract

An end-use energy model is presented for assessing policy options to reduce greenhouse gas emissions. This model evaluates effects of imposing a carbon tax on various carbon-emitting technologies for reducing CO_2 emissions. It also estimates effects of combining a carbon tax with subsidies. The problem can be formulated as two-level mathematical programming. An algorithm is proposed and applied to estimate Japanese CO2 emissions. The conditions under which the energy-saving technologies would be selected are analyzed with different carbon tax rates and subsidies. The reduction of CO_2 emissions is calculated based on the introduction of energy-saving technologies. It is found that to stabilize CO_2 emissions in the 1990 level in Japan, 30,000 yen per ton carbon (tC) is necessary and it is difficult to stabilize CO_2 emissions with a low carbon tax, such as 3,000 yen/tC. The proposed algorithm shows that the Japanese total emission in 2000 can be stabilized at the 1990 level with 3,000 yen/tC if tax revenues are used to subsidize the introduction of energy-saving technologies.

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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 [13]. 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 [19]. The model takes into accounts final energy consumption based on actual energy use and the way energy services are performed. It evaluates the effects of introducing policy measures such as a carbon tax and subsidies.

The model for analyzing effective subsidies is formulated as two-level mathematical programming. The two-level programming is a static Stackelberg game in which two players try to maximize their individual objectives [5], [6], [16], [17], [18], [23]. 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 [20]. When master-level decision-making situations require inclusion of zero-one variables representing yes-no decisions, the problem is formulated as mixed-integer two-level programming [25]. The greatest barrier to the effective use of these concepts is the lack of efficient algorithmic procedures to solve the resulting mathematical programming problems [24].

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 [2], [20], [21], [22]. Branch and bound methods are also applied to the Stackelberg problem [5], [15]. Edmunds and Bard [8] proposed a hybrid branch and bound scheme and a method based on objective function cuts. Júdice and Faustino [12] proposed a hybrid enumerative method. However, an effective algorithm for solving large-scale systems is not known because of their 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.

An 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 on several scenarios on energy-service demands and energy-saving technologies.

2 Modeling of End-Use Energy Consumption

The AIM/end-use model determines final energy consumption based on actual energy use and the way energy services are provided by energy-service technologies. We use a lot of energy in our daily life. This encompasses our cooling and heating, lighting, and locomotion as well as energy not used directly in the households such as energy used in the production of steel, cement, and plastic. Technologies such as air conditioning and blast furnaces offer energy services for heating and steel production.

As shown in Figure 1, the AIM/end-use model first estimates energy service demands based on socio-economic factors such as population, economic growth, industrial structure, and lifestyle, and then calculates what kind of technology will be used to what extent. To compare and consider energy technologies, detailed technological data and energy data are prepared. Once the kind of energy technology to be used is known, the model calculates the energy necessary to provide the energy services and the amount of CO_2 emissions produced when each type of energy technology operates.

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

It is assumed that decision are made by two types of players; policy makers and private individuals or consumers. Policy makers want 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.

A. Model Structure

This end-use problem can be formulated as the following two-level minimization problem:

$$
\begin{aligned}
& f_1(\mathrm{a},\mathrm{b}^s,\hat{\boldsymbol{x}}(\mathrm{a},\mathrm{b}^s)) = \min_{\mathrm{b}} \, (\boldsymbol{d}^{\mathrm{T}} \cdot \hat{\boldsymbol{x}}\,(\mathrm{a},\mathrm{b})) \\
& \qquad \text{subject to} \\
& \qquad\qquad f_2(\mathrm{a},\mathrm{b},\hat{\boldsymbol{x}}(\mathrm{a},\mathrm{b})) = \min_{\boldsymbol{x}} \sum_{i=1}^{n} c_i(\mathrm{a}) \cdot (1-\mathrm{b}_i) \cdot x_i \\
& \qquad\qquad\quad \text{subject to} \\
& \qquad\qquad\quad \sum_{i=1}^{n} c_i(\mathrm{a}) \cdot \mathrm{b}_i \cdot x_i \le T \\
& \qquad\qquad\quad \boldsymbol{A}\,\boldsymbol{x} \ge \boldsymbol{b} \\
& \qquad\qquad\quad \boldsymbol{x} \ge \boldsymbol{0},
\end{aligned}
\tag{1}
$$

where following notations are used:

- $\mathrm{a} = (\mathrm{a}_1,\cdots,\mathrm{a}_K)^{\mathrm{T}}$: carbon tax rates determined by the government. K is the number of energy types.
- $\mathrm{b} = (\mathrm{b}_1,\cdots,\mathrm{b}_n)^{\mathrm{T}}$: subsidy rates of service technologies determined by the government. b^s is an optimal strategy of the government.
- $\boldsymbol{x} = (x_1,\cdots,x_n)^{\mathrm{T}}$: numbers of service technologies used by consumers. $\hat{\boldsymbol{x}}(\mathrm{a},\mathrm{b})$ is an optimal strategy of consumers when a and b are given;
- $\boldsymbol{d} = (d_1,\cdots,d_n)^{\mathrm{T}}$: CO_2 emissions from a unit of service technology.

- $\boldsymbol{c} = (c_1, \cdots, c_n)^{\mathrm{T}}$: annual costs of service technologies without subsidies.
- $\boldsymbol{A}$: a $m \times n$ coefficient matrix and m is a number of constraints.
- $\boldsymbol{b} = (b_1, \cdots, b_m)^{\mathrm{T}}$: a constraint vector.
- T : the total amount of subsidy.

The problem expressed by Equation (1) can be solved in several ways when the number of variables is small. However, it is difficult to obtain a solution when the number of variables becomes large. An algorithm is proposed to obtain a solution that minimize CO2 emissions and that satisfy consumers' criterion to use the cheapest technologies. We assume that the $\hat{\boldsymbol{x}}$ is a global optimal solution, $\boldsymbol{x}^*$ is a solution to minimize CO2 emissions, and $\tilde{\boldsymbol{x}}$ is a solution of consumers' problem, minimizing their costs excluding subsidies. The procedure to obtain a solution can be formulated in the following way:

$$
\begin{aligned}
& f_1(\boldsymbol{x}^*) = \min_{\boldsymbol{x}} \boldsymbol{d}^T \cdot \boldsymbol{x} \\
& \text{subject to} \qquad\qquad\qquad\qquad\qquad\qquad (2) \\
& \boldsymbol{A}\ \boldsymbol{x} \geq \boldsymbol{b} \\
& \boldsymbol{C}^T \boldsymbol{x} \leq P \\
& \boldsymbol{x} \geq \boldsymbol{0},
\end{aligned}
$$

where P is the maximum amount of money that can be used to install technologies. $\boldsymbol{C}$ is a cost vector, the component of which is the present value for purchasing or reforming a unit technology.

Consumers minimize annual costs that they have to pay for producing certain amount of products and services. As subsidies are given by the government, consumers cost amounts to be annual values of technologies minus subsidies. Consumers' problem is defined as follows:

$$f_2(\tilde{\boldsymbol{x}}) = \min_{\boldsymbol{x}} \sum_{i=1}^{n} c_i \cdot (1 - \mathrm{b}_i) \cdot x_i$$

$$\text{subject to} \qquad (3)$$

$$\boldsymbol{A}\,\boldsymbol{x} \geq \boldsymbol{b}$$

$$\boldsymbol{C}^{\boldsymbol{T}}\boldsymbol{x} \leq P$$

$$\boldsymbol{x} \geq \boldsymbol{0}$$

The subsidy rate b is determined so that the solution to problem (3), $\tilde{\boldsymbol{x}}$, should be identical with the solution to problem (2), $\boldsymbol{x}^*$. As $\boldsymbol{x}$ is fixed to $\boldsymbol{x}^*$, it is not possible to change $\boldsymbol{x}$ in problem (3) for finding b. The duality theorem is applied to do it. If the primal problem has an optimal solution, then the dual problem has an optimal solution as well. If $\boldsymbol{x}$ and $\boldsymbol{u}$ are feasible solutions of the primal and dual problems respectively, and the optimality condition is satisfied, they are optimal solutions. The subsidy b is searched in the space where $\boldsymbol{x}$ and $\boldsymbol{u}$ satisfy their constraints and the optimality condition.

The dual problem of (3) is given as follows:

$$f_3(\boldsymbol{u}^*) = \max_{\boldsymbol{u}} \boldsymbol{b}^T\boldsymbol{u}$$

$$\text{subject to}$$

$$\begin{aligned}&\sum_{j=1}^{m} a_{j,i}\cdot u_j \le c_i\cdot(1-\beta_i),\quad i=1,\cdots,n\\ &\boldsymbol{u}\ge\boldsymbol{0}\,,\end{aligned}\tag{4}$$

The optimal solutions of the problems (3) and (4) should satisfy the following optimality condition:

$$\sum_{i=1}^{n} c_i\cdot(1-\beta_i)\cdot x_i^{*} = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{u}^{*}\,,\tag{5}$$

where $\boldsymbol{u}^{*}$ is the optimal solution of problem (4).

The optimal solutions of the primal and dual problems should satisfy the optimality condition and their own constraints. $\boldsymbol{x}^{*}$ satisfies the constraints of problem (3). The constraints of the dual problem (4) should also be satisfied. A subsidy rate β that satisfies such constraints is a feasible solution. As it is preferable that the total subsidy is smaller if the total emissions are the same, the total subsidy is minimized under the constraints of the dual problem, the optimality condition, and $\boldsymbol{x}=\boldsymbol{x}^{*}$. As $\boldsymbol{x}$ is given, the problem becomes linear programming. The problem to determine β is described as follows:

$$f_4(\beta^{*},\boldsymbol{u}^{*}) = \min_{\beta,\boldsymbol{u}} \sum_{i=1}^{n} C_i\cdot\beta_i\cdot x_i^{*}$$

subject to

$$\sum_{j=1}^{m} a_{j,i} \cdot u_j \le c_i \cdot (1 - \mathrm{b}_i), \quad i = 1, \cdots n$$

$$\sum_{i=1}^{n} c_i \cdot (1 - \mathrm{b}_i) \cdot x_{\mathrm{i}}^{*} = \boldsymbol{b}^{\mathrm{T}} \boldsymbol{u} \qquad (6)$$

$$\mathrm{b} \ge \boldsymbol{0}, \quad \boldsymbol{u} \ge \boldsymbol{0},$$

The required subsidy is calculated by

$$S = \sum_{i=1}^{n} C_i \cdot \mathrm{b}_i^{*} \cdot x_i^{*} \quad , \qquad (7)$$

where S is the subsidy required and S is an optimal solution of problem (6). As the available subsidy is limited by T, the following condition should be satisfied.

$$S \le T . \qquad (8)$$

The objective of problem (2) is to minimize CO$_2$ emissions from the government side, while that of problem (3) is to minimize the cost of the consumers. Problem (6) determines the subsidy rate to minimize the total amount of subsidies where the optimal solution of the problem (3) becomes the optimal solution of the problem (2), $\boldsymbol{x}^*$. The procedure to find solutions of problems (2) and (6) are iterated by changing P. If S is smaller or greater than T, P is changed to find a new set of solutions. This process is iterated until the largest S is found where S is less than T.

It should be noted that present values of introducing and/or reforming technologies are used when we are considering subsidies. The present cost is expressed as ***C***. On the other hand, annual costs are considered when technologies are compared to find minimum cost technologies. The annual cost is expresses as $\boldsymbol{c}$. A subsidy is determined based on a present value of a technology and an annual cost is considered when one compares costs of different technologies.

B. Algorithm

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

Step 1: Problem (3) is solved, assuming $\beta = \boldsymbol{0}$. Its optimal solution is defined as $\boldsymbol{x}_0$ and the total cost, as P_0, respectively.

Step 2: Problem (2) is solved assuming P is large; that is, the constraint concerning cost to introduce new technologies is not active. Its optimal solution is defined as $\boldsymbol{x}^*$ and the total cost, as P_1, respectvely.

Step 3: The optimal subsidy rate β^* is calculated by problem (6). The total required subsidy, S, is calculated by equation (7).

Step 4: If S is less than the total amount of usable subsidy T,

$$S \leq T,$$

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

Step 5: The search interval of an optimal solution is set on the P axis (the total cost axis). The left side of the interval, P_{left}, is set to be P_0 and the right side of the interval, P_{right}, is set to be P_1.

Step 6: The total required subsidy, S, is less than T if $P = P_{left}$, and it is greater than T if $P = P_{left}$. Therefore P, which corresponds to the final solution, is between [P_{left} , P_{right}].

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

Step 7: A new P is set as follows:

$$P = (P_{left} + P_{right}) /2.$$

The CO_2 minimization problem, (2), is solved with a new P , and a new solution $\boldsymbol{x}^*$ is obtained.

Step 8: The subsidy minimization problem, (6), is solved with the new $\boldsymbol{x}^*$. A new b^* and S are calculated.

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

If $S \leq T$, set P_{left} to be P and return to Step 6.

If $S \geq T$, set P_{left} to be P and return to Step 6.

3 Case Studies in Japan

Several policy options to reduce greenhouse-gas emissions are studied using the AIM/end-use model, the algorithm proposed in this paper, and recent information on Japan's economic growth.

The total of 5 sectors; industry, residence, commerce, transportation, and power plant , are examined for estimating Japanese CO2 emissions. Several fields are studied in each sector. For example, the total of 4 fields; iron and steel, cement, petrochemical, and pulp and paper industries are intensively studied in the industrial sector. Energy-service demand is given for each sector and field.

Technologies are selected for meeting energy-service demands. This selection results in estimating 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. All scenarios assume that Japan's economic growth will be 3.0% from 1994 to 2000 and 2.0% from 2000 to 2010.

Data of service technologies have been studied for each production process in each sector. More than 100 kinds of energy technologies are examined in this study [14]. Basic data such as an initial price, amounts of service and consumption per unit of technology, life time, the years that the production started and will be stopped, historical share, potential share in future, and payback time are studied and included in the technology database. Fuel prices and CO2 emission factors are also stored.

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

(1) It calculates the amount of energy-service (the demand for manufacturing of products, transportaton, and air-conditioning, etc.).

(2) It selects the service technologies to meet this service demand, considering carbon taxes and subsides.

(3) It calculates the amount of energy necessary for operating the technologies.

(4) It estimates the amount of CO_2 emissions on the basis of energy consumption by fuel type and CO_2 emission factors.

The most important judgment made in this procedure is that of selecting service technologies. Since the technology selection process is programmed in, technology selection changes when a carbon tax or subsidies are introduced, and as a consequence, the energy consumption and amount of CO_2 emissions change as well. For example, when one introduces a carbon tax, the price of energy increases, and because of this, the energy cost saved by not using as much fuel increases, and as a result, relatively expensive energy-saving technologies can be introduced. Similarly, if the initial cost of energy-saving technology decreases due to the introduction of a subsidy, the introduction of that technology will be promoted.

A. Simulation cases

Simulations are performed for the following three cases from 1990 to 2010.

Case I (Base Case): Technology selection is based solely on a reasonable policy of economic efficiency. Countermeasures are not considered.

Case II (Carbon Tax Case): A carbon tax is introduced at the beginning in 1997. No subsidy is assumed. Four different carbon taxes are assumed; 3,000 yen/tC in Case

II-1, 10,000 yen/tC in Case II-2, 30,000 yen/tC in Case II-3, and 100,000 yen/tC in Case II-4.

Case III (Subsidy Option): A carbon tax is introduced, and the tax revenue is used to subsidize energy-saving technologies. Subsidies are assigned to technologies that lower total CO_2 emissions. The following four cases are studied in Case III.

(1) Case III-1: A carbon tax of 3,000 yen/tC is introduced, and the tax revenue is used to subsidize the introduction of energy-saving technologies. In this case, tax revenue cannot be transferred between sectors.

(2) Case III-2: In addition to Case III-1, tax revenue may be transferred between sectors. This case is expected to reduce more CO_2 emission than Case III-1, as the subsidy is assigned to the sector in which it will be most effective.

(3) Case III-3: The subsidy of 1 trillion yen 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 3,000 yen/tC tax. This case is not expected to reduce more CO_2 emission than Case III-2, since fuel prices do not rise.

(4) Case III-4: In addition to the terms in Case III-2, the payback period is extended to 10 years.

B. Simulation results

Table 1 shows the simulation results by case and sector.

Case I (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-saving technologies, such as an electric arc furnace in the industrial sector, fluorescent lights of incandescent type in the residential sector, high frequency 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.

Total CO_2 emission levels will begin to decrease only after 2005 in Case I. 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 II (Carbon Tax Case): The results from Case I 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 II, a carbon tax is imposed as a countermeasure for mitigating emissions.

Figure 2 shows CO_2 emission levels with different carbon taxes: 3,000 yen, 10,000 yen, 30,000 yen, and 100,000 yen per metric ton of carbon. To stabilize the CO_2 emissions after 2000 at the 1990 level, the introduction of a carbon tax of 30,000 yen/tC in 2000, 10,000 yen/tC in 2005, and 5,000 yen/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 stabilize CO_2 emissions with a low carbon tax, such as 3,000 yen/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 III (Subsidy Option): Case II shows that the introduction of low carbon tax is not enough to stabilize CO_2 emissions. In Case III, it is assumed that a low carbon tax is imposed and the tax revenue is used to subsidize the introduction of energy-saving technologies.

If tax revenues are not transferred between sectors (Case III-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 III-2), then total emissions are 0.2% below the 1990 level in 2000 and 2.9% below that level in 2010. Case III-2 is more effective in mitigating CO_2 emissions than Case III-1, since subsidies are assigned to sectors that will benefit the most. In this case tax revenues would be allocated in 2000 as follows: 15% to the industrial sector, 43% to the residential sector, 0% to the commercial sector, and 41% to the transportation sector.

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

Moreover, if the payback period is extended to 10 years in the residential and commercial sectors (Case III-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 the residential and commercial 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-saving 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.

4. **Major Fingings**

Several interesting findings are obtained from this simulation.

(1) If the Japanese are presented with the economic benefits of energy saving, then they will accept the introduction of energy-saving 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.

(2) A carbon tax would promote the introduction of energy-saving technologies. In the case of 30,000 yen/tC, total CO_2 emissions would stabilize 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 carbon tax, e.g., 30,000 yen/tC, would be difficult to impose. The introduction of carbon tax rate at 30,000 yen/tC is nearly equal to a tax increase of 10 trillion yen. Consumers would probably resist this high tax. However, a low carbon tax would not be sufficient to stabilize the emission.

(3) The introduction of a low carbon tax alone cannot stabilize total CO_2 emission. Revenues from the tax must be used as subsidies for introducing energy-saving 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. Further, 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.

(4) 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 30,000 yen/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 Concluding Remarks

An end-use model has been developed to evaluate policy options to reduce greenhouse-gas emissions and applied to the cases in Japan. To analyze the strategies of two different groups; policy makers and consumers, the model is formulated with linear two-level programming, and an algorithm for solving it is proposed.

It is found that in order to stabilize CO_2 emissions in the 1990 level, 30,000 yen/tC is necessary and it is difficult to stabilize CO_2 emissions with a low carbon tax, such as

3,000 yen/tC. The proposed algorithm can show that the Japanese total emissions in 2000 can be stabilized at the 1990 level with 3,000 yen/tC if tax revenues are used to subsidize the introduction of energy-saving technologies. The model can also identify which technologies should be subsidized to stabilize the CO_2 emissions.

The linear bilevel programming is a nonconvex optimization problem, and local optima can exist in it. In general, it is very difficult to find a global optimal solution. Although the solution given by the proposed algorithm may not be a global optimal solution, it gives an optimal solution and it is certainly better than the solution without policy measures from the environmental point of view.

Subsidies have limited effects in the commercial sector. One reason is that there are not enough effective energy-saving technologies. New energy-saving technologies should be developed. Another reason is that some energy-saving technologies are too expensive to introduce. The extension of the payback period and use of subsidies are effective to introduce such expensive technologies. In this case, consumers should recognize the importance of energy-saving.

The model estimates energy consumption based on energy service demands. Service demands could be reduced if social systems change. Soft technologies such as recycling systems, summer time, satellite offices and video conferences, should be evaluated to estimate future energy service demands.

Another point we should discuss is that the AIM/end-use model gives national CO_2 emissions based on end-use energy demands. However, the AIM/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 macroeconomic losses because it does not take into account direct effects of higher prices in controlling energy demand and indirect economic effects through suppression of consumption or reduction of savings. A second problem is that since it does not consider social costs, such as institutional obstacles, while selecting technologies, it might overestimate the reduction of CO_2 emissions caused by each technology. A third is that it might underestimate the overall CO_2 emissions reduction potentials, because technologies such as those currently not available are not included. Some of these limits arise from the inherent restrictions of the end-use model, as well as the model being still under development. Thus, it is necessary to take these points into considerations when interpreting the results of this research.

However, even with these limitations, this model is useful as a tool for judging the effects of each policy options or joint effects of various policies. The AIM/end-use model can determine which technologies would be used to supply energy-service demands and suggest which technologies should be subsidized to mitigate CO_2 emissions.

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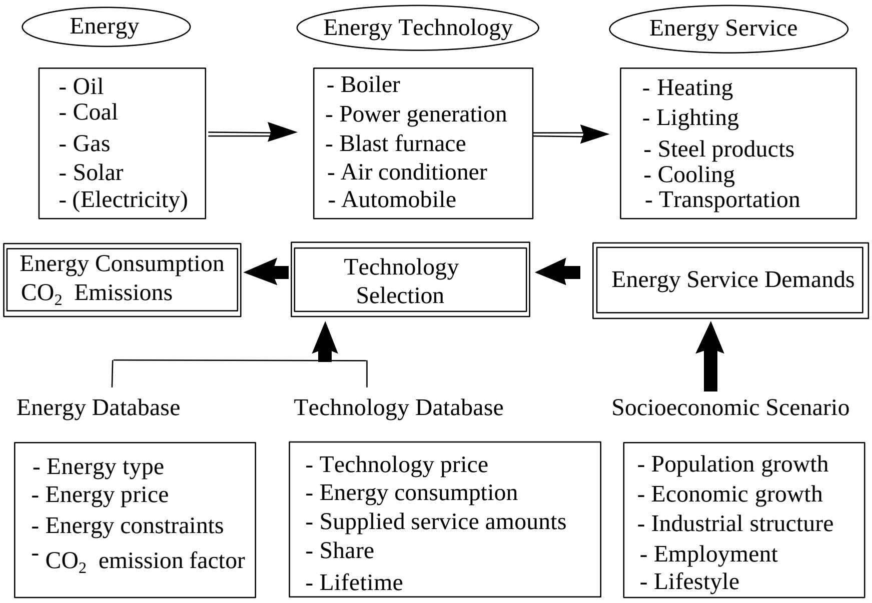

Figure 1 Structure of the AIM/end-use model

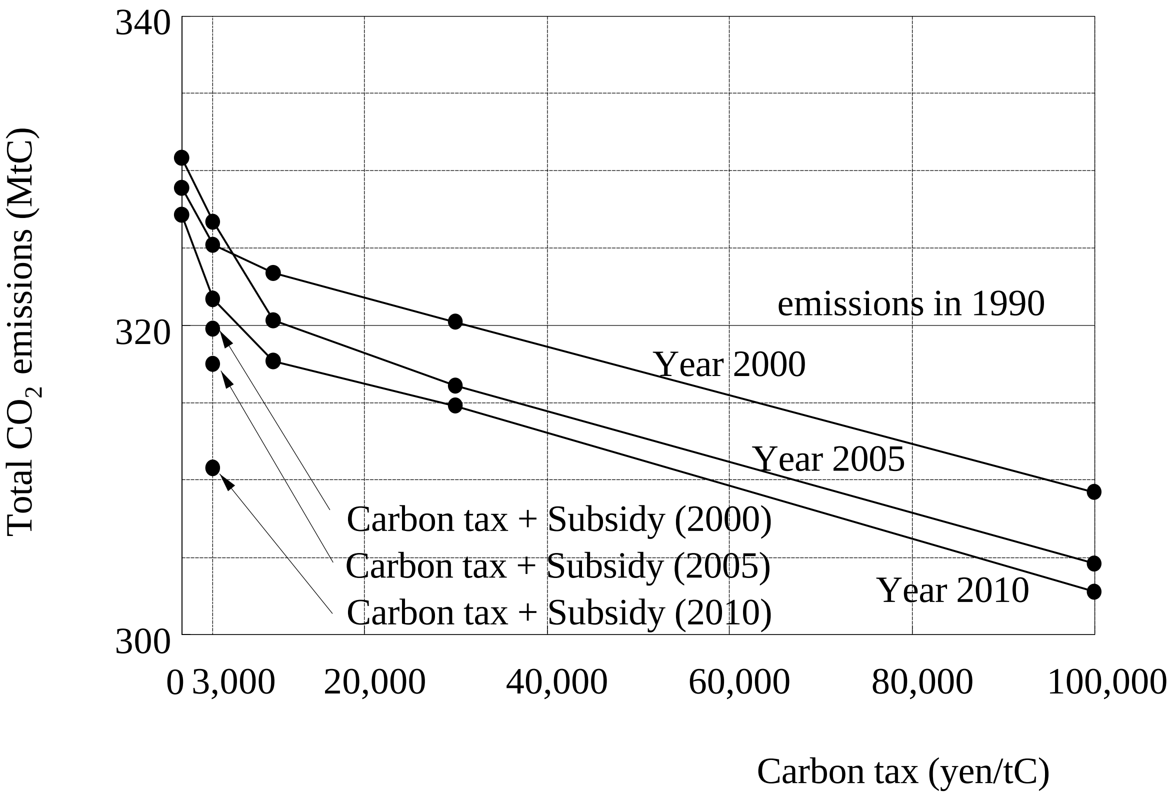

Figure 2 Total CO_2 emissions with different carbon taxes.

Table 1: Simulation results by case and sector.

Case		**Year**	**Industry**	**Residence**	**Commerce**	**Transport**	**Total**
Case I		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 II	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 III	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%)
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		2010	138.2 (-10.1%)	37.9 (-0.3%)	32.5 (-3.3%)	59.5 (1.7%)	304.4 (-4.9%)