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Contents

List of Tables

List of Figures

Chapter 1

Introduction

The United Nations Framework Convention on Climate Change was held in 1992 and the Conference of the Parties (COP) adopted this framework with the aim of preventing global warming. At COP19 in Warsaw, Poland in November 2013, a list was drafted of voluntary reduction goals to be achieved by COP21, which will be held in Paris in 2015. New measures to try to reduce greenhouse gases are being seen almost every day.

In the Kyoto Protocol, which was adopted at COP3 (Kyoto Conference) in December 1997, emissions trading systems were defined as systems that lead to the efficient reduction of greenhouses gases, and the introduction of emissions trading has since progressed around the world. Emissions trading has already been introduced in the European Union, some states of the United States, Canada, and New Zealand, and efforts are being made to introduce it into Australia, China, and Korea.

Emissions trading aims to regulate total emissions, but in recent years, some countries have set a goal of reducing the emission rate. Emission rate is the quantity of greenhouse gas emission per unit of output (GDP). China set a target of a 40–45% reduction in emissions rates by 2020 compared to 2005 levels. Similarly, India has set a target of a 20–25% reduction and Malaysia a 40% reduction. Furthermore, in Japan, since 1998, as a voluntary environmental action plan, the Federation of Economic Organizations (Nippon Keidanren) has published a target value and the actual value of the emission rate of domestic industry. Thus, while some countries have a target value for the reduction of emissions, environmental regulation of emission rates will draw attention no matter what effect it has on the environment and the economy.

Based on this, this thesis aims to investigate the following points, which have not been analyzed in previous studies: When direct rate-based regulation is introduced, how should the government set the emission rate? When the government sets the emission rate incorrectly, how much additional abatement cost is generated? How does the impact on the economy differ between rate-based regulation and total emission control? What kind of impact is there on GDP and emissions under rate-based regulation?

The remider of the thesis is organized as follows. We analyze in Chapter Two the effects of the direct regulation of the emission rate on the Japanese economy. When exogenously changing the value of the emission rate for each industry, we calculate how to change the total reduction cost. In Chapter Three, we perform a theoretical analysis of emissions trading using rate-based policy which is considered to be one of the means by which to realize emission rate targets, and to distribute free emission permits according to the emission rate. In Chapter Four, we simulate the introduction of a domestic emissions trading scheme in Japan using the rate-based policy analyzed in Chapter Three. We also compare the rate-based policy and the cap-and-trade policy which regulates total emission. Chapter Five presents our concluding remarks.

We note that Chapter Two differs substantially from Chapters Three and Four. In Chapter Two, we analyze the direct regulation of the emission rate, and in Chapters Three and Four, we analyze the rate-based policy which tries to achieve emission rate targets by allocating emission permits according to the amount of output. At present, no countries have adopted the rate-based policy; however, this policy can be considered as a method by which a country can achieve its desired emission rate.

It should be noted that at COP19, Japan announced a new goal of reducing the 2005 greenhouse gas ratio by 3.8% by 2020. Since the analysis in this paper was carried out before the new goal was announced, analysis was carried out with the previous goal of a 25% reduction of 1990 levels by 2020. In addition, in the analysis, carbon dioxide is treated as the only greenhouse gas.

Chapter 2

Estimation of marginal abatement cost and rate-based regulation

2.1 Introduction

In Japan, the Bill of the Basic Act on Global Warming Countermeasures was approved by the Cabinet on March 12, 2010. It defines the basic principles for achieving a 25% reduction of greenhouse gas emissions from 1990 levels by 2020. In the bill, an emissions trading scheme will contribute significantly to the 25% reduction in greenhouse gas emissions. Paramount to the bill is a cap-and-trade policy to impose an upper limit on the total amount of greenhouse gas emissions, but it also includes rate-based regulation that mandates the reduction of emissions per output unit.

In rate-based regulation, even if it is possible to achieve the desired emission rate by increasing emission efficiency, the total emissions increase when output is increased. However, the introduction of rate-based regulation is desirable from the viewpoint of some industries and the labor unions. This is because even if the output increases more than the emission rate, the emission rate is improvable.

In this chapter, our analysis assumes that rate-based regulation has been introduced in industries in Japan that produce substantial amounts of carbon dioxide emissions, including iron and steel (iron), chemical (chem), ceramic, stone, and clay (nmm), and pulp and paper (pulp).

According to the Greenhouse gas report (April 2010) of the National Institute for Environmental Studies in Japan, carbon dioxide emissions from the industrial sector in 2008 was 387 million tons ($MtCO_2$), of which iron is $143MtCO_2$ (37%), chem is $563MtCO_2$ (14%), nmm is $47MtCO_2$ (12%) and pulp is $23MtCO_2$ (6%). These four industries account for nearly 70% of total carbon dioxide emssions. Therefore, introducing policies to facilitate the reduction of emissions in these industries is considered to be an effective approach.

We analyze the introduction of rate-based regulation in these four industries. With rate-based regulation, the government sets the emission rate for each industry; however, depending on the setting, the cost to reduce carbon dioxide emissions will increase or decrease in some industries. That is, it is necessary for the government to set the emission rate so as to achieve a 25% reduction and minimize the cost to the entire industry. We calculate the value of the emission rate that the government should set to minimize the total abatement cost. To set an optimal emission rate, information on the marginal abatement cost is necessary. When there is information asymmetry, the government might set an emission rate that is different from the efficient level. We investigate how the total abatement cost will change when the government incorrectly sets the value of the emission rate. Böhringer et al. (2006) analyzed the variation of the total abatement cost when changing the number of industries participating in cap-and-trade emissions trading in Germany. In this chapter, we analyze changes in the total abatement cost due to changes in the emission rate set by the government in rate-based regulation.

Fischer (2001) conducted a theoretical study of rate-based regulation. In Fischer (2001), regulators distribute free emission permits according to industry output; this makes it possible to realize the target emission rate. Fischer (2001) reports that emissions become excessive by regulating the emission rate, and this generates a welfare loss. However, there is no empirical analysis of rate-based regulation in Japan. In this chapter, we find that the total abatement cost can be excessive if the government sets even a slightly incorrect emission rate from the optimal level.

2.2 Profit function and marginal abatement cost function

In this section, we derive the marginal abatement cost function and profit function for each industry. Let us define the following profit function with reference to the formulation of Yiannaka et al. (2001) and Nakano (2004):

$$\begin{aligned}\Pi_t &= \Pi(E_t)\\ &= B(E_t) - C(E_t) \qquad (2.1)\end{aligned}$$

where Π_t is the profit of the industry in period t, E is the amount of emissions, and $B(E_t)$ and $C(E_t)$ are added value function (benefit function) and cost function respectively. The cost is assumed to comprise the capital rental cost and labor cost, but not the cost for intermediate input. We define the profit function and the benefit function as follows:

$$\begin{aligned}\Pi_t &= B(E_t) - C(E_t)\\ &= aE_t^b e^{cT+\frac{1}{2}dT^2} - C(E_t) \qquad (2.2)\end{aligned}$$

where t is the time period, which is from 1970 to 2008 in this chapter, b is the elasticity with respect to the carbon dioxide emissions of added value, and T is a time trend where $T = 1$ represents the year 1970. $cT + \frac{1}{2}dT^2$ is a quadratic function that takes into account technological progress, it indicates that the technical level will increase as time passes.

Here, in the case where carbon dioxide emissions increase at an average growth rate during the analysis period, the emissions are defined as business-as-usual (BaU) emissions $\bar{E}_t$. On the other hand, during the analysis period when emission reduction methods are performed, emissions are defined as $\tilde{E}_t$. In addition, when maximizing profits for emissions level $\bar{E}_t$, the following is satisfied:

$$\frac{d\Pi(\bar{E}_t)}{dE_t} = 0 \qquad (2.3)$$

(2.2) can then be reduced to

$$ab\bar{E}_t^{b-1}e^{cT+\frac{1}{2}dT^2} - \frac{dC(\bar{E}_t)}{dE_t} = 0$$

Thus,

$$\frac{dC(\bar{E}_t)}{dE_t} = ab\bar{E}_t^{b-1}e^{cT+\frac{1}{2}dT^2} \tag{2.4}$$

Next, the marginal cost function MAC can be expressed as follows:

$$MAC = \frac{\Pi(\bar{E}_t) - \Pi(\tilde{E}_t)}{\bar{E}_t - \tilde{E}_t} \tag{2.5}$$

Here, the profit function can be approximated using Taylor expansion as follows:

$$\Pi(\bar{E}_t) \fallingdotseq \Pi(\tilde{E}_t) + \frac{d\Pi(\tilde{E}_t)}{dE_t}(\bar{E}_t - \tilde{E}_t) \tag{2.6}$$

Using (2.6), (2.5) reduces to

$$\begin{aligned} MAC &= \frac{\frac{d\Pi(\tilde{E}_t)}{dE_t}(\bar{E}_t - \tilde{E}_t)}{\bar{E}_t - \tilde{E}_t} \\ &= ab\tilde{E}_t^{b-1}e^{cT+\frac{1}{2}dT^2} - \frac{dC(\tilde{E}_t)}{dE_t} \end{aligned} \tag{2.7}$$

The cost function is then assumed to be linear without a constant term, as follows:

$$C(E_t) = gE_te^{cT+\frac{1}{2}dT^2} \tag{2.8}$$

From (2.8), we have

$$\frac{dC(\bar{E}_t)}{dE_t} = \frac{dC(\tilde{E}_t)}{dE_t} = ge^{cT+\frac{1}{2}dT^2} \tag{2.9}$$

From (2.4) and (2.9), we can derive

$$ab\bar{E}_t^{b-1}e^{cT+\frac{1}{2}dT^2} = ge^{cT+\frac{1}{2}dT^2}$$

Thus,

$$g = ab\bar{E}_t^{b-1} \tag{2.10}$$

Therefore, using (2.4) and (2.9), we can rewrite (2.7) as follows:

$$\begin{aligned} MAC &= ab\tilde{E}_t^{b-1}e^{cT+\frac{1}{2}dT^2} - \frac{dC(\bar{E}_t)}{dE_t} \\ &= ab(\tilde{E}_t^{b-1} - \bar{E}_t^{b-1})e^{cT+\frac{1}{2}dT^2} \end{aligned} \tag{2.11}$$

Additionally, from (2.8) and (2.10), (2.2) becomes

$$\begin{aligned} \Pi_t &= aE_t^b e^{cT+\frac{1}{2}dT^2} - C(E_t) \\ &= a(E_t^b - \bar{E}_t^{b-1}E_t)e^{cT+\frac{1}{2}dT^2} \end{aligned} \tag{2.12}$$

In section 2.5, in order to estimate the profit function, we use the following estimation equation taking natural log of the benefit function:

$$\ln B(E_t) = A + b\ln E_t + cT + \frac{1}{2}dT^2 + u_t \tag{2.13}$$

where A denotes $\ln a$ and u_t is the error term. In this chapter, with carbon dioxide emissions data and the value added of iron, chem, nmm, and pulp from 1970 to 2008, using (2.13), we can estimate the value of A, b, c and d using the OLS.

2.3 Data

Using the carbon dioxide emissions data and the value added of steel, chem, nmm, and pulp from 1970 to 2008, we estimate the marginal abatement cost function and the profit function for each industry.

In order to determine the value added of each industry, we use the real gross domestic product of producer prices listed in the *National Accounts Annual Report* (base year = 2000), which was created by the Economic and Social Research Institute, Cabinet Office. However, since the system of national accounts changed, there is a discontinuity in the data between 1989 and 1990. Therefore, we create continuous data by multiplying the data for 1990 and onward by the growth rate of value added from 1970 to 1990.

Next, the carbon dioxide emissions of each industry are calculated by using a carbon dioxide conversion factor taken from the energy consumption of each year. The energy consumption data for 1970 to 1997 were obtained from *General Energy Statistics* (2011 edition), which was created by the

Ministry of International Trade and Industry's Agency for Natural Resources and Energy Research Secretariat Planning and Research Division, and the data for 1998 to 2008 were obtained from the total energy supply and balance table in the *EDMC Handbook of Energy & Economic Statistics* (2000–2010 edition), which was issued by the Institute of Energy Economics, Japan. The amount of carbon dioxide emissions was calculated for each industry by multiplying the energy source of the carbon dioxide equivalent coefficient from 3EID (*Embodied Energy and Emission Intensity Data for Japan Using Input–Output Tables*, Nansai et al. 2002) by the amount of energy consumed.

2.4 Unit root test and co-integration test

In order to estimate (2.13) using OLS with the time series data of carbon dioxide emissions and the amount of value added, it is necessary to perform unit root tests to determine whether these data are stationary or non-stationary. We used the augmented Dickey–Fuller test (ADF test) for the unit root tests. The results are shown in Tables 2.1 and 2.2.

From Tables 2.1 and 2.2, the values of $\ln B(E_t)$ and $\ln E_t$ are non-stationary data because we cannot reject the null hypothesis that each industry has a unit root. However, they become steady data when taking the first difference in all industries. Therefore, $\ln B(E_t)$ and $\ln E_t$ are confirmed as I(1) variables.

Even if the time series data are non-stationary, when $\ln B(E_t)$ and $\ln E_t$ are I(1) variables and the error term u_t is an I(0) variable, $\ln B(E_t)$ and $\ln E_t$ have a cointergration relationship. At this point, it is possible to apply regression analysis to $\ln B(E_t)$ and $\ln E_t$. Thus, we conduct a cointegration test using the Johansen test for the four industries.

We find that there is a cointegration relationship in the $\ln B(E_t)$ and $\ln E_t$ of iron and chem at the 5% significance level, but there is no cointegration relationship in $\ln B(E_t)$ and $\ln E_t$ in nmm and pulp. Therefore, it is valid to perform OLS for iron and chem, but in this chapter, it is assumed that we performed OLS for nmm and pulp.

2.5 Estimation

2.5.1 Estimation of profit function

In this subsection, we estimate the profit function for the four industries, iron, chem, nmm and pulp. We use (2.13), which calculates the natural logarithm of the benefit function $B(E_t)$ as the estimating equation.

Using the carbon dioxide emissions data and the value added of the four industries from 1970 to 2008, using (2.13), we can estimate the values of A, b, c, and d using OLS; these results are shown in Table 2.3. From Table 2.3, we can see that nmm and pulp have coefficients that are not significant. However, in this chapter, we assume that these coefficients are also used. Using the values in Table 2.3, the benefit functions of the four industries can be expressed as follows:

iron $B(E_t) = 220092E_t^{0.86}e^{0.057T+0.0012T^2}$
chem $B(E_t) = 17336246E_t^{0.62}e^{0.14T-0.0024T^2}$
nmm $B(E_t) = 25177216E_t^{0.66}e^{0.017T-0.00016T^2}$
pulp $B(E_t) = 151617994448E_t^{0.13}e^{0.066T+0.00125T^2}$

From this, the profit functions of the four industries can be expressed as follows:

iron $\Pi_t = 220092(E_t^{0.86} - \bar{E}_t^{-0.14}E_t)e^{0.057T+0.0012T^2}$
chem $\Pi_t = 17336246(E_t^{0.62} - \bar{E}_t^{-0.38}E_t)e^{0.14T-0.0024T^2}$
nmm $\Pi_t = 25177216(E_t^{0.66} - \bar{E}_t^{-0.34}E_t)e^{0.017T-0.00016T^2}$
pulp $\Pi_t = 151617994448(E_t^{0.13} - \bar{E}_t^{-0.87}E_t)e^{0.066T+0.00125T^2}$

2.5.2 Estimation of marginal abatement cost function

In this subsection, we estimate the marginal abatement cost function of iron, chem, nmm, and pulp. Once again, (2.11) is the marginal abatement cost function.

$$MAC = ab(\tilde{E}_t^{b-1} - \bar{E}_t^{b-1})e^{cT+\frac{1}{2}dT^2} \tag{2.11}$$

Here, we consider the marginal abatement cost to be $t = 2020$. $\bar{E}_{2020}$ (hereafter denoted by $\bar{E}$) represents carbon dioxide emissions in the BaU scenario in the absence of efforts to reduce emissions, and $\tilde{E}_{2020}$ (hereafter denoted by

E) represents carbon dioxide emissions under reduction efforts. We can calculate $\bar{E}$ for the year 2020 by using the average growth rate of carbon dioxide emissions in the analysis period. Table 2.4 shows the calculation results. In addition, we also present in Table 2.5 the result of the marginal abatement cost calculation. The values in Table 2.5 are shown in graph form in Figure 2.1.

2.6 Determination of optimal emission rate

In this section, when it is assumed that rate-based regulation has been implemented, the carbon dioxide emissions target set by the government can be achieved, and the emission rate is calculated to minimize the total abatement cost. The emission rate represents the amount of carbon dioxide emissions per added value. Therefore, the optimal emission rate is the ratio of emissions to value added that is achieved when the marginal benefit of each industry is equalized.

In 2020 ($T = 51$), the marginal benefit function of industry i ($i = 1, 2, 3, 4$) can be expressed as follows:

$$MB_i = a_i b_i (E_i^{b_i-1} - \bar{E}_i^{b_i-1}) e^{51c_i + \frac{1}{2}\cdot 51^2 d_i} \tag{2.14}$$

(2.14) can be tranformed to become

$$E_i = \left[\frac{MB_i + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i + 1300.5d_i}}{a_i b_i e^{51c_i + 1300.5d_i}} \right]^{\frac{1}{b_i-1}} \tag{2.15}$$

Here, $\hat{E}$ is the carbon dioxide emissions target set by the government. By considering that the marginal benefit for each industry becomes equal to p, the following equation is satisfied using (2.15):

$$\sum_{i=1}^{4} E_i = \sum_{i=1}^{4} \left[\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i + 1300.5d_i}}{a_i b_i e^{51c_i + 1300.5d_i}} \right]^{\frac{1}{b_i-1}} = \hat{E} \tag{2.16}$$

We insert a_i, b_i, c_i, and d_i from Table 2.4 into (2.16), and since it is necessary to insert the emissions level in 2020 that comprises a 25% reduction compared to 1990 into $\hat{E}$, we adopt $\hat{E}$ (22.4MtCO$_2$) as the value of 75% of the total carbon dioxide emissions of the four industries in 1990. Calculating this gives

$p = 657$. This value is the marginal benefit of each industry; in other words, when emissions trading is implemented using the cap-and-trade policy, the permit price is 657 yen.

When we insert $p = 657$ into MB_i in (2.15), it is possible to obtain the optimum emissions E_i^* of each industry. Further, when we insert each benefit function of each industry into the optimal emissions, we obtain the added value under optimal choice. Then, by dividing E_i^* by $B_i(E_i^*)$, we can determine the optimum emission rate. The results of this calculation are shown in Table 2.6.

2.7 Relationship between emission rate and total abatement cost

2.7.1 Iron industry

In this subsection, with the introduction of rate-based regulation for the four industries, we analyze the total abatement cost when the government changes the emission rate. For the sake of simplicity, we assume the introduction of rate-based regulation in only one of the four industries at a time. In this subsection, we analyze the case where this regulation is introduced into iron. Since iron has the highest amount of emissions among the four industries, iron must reduce missions most when emissions trading is introduced. Therefore, we expect that the introduction of rate-based regulation is most desirable for iron.

Here, regarding the emissions regulation imposed on iron ($i = 1$) as α, the amount of emissions for iron is expressed as follows:

$$E_1 = \alpha B_1(E_1) \tag{2.17}$$

By (2.17), emissions E_1 are expressed as follows:

$$E_1 = \alpha a_1 E_1^{b_1} e^{51c_1 + \frac{1}{2} \cdot 51^2 d_1}$$

Thus,

$$E_1 = \left[\alpha a_1 e^{51c_1 + 1300.5d_1}\right]^{-(b_1 - 1)} \tag{2.18}$$

(2.18) expresses the relationship between E_1 and α.

The profit function of iron is calculated by (2.12) and (2.18). When E_1 from (2.12) is inserted into (2.18), we can derive the following equation. In order to prevent complicating the formula, we substitute values for a_1, b_1, c_1, and d_1.

$$\begin{aligned}\Pi_1 &= a_1\left[\{\alpha B_1(E_1)\}^{b_1} - \bar{E}_t^{b_1-1}\alpha B_1(E_1)\right] e^{51c_1+1300.5d_1} \\ &= a_1\left[\left\{\alpha a_1 E_1^{b_1} e^{51c_1+1300.5d_1}\right\}^{b_1} - \bar{E}_t^{b_1-1}\alpha a_1 E_1^{b_1} e^{51c_1+1300.5d_1}\right] \qquad (2.19)\end{aligned}$$

Next, we suppose the total abatement cost TC_1 for iron to be the difference between the BaU profits $\bar{\Pi}_1$ and Π_1 as follows:

$$TC_1 = \bar{\Pi}_1 - \Pi_1 \qquad (2.20)$$

This equation can give us the BaU profits $\bar{\Pi}_i$ of each industry in 2020 when we insert the BaU emissions for the profit function. Table 2.7 shows the values obtained.

From (2.19) and (2.20) we have

$$\begin{aligned}TC_1 = \bar{\Pi}_1 - a_1&\left[\left\{\alpha a_1 E_1^{b_1} e^{51c_1+1300.5d_1}\right\}^{b_1}\right. \\ &\left.-\bar{E}_t^{b_1-1}\alpha a_1 E_1^{b_1} e^{51c_1+1300.5d_1}\right] e^{51c_1+1300.5d_1} \qquad (2.21)\end{aligned}$$

In addition, by (2.21) and (2.18), we have

$$\begin{aligned}TC_1 = \bar{\Pi}_1 - a_1&\left[\left\{\alpha a_1\left(\frac{1}{\alpha a_1 e^{51c_1+1300.5d_1}}\right)^{\frac{b_1}{b_1-1}} e^{51c_1+1300.5d_1}\right\}^{b_1}\right. \\ &\left.-\bar{E}_t^{b_1-1}\alpha a_1\left(\frac{1}{\alpha a_1 e^{51c_1+1300.5d_1}}\right)^{\frac{b_1}{b_1-1}} e^{51c_1+1300.5d_1}\right] e^{51c_1+1300.5d_1} \\ &\qquad (2.22)\end{aligned}$$

Since $\bar{\Pi}_1$, a_1, b_1, c_1, and d_1 are known, (2.22) expresses the relationship between α and TC_1. Next, by combining (2.16) and (2.18), we have

$$\left[\alpha a_1 e^{51c_1+1300.5d_1}\right]^{-(b_1-1)} + \sum_{i=2}^{4}\left[\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i+1300.5d_i}}{a_i b_i e^{51c_i+1300.5d_i}}\right]^{\frac{1}{b_i-1}} = \hat{E} \qquad (2.23)$$

(2.23) represents the relationship between emission rate α and permit price p. Finally, we give the total abatement cost of chem, nmm and pulp ($i = 2, 3, 4$). By (2.12), (2.16), and (2.20), we can derive the following:

$$\begin{aligned}
TC_1 &= \bar{\Pi}_i - \Pi_i \\
&= \bar{\Pi}_i - a_i \left[\left(\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i+1300.5d_i}}{a_i b_i e^{51c_i+1300.5d_i}} \right)^{\frac{b_i}{b_i-1}} \right. \\
&\left. -\bar{E}_i^{b_i-1} \left(\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i+1300.5d_i}}{a_i b_i e^{51c_i+1300.5d_i}} \right)^{\frac{1}{b_i-1}} \right] e^{51c_i+1300.5d_i} \qquad i = 2, 3, 4
\end{aligned} \tag{2.24}$$

(2.24) represents the relationship between the total abatement cost TC_1 and permit price p. From (2.22) and (2.24), the total abatement cost TC is given by

$$\begin{aligned}
TC &= \sum_{i=1}^{4} TC_i \\
&= TC_1 + \sum_{i=2}^{4} TC_i \\
&= \bar{\Pi}_1 - a_1 \left[\left\{ \alpha a_1 \left(\frac{1}{\alpha a_1 e^{51c_1+1300.5d_1}} \right)^{\frac{b_1}{b_1-1}} e^{51c_1+1300.5d_1} \right\}^{b_1} \right. \\
&\left. -\bar{E}_t^{b_1-1} \alpha a_1 \left(\frac{1}{\alpha a_1 e^{51c_1+1300.5d_1}} \right)^{\frac{b_1}{b_1-1}} e^{51c_1+1300.5d_1} \right] e^{51c_1+1300.5d_1} \\
&+ \sum_{i=2}^{4} \left[\bar{\Pi}_i - a_i \left\{ \left(\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i+1300.5d_i}}{a_i b_i e^{51c_i+1300.5d_i}} \right)^{\frac{b_i}{b_i-1}} \right. \right. \\
&\left. \left. -\bar{E}_i^{b_i-1} \left[\frac{p + a_i b_i \bar{E}_i^{b_i-1} e^{51c_i+1300.5d_i}}{a_i b_i e^{51c_i+1300.5d_i}} \right]^{\frac{1}{b_i-1}} \right\} e^{51c_i+1300.5d_i} \right]
\end{aligned} \tag{2.25}$$

(2.25) represents the relationships among the total abatement cost TC, emission rate α and permit price p. Since (2.23) shows the relationship between emission rate α and permit price p, from (2.23) and (2.25), we can obtain the relationship between the total abatement cost TC and emission rate α. We show this relationship in Figure 2.2.

As Table 2.2 shows, the total abatement cost is 17.8 billion yen when the emission rate is $\alpha^* = 73$ (tCO_2/million yen), as shown in Table 2.6. We estimate that the total cost reduction increases by about 3.6 billion yen when the government incorrectly sets the emission rate—for example, when the emission rate is 1% higher than the optimum.

2.7.2 Ceramic and clay industry

In subsection 2.7.1, we analyzed the introduction of rate-based regulation to the iron industry only. However, in this subsection, we consider the case of the introduction of rate-based regulation only to nmm, which has the highest marginal abatement cost. For high marginal abatement cost industries, there are higher costs for reduction efforts when emissions trading is introduced, so it is expected that the introduction of rate-based regulation is desirable for these industries. We determined the relationship between the total abatement cost TC and emission rate α in subsection 2.7.1, and the results can be seen in Figure 2.3.

From Figure 2.3, we can see that the total abatement cost is 17.8 billion yen when the emission rate is $\alpha^* = 9.4$ (tCO_2/million yen). We estimate that the total cost reduction increases by about 0.37 billion yen when the government incorrectly sets the emission rate—for example, when the emission rate is 1% higher than the optimal. However, even if the government sets the wrong emission rate, the total abatement cost is smaller than it is for the iron industry. In other words, by introducing rate-based regulation for high marginal abatement cost industries, the total abatement cost is relatively low even if the government makes a mistake in setting the emission rate.

2.8 Conclusion

In this chapter, with the target of reducing carbon dioxide emissions by 25% of 1990 levels by 2020, we assumed that rate-based regulation had been introduced into industries that emit a great deal of carbon dioxide: Japan's iron and steel; chemical; ceramic, stone, and clay; and pulp and paper industries.

To reduce emissions by 25% in these four industries, the cost would be about 17.8 billion yen. This cost can be adjusted to the amount of the total abatement cost if the government has set an optimum emission rate. However, setting the emission rate is difficult, and it is possible that the government may set an incorrect rate. For example, if the government set the emission rate 1% higher than the optimal level for the iron and steel industry only, we estimate that the total cost would increase by about 3.6 billion yen. Moreover, if the government set the emission rate 1% higher than the optimal level for the ceramic, stone, and clay industry only, we estimate that the total cost would increase by about 0.37 billion yen. The increase of the total abatement cost depends on the sector and it is more serious in the iron and steel sector. In other words, the increase of the total abatement cost is relatively low when the government sets an incorrect emission rate for a sector in which the marginal cost of abatement is relatively low.

In this chapter, the analysis is based on the assumption that the regulators are completely aware of the technological progress of each industry. The rate-based regulation is preferred because it can easily realize the emission rate of the target industry without significantly reducing output and emissions with a rising technological level. However, in this chapter, because the government has completely foreseen the technological progress of each industry, it can directly regulate the emission rate. Moreover, the benefit function is non-linear, and the direct regulation of the emission rate, added value, and emissions for each industry are uniquely determined. Therefore, it should be noted that it has substantially the same characteristics as controlling the total volume of emissions.

Thus, in Chapter Three, we analyze the case where each industry determines the technological level endogenously and the government determines the emission rate exogenously. By not setting the emission rate endogenously (as in this chapter), it is assumed that there will be a focus on the difference between the cap-and-trade policy and rate-based regulation.

Table 2.1: Unit root test of $\ln B(E_t)$

	$\ln B(E_t)$			
	Level		First difference	
	ADF	Augmented term	ADF	Augmented term
iron	-1.45	$k = 0$	-4.92***	$k = 0$
chem	-1.82	$k = 0$	-5.39***	$k = 3$
nmm	-1.74	$k = 0$	-4.92***	$k = 0$
pulp	-1.38	$k = 0$	-6.01***	$k = 0$

Note: *** indicates statistical significance at the 1% level and k is the order of the augmented term.

Table 2.2: Unit root test of $\ln E_t$

	$\ln E_t$			
	Level		First difference	
	ADF	Augmented term	ADF	Augmented term
iron	-2.88	$k = 0$	-5.29***	$k = 1$
chem	-3.20*	$k = 0$	-6.99***	$k = 0$
nmm	-2.62	$k = 1$	-4.84***	$k = 0$
pulp	-1.68	$k = 1$	-4.45***	$k = 0$

Note: *** and * indicate statistical significance at the 1% and 10% levels, respectively, and k is the order of the augmented term.

Table 2.3: Results of OLS

	iron	chem	nmm	pulp
A	12.30**	16.67***	17.04***	25.74***
	(-2.51)	(-3.42)	(-4.32)	(-14.79)
b	0.86***	0.62**	0.66***	0.13
	(-3.36)	(-2.23)	(-2.92)	(-1.24)
c	0.057***	0.14***	0.017***	0.066***
	(-9.02)	(-17.86)	(-2.76)	(-16.5)
d	0.0024***	-0.0048***	-0.00032	0.0025***
	(-8.45)	(-10.66)	(-1.01)	(-13.61)
R^2	0.7121	0.9645	0.6849	0.9409

Note: *** and ** indicate statistical is given significance at the 1% and 5% levels, respectively, and the *t*-value in parentheses.

Table 2.4: Business-as-usual CO_2 emissions in 2020 ($MtCO_2$)

	iron	chem	nmm	pulp
Emissions	154.1	67.9	37.7	23.5

Table 2.5: Marginal abatement cost in 2020 (yen/tCO_2)

CO_2 reduction	iron	chem	nmm	pulp
1%	16	129	238	72
5%	80	662	1,223	374
10%	164	1,374	2,535	788
15%	254	2,143	3,949	1,246
20%	350	2,977	5,478	1,758
25%	454	3,887	7,142	2,334
30%	565	4,884	8,961	2,986
35%	686	5,984	10,963	3,732
40%	819	7,208	13,183	4,593

Table 2.6: Optimal CO_2 emissions, added value, and emission rate

	iron	chem	nmm	pulp
CO_2 emissions ($MtCO_2$)	102	64.6	36.6	21.5
Added value (billion yen)	1,395	3,571	3,897	1,480
Emission rate (tCO_2/million yen)	73.1	18.1	9.4	14.5

Table 2.7: Business-as-usual profits in 2020 (million yen)

	iron	chem	nmm	pulp
Profits	2,767	1,401	1,348	1,305

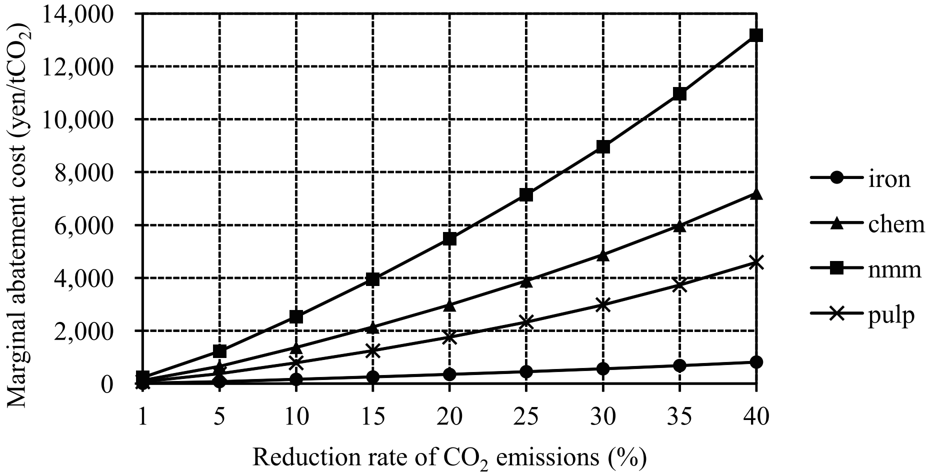

Figure 2.1: Marginal abatement cost in 2020

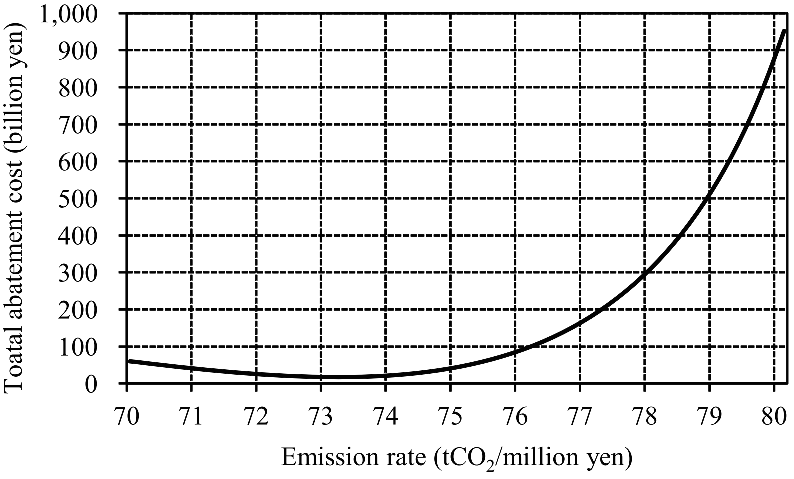

Figure 2.2: Relationship between the emission rate and total abatement cost in the iron industry

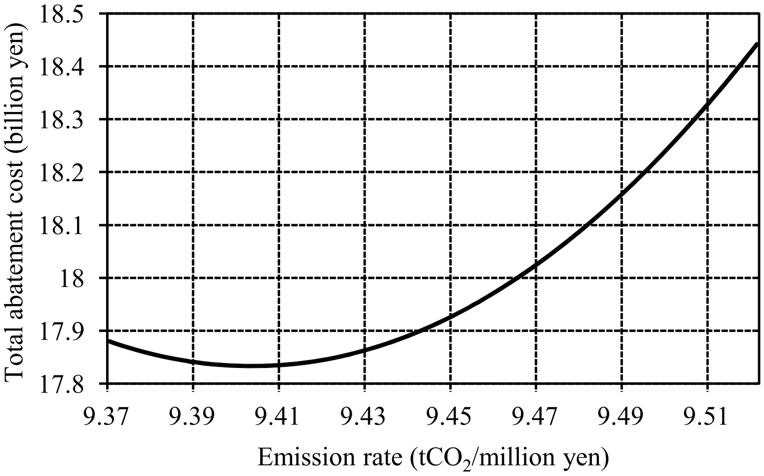

Figure 2.3: Relationship between the emission rate and total abatement cost in the ceramic and clay industry

Chapter 3

Theoretical comparison of cap-and-trade policy and rate-based policy

3.1 Introduction

In previous studies on the system design of emissions trading, cap-and-trade policy with total control of emissions volume has been discussed the most (Matumoto 2008; Maeda 2009). However, Japan's government has proposed introducing rate-based emission regulations for some industries in Japan. The Global Warming Countermeasures Bill was submitted to the 174th ordinary session of the Diet but was not passed. This bill reads as follows:

"While there is the basic need to determine the extent of the total amount of greenhouse gas emissions during a given period of time, we also need to take into account how to determine the extent of greenhouse gas emissions per unit of output."

Moreover, the Japanese Ministry of the Environment has discussed in its council the introduction of the cap-and-trade and rate-based policies (Japanese Ministry of the Environment 2010). In addition, both China and India have set targets for greenhouse gas emissions per unit of gross domestic product for the year 2020; in order to achieve their targets, both countries may have to develop international or domestic emissions regulations (Marschinski and Edenhofer 2010; Stern and Jotzo 2010). As described above, domestic and international rate-based emission regulations have attracted the attention of various countries, but insufficient research has been done on these. Finding the effect of rate-based policies on emissions and GDP and comparing that with the effect of cap-and-trade policies and rate-based regulations is important when considering climate change policies.

Examples of theoretical studies of emissions trading under rate-based regulations include Fischer (2003) and Boom and Dijkstra (2009). Fischer (2003) proposes the free allocation of emission permits in accordance with an emission rate. This method enables countries to achieve their emission rate targets. Henceforth, we call this the rate-based policy method. Fischer (2003) further shows that the total amount of emissions tends to increase when the cap-and-trade and rate-based policies are combined than under the cap-and-trade policy alone. However, it is not enough that we compare the cap-and-trade and rate-based policies. Boom and Dijkstra (2009) show that the amount of output is larger under the rate-based policy than under the cap-and-trade policy in the long term, and, theoretically, even in the short term. However, the conclusion of this study, obtained on assumptions, is that of identical emissions levels under both policies, and that it is not possible to compare the magnitude relationship of emissions by themselves. There are several studies on the regulation of the emission rate (Pizer 2005; Quirion 2005), but since these studies do not consider emissions trading as a policy.

In this chapter, we compare emissions and output under the cap-and-trade and rate-based policies by using theoretical models capable of changing the intensity of emissions in the long run. However, these models are assumed not to take into account the entry and exit of enterprises. In addition, we analyze the difference between emissions and output under both policies; for this, we assume that in the vicinity of the production level of the industry as a whole, in which each company realizes its profit maximization behavior, the relationship of output and emissions is a linear approximation expressed as a linear function. As a result, the rate-based policy tends to show increased output and emissions by the industry as a whole compared to the cap-and-trade policy.

3.2 Theoretical analysis

3.2.1 Model

In this subsection, we present some of our assumptions. First, with x and e denoting output and emissions, respectively, we assume the following relationship.

$$e(x, a) = ax + b$$

where $a \geq 0$ is the emission intensity representing the emission efficiency of a company, $b > 0$ the fixed emissions, and $e(x, a)$ the emission function.

The cost function $c(x, a)$ is a function of output and emission intensity, with the partial derivatives of each assumed to be $c_x > 0$ and $c_a \leq 0$. The second-order partial derivatives are assumed to be $c_{xx} > 0$, $c_{xa} = 0$, and $c_{aa} \geq 0$. Here, we assume that the marginal cost of production is not affected by emission intensity, but this assumption seems to slacken when we discuss the whole industry. In addition, the output price p and factor prices are given. This means that the company does not have a price control mechanism, and that the supply of and demand for the production factors are not changed by changes in emission intensity.

3.2.2 Individual firm level

In this subsection, we compare the output and emissions of a company when emissions trading is introduced, when cap-and-trade (represented by the subscript q) or rate-based (represented by the subscript s) policies are adopted, and when emissions trading is not introduced and there is no regulation (represented by the subscript o). Emissions trading represents a perfectly competitive market with permit price p regardless of whether it is under the cap-and-trade or rate-based policy. This indicates that the emissions trading market is not closed in the country. The number of companies in an industry is N.

In the case of no regulation, the profit function of an industry $\pi_o(x_o, a_o)$ can be represented as shown below: The subscript $i = 1, \ldots, N$ is omitted to indicate individual firms.

$$\pi_o(x_o, a_o) = px_o - c(x_o, a_o) \tag{3.1}$$

The profit maximizing conditions of the firm are

$$\frac{\partial \pi_o(x_o, a_o)}{\partial x_o} = p - c_x(x_o, a_o) = 0 \tag{3.2}$$

$$\frac{\partial \pi_o(x_o, a_o)}{\partial a_o} = -c_a(x_o, a_o) = 0 \tag{3.3}$$

Here, the cost function that is constantly higher than a_o^* holds (3.3), and it is differentiable on a_o^*. We assume this in order to avoid degrading the technological level.

Next, when we introduce emissions trading under the cap-and-trade policy, the profit function $\pi_q(x_q, a_q)$ of the firm is

$$\pi_q(x_q, a_q) = px_q - c(x_q, a_q) + r\left[\bar{e} - e(x_q, a_q)\right] \tag{3.4}$$

where $\bar{e}$ denotes the emission permits assigned to the firm and the emission function is $e(x_q, a_q) = a_q x_q + b$. From (3.4), the profit maximization conditions are

$$\frac{\partial \pi_q(x_q, a_q)}{\partial x_q} = p - c_x(x_q, a_q) - ra_q = 0 \tag{3.5}$$

$$\frac{\partial \pi_q(x_q, a_q)}{\partial a_q} = -c_a(x_q, a_q) - rx_q = 0 \tag{3.6}$$

In addition, when we introduce emissions trading under the rate-based policy, the profit function $\pi_s(x_s, a_s)$ is

$$\pi_s(x_s, a_s) = px_s - c(x_s, a_s) + r\left[\bar{a}x_s - e(x_s, a_s)\right] \tag{3.7}$$

where $\bar{a}$ is the emission rate set for the firm and $\bar{a}x_s$ is the emission permits assigned to it. We will discuss how $\bar{a}$ is determined later. From (3.7), the profit maximization conditions are

$$\frac{\partial \pi_s(x_s, a_s)}{\partial x_s} = p - c_x(x_s, a_s) + r(\bar{a} - a_s) = 0 \tag{3.8}$$

$$\frac{\partial \pi_s(x_s, a_s)}{\partial a_s} = -c_a(x_s, a_s) - rx_s = 0 \tag{3.9}$$

Next, by comparing the profit maximization conditions derived so far, we consider the magnitude of the output and emissions relationship in each policy. From (3.2) and (3.5), assuming that the output price p is constant, we obtain

$$c_x(x_o, a_o) = c_x(x_q, a_q) + ra_q \tag{3.10}$$

Since the second term on the right-hand side (RHS) of (3.10) is positive, the term on the left-hand side (LHS) of the equation should be larger than the first term on the RHS for the equation to be satisfied. Considering the assumptions $c_{xx} > 0$ and $c_{xa} = 0$, $x_o > x_q$. That is, when the cap-and-trade policy is introduced, the output of the firm decreases.

Combining (3.2) and (3.8), we obtain

$$c_x(x_o, a_o) = c_x(x_s, a_s) - r(\bar{a} - a_s) \tag{3.11}$$

Since the relationship between output and emissions is assumed to be linear, $\bar{a} > a_s$ is satisfied. This is because if $\bar{a} > a_s$ is not satisfied, it is not possible to satisfy the rate-based regulation. Thus, the second term on the RHS of (3.11) is positive, and for the equation to be satisfied, the term on the LHS of the equation must be smaller than the first term on the RHS. Considering the assumptions $c_{xx} > 0$ and $c_{xa} = 0$, $x_o < x_s$. That is, when the rate-based policy is introduced, the output of the firm increases.

Next, combining (3.3) and (3.6), we obtain

$$c_a(x_o, a_o) = c_a(x_q, a_q) + rx_q \tag{3.12}$$

Since the second term on the RHS of (3.12) is positive, for the equation to be satisfied, the term on the LHS of the equation must be larger than the first term on the RHS. Considering the assumptions $c_{aa} \geq 0$ and $c_{xa} = 0$, $a_o^* > a_q^*$. That is, when the cap-and-trade policy is introduced, the emission intensity of the firm increases.

Here, because $e(x_o, a_o) = a_o x_o + b$, $e(x_q, a_q) = a_q x_q + b$ and b is constant; we therefore obtain

$$e(x_o, a_o) - a_o x_o = e(x_q, a_q) - a_q x_q \tag{3.13}$$

From $x_o^* > x_q^*$ and $a_o^* > a_q^*$, the second term on the LHS of (3.13) is greater than the second term on the RHS. For the equation to be satisfied, the first term on the LHS of the equation must be larger than the first term on the RHS. That is, from $e(x_o^*, a_o^*) > e(x_q^*, a_q^*)$, when the cap-and-trade policy is introduced, the emission intensity of the firm decreases.

Next, from (3.3) and (3.9), we have

$$c_a(x_o, a_o) = c_a(x_s, a_s) + rx_s \tag{3.14}$$

Since the second term of the RHS of (3.14) is positive, the first term on the LHS of the equation must be larger than the first term on the RHS. Considering the assumptions $c_{aa} \geq 0$ and $c_{xa} = 0$, $a_o^* > a_s^*$. That is, when the rate-based policy is introduced, the emission intensity of the firm decreases. From our earlier discussions, $x_o^* < x_s^*$; therefore, when the rate-based policy is introduced, the emission intensity of the firm improves but the output increases. Thus, it is not clear whether the emission increases can be compared when there is no restriction. We summarize the results in Table 3.1.

3.2.3 Industry level

In the previous subsection, we analyzed the difference between the cap-and-trade and rate-based policies at the individual firm level. In this subsection, we analyze the difference between the two policies at the industry level, aggregating the individual firms. The assumption of the cost function C at the industry level is the same as in the previous subsection. First, we intuitively describe each policy at the industry level from Figure 3.1.

Figure 3.1 presents a method to determine the level of output $X = \sum\limits_{i=1}^{N} x_i$ of the whole industry under the cap-and-trade policy. In the case of output and emissions with no regulation at point A, the profit is the value at point A′. Next, when the government sets $\bar{E} = \sum\limits_{i=1}^{N} e_i$ as the emissions target, the output and emission values to maximize profits are at point B and the profit is the value at point B′. In addition, we assume that the emission function of small slopes can be realized by changing the emission intensity through technology changes. The profit that can be achieved under the new emission intensity regime is the value at point C′. Therefore, this value is greater than the profit at point B′, and the emission intensity a (note that this is not the a at the individual firm level) of the entire industry is subject to change. Moreover, the profit curve is shifted to a lower level and the profit is reduced. Further, increasing the production level when there is no regulation also means that the profit is reduced. Therefore, when we assume that $C_{Xa} = 0$ with respect to the cost function at the industry level, introducing the cap-and-trade policy does not lead to the output becoming excessive.

Figure 3.2 shows a method by which to determine the output and emission levels of the whole industry under the rate-based policy. As shown earlier, when the output and emissions realized with no regulation are at point A, the profit is the value at point A′. Next, when the government sets $\bar{E}$ as the emissions target, we assume that the emission rate, such as the emission intensity, is set under the output at point A. If this does not change the emission intensity, the output and emission values necessary to maximize the profit under the rate-based policy are at point D, and the profit is the value at point D′. If the emission intensity improves through technology changes, the output and emission values can be obtained at point E and the profit is the value at point E′. By the profit magnitude relation at points D′ and E′, we can determine whether the emission intensity changes. Reducing the output level when there is no restriction means that the profit becomes less. Therefore, when the profit curve shifts downward, as in the figure, we find that introducing the rate-based policy does not lead to the output becoming too small.

In the case of no regulation, the emission intensity of the industry is a_o, and the profit function at the industry level can be shown as

$$\Pi_o(X_o) = pX_o - C(X_o, a_o) \tag{3.15}$$

Therefore, the profit maximization condition is

$$\frac{d\Pi_o(X_o)}{dX_o} = p - C_X(X_o, a_o) = 0 \tag{3.16}$$

Thus,

$$p = C_X(X_o, a_o) \tag{3.17}$$

Next, in the case of introducing emissions trading under the cap-and-trade policy, the profit function $\Pi_q(a_q)$ at the industry level can be written as shown below in order to constrain $\bar{E} = a_q X_q + B$, where B is defined as $\sum_{i=1}^{N} b_i$.

$$\begin{aligned}\Pi_q(a_q) &= pX_q - C(X_q, a_q) \\ &= p\frac{\bar{E} - b}{a_q} - C\left(\frac{\bar{E} - b}{a_q}, a_q\right)\end{aligned} \tag{3.18}$$

Since the emission function is a linear equation, the emission intensity at the industry level can be determined by the amount of output. From this, since the profit function can be written as an emission intensity function, the profit maximization condition is

$$\frac{d\Pi_q(a_q)}{da_q} = -p\frac{\bar{E}-B}{(a_q)^2} + C_X(X_q, a_q)\frac{\bar{E}-B}{(a_q)^2} - C_a(X_q, a_q) = 0$$

Thus,

$$p = C_X(X_q, a_q) - \frac{a_q}{X_q}C_a(X_q, a_q) \tag{3.19}$$

Then, when emission trading is introduced under the cap-and-trade policy, to satisfy the emission target, we impose the following restriction:

$$\begin{cases} E_s = a_s X_s + B \\ E_s = \bar{a} X_s \end{cases}$$

From this, the restriction becomes

$$X_s = \frac{B}{\bar{a} - a_s} \tag{3.20}$$

Since the industry as a whole is subject to constraint (3.20), the profit function $\Pi_s(a_s)$ can be denoted as

$$\begin{aligned} \Pi_s(a_s) &= pX_s - C(X_s, a_s) \\ &= p\frac{B}{\bar{a}-a_s} - C\left(\frac{B}{\bar{a}-a_s}, a_s\right) \end{aligned} \tag{3.21}$$

From (3.21), the profit maximization condition is

$$\frac{d\Pi_s(a_s)}{da_s} = p\frac{B}{(\bar{a}-a_s)^2} - C_X(X_s, a_s)\frac{B}{(\bar{a}-a_s)^2} - C_a(X_s, a_s) = 0$$

Thus,

$$p = C_X(X_s, a_s) + \frac{\bar{a}-a_s}{X_s}C_a(X_s, a_s) \tag{3.22}$$

Next, when we assume that $C_{Xa} < 0$, $C_{Xa} = 0$, and $C_{Xa} > 0$, by comparing the profit maximization conditions obtained, we can consider the output and emissions magnitude relation under each policy. First, we compare the output and emissions with no regulation under the cap-and-trade policy. When we compare (3.17) and (3.19), since the output price is assumed to be constant, the following equation is satisfied.

$$C_X(X_o, a_o) = C_X(X_q, a_q) - \frac{a_q}{X_q} C_a(X_q, a_q) \tag{3.23}$$

- $C_{Xa} < 0$

  Since the second term on the RHS of (3.23) is positive, $a_o > a_q$, and $C_{Xa} < 0$, the term on the LHS of the equation, is smaller than the first term on the RHS. To satisfy the equation, from the assumption that $C_{XX} > 0$, it is necessary that $X_o^* > X_q^*$ be satisfied. That is, when the cap-and-trade policy is introduced, the total output decreases.

- $C_{Xa} = 0$

  Since the second term on the RHS of (3.23) is positive, to satisfy the equation, it is necessary that the term on the LHS of the equation be larger than the first term on the RHS. Furthermore, from the assumption that $C_{Xa} = 0$, $X_o^* > X_q^*$. That is, when the cap-and-trade policy is introduced, the total output decreases.

- $C_{Xa} > 0$

  Since the second term on the RHS of (3.23) is positive, $a_o > a_q$, and $C_{Xa} < 0$, the term on the LHS of the equation, is smaller than the first term on the RHS. However, the magnitude relation of X_o^* and X_q^* is ambiguous.

Next, we compare the output and emissions under no regulation and the rate-based policy. From (3.17) and (3.22), we obtain

$$C_X(X_o, a_o) = C_X(X_s, a_s) + \frac{\bar{a} - a_s}{X_s} C_a(X_s, a_s) \tag{3.24}$$

- $C_{Xa} < 0$

  Since $\bar{a} > a_s$ and $C_a < 0$, the second term on the RHS of (3.24) is negative. Furthermore, since $a_o > a_s$ and $C_{Xa} < 0$, the term on the LHS of the equation is smaller than the first term on the RHS. In this case, the magnitude relation of X_o^* and X_s^* is ambiguous.

- $C_{Xa} = 0$

  Since the second term on the RHS of (3.24) is negative, to satisfy the equation, it is necessary that the term on the LHS of the equation be smaller than the first term on the RHS. From the assumption that $C_{Xa} = 0$, $X_o^* < X_s^*$. That is, when the rate-based policy is introduced, the total output increases.

- $C_{Xa} > 0$

  Since the second term on the RHS of (3.24) is negative, $a_o > a_s$, and $C_{Xa} > 0$, the term on the LHS of the equation, is larger than the first term on the RHS. To satisfy the equation, from the assumption that $C_{XX} > 0$, it is necessary that $X_o^* < X_s^*$ be satisfied. That is, when the rate-based policy is introduced, the total output increases.

We summarize the above results in Table 3.2. It is natural for the emissions target of the government to be realized under the cap-and-trade policy. In Table 3.2, the emissions shown under the rate-based policy give the emissions realized when the emissions rate is set by the government to satisfy $\tilde{a} = \frac{\bar{E}}{X_o^*}$. $\tilde{a}$ is the ratio of emissions to output under no regulation. Even under the rate-based policy, the government can help achieve the emissions target $\bar{a}$ by choosing the appropriate emissions rate $\bar{E}$. However, in order to set the optimum emission rate, the government should know the firms' marginal cost of emission intensity. Since it is expensive to obtain such information, we set this to $\tilde{a} = \frac{\bar{E}}{X_o^*}$, the emission rate established by the government.

Thus, when the emission rate is set to satisfy $\tilde{a}$, the emission target is greater than $\bar{E}$. This is because it can be said that $\tilde{E}_s = \tilde{a}X_s^* = \frac{\bar{E}}{X_o^*} \cdot X_s^* = \bar{E} \cdot \frac{X_s^*}{X_o^*}$ and $X_o^* < X_s^*$. Further, the assumption that $C_{Xa} < 0$ is based on the cost function; thus the marginal cost of production increases when improving the emission intensity. Further, from (3.17) and $C_{XX} > 0$, the marginal cost of production increases by improving the emission intensity. Thus, the vertex of the profit curve moves lower and leftward in Figures 3.1 and 3.2. Therefore, under the rate-based policy, by increasing the output, we cannot ultimately conclude whether to increase or decrease the output. Neither can we conclude whether to increase or decrease the emissions to be achieved. Similarly, when the cost function is $C_{Xa} > 0$, for the same reason, we cannot conclude whether to increase or decrease the output under the cap-and-trade policy.

3.3 Simulation

The emission rate shown in Table 3.2 is set by the government in a relatively simple manner. However, this is one of the emission rate-setting methods. In this section, we simulate how the total emissions change when the settings of the emission rate are changed. In addition, we examine the efficiency of each policy and compare the total profits realized at the industry level under the cap-and-trade and rate-based policies.

3.3.1 Relationship between emission rate settings and emissions

To satisfy the assumptions made so far, we consider the cost function as $C(X, a) = X^2 + a^2 - 2a + 2$, where $0 \leq a \leq 1$, the output price as $p = 1$, and the fixed emissions level as $B = 1$. Figure 3.3 shows the relationship between the emission rate $\bar{a}$ and emissions E.

Under the parameters identified, the optimal emissions level is $E_o^* = 1.5$ and the optimal emission rate is $a_o^* = \frac{E_o^*}{x_o^*} = 3$ with no regulation. From Figure 3.3, we find that the emissions level can be larger than that with no regulation depending on the emission rate set by the government. However, by lowering the emission rate set, the emissions level can be made smaller than in the case of no regulation. However, Figure 3.3 shows that unless the rate is set to levels that are half the emission rate under no restrictions, this does not lead to the desired result. The advantage of the emissions trading scheme is that the emissions target is likely to be achieved. However, when introducing emissions trading under the rate-based policy, the policy should carefully consider the influence of total emissions.

3.3.2 Comparison of efficiency between cap-and-trade policy and rate-based policy

Figure 3.4 shows the relationship between emissions and profits under the cap-and-trade and rate-based policies. In this subsection, we show that the cost function is $C(X, a) = X^2 + a^2 - 2a + 2$, where $0 \leq a \leq 1$, the output price is $p = 4$, and the fixed emissions level is $B = 1$. In the case of no regulation, the optimal emissions level is $E_o^* = 3$ and that of profits is $\pi_o^* = 3$. Figure 3.4 shows the profit levels under emissions trading with a variety of emission targets under the cap-and-trade and rate-based policies. From this figure, when we estimate the results to obtain the same emission levels, the rate-based policy shows lower profits compared to the cap-and-trade policy. Because the rate-based policy has a more constrained setup than the cap-and-trade policy, the efficiency of the policy is naturally reduced.

3.4 Conclusion

In this chapter, we compared the cap-and-trade and rate-based policies in emissions trading. Under the assumption of a linear relationship between output and emissions, we showed that output and emissions at the industry level tend to decrease under the cap-and-trade policy, and tend to increase under the rate-based policy. In addition, using numerical simulations, we analyzed the changes in emissions and profits when the settings of the emission rate are changed. When trying to achieve the same emissions target, we found that the profit under the rate-based policy is less than that under the cap-and-trade policy; in other words, efficiency under the rate-based policy is low.

Even under the rate-based policy, by setting the emission rate very low, it is possible to achieve emissions that are lower than in the case of no regulation. However, setting the emissions intensity level very low can lead to difficulties. This is because under rate-based regulation, there could be resistance to constraints on economic activities that could be considered burdensome to the industrial sector.

In the next chapter, we simulate a CGE analysis based on the model of this chapter. However, the parameters in Chapter Four do not seem to represent the technological level explicitly, unlike in this chapter, and since the parameters in the CES function represent the technological level, the conclusions of this chapter cannot be shown directly in the next chapter.

Table 3.1: Comparison of emissions and output at the individual firm level

	Output	Emission intensity	Emissions
Cap-and-trade policy	$-$	$-$	$-$
Rate-based policy	$+$	$-$	ambiguous

Note: The signs indicate a comparison with no regulation.

Table 3.2: Comparison of emissions and output at the industry level

Assumption	$C_{Xa} < 0$		$C_{Xa} = 0$		$C_{Xa} > 0$	
	Output	Emissions	Output	Emissions	Output	Emissions
Cap-and-trade	$-$	$\bar{E}$	$-$	$\bar{E}$	?	$\bar{E}$
Rate-based	?	?	$+$	$\tilde{E}_s > \bar{E}$	$+$	$\tilde{E}_s > \bar{E}$

Notes: The signs indicate a comparison with no regulation. $\tilde{E}_s$ is the emission level to be achieved when the rate-based policy is introduced, and the emissions rate is set to divide the government's emissions target $\bar{E}$ by the amount of output with no regulation.

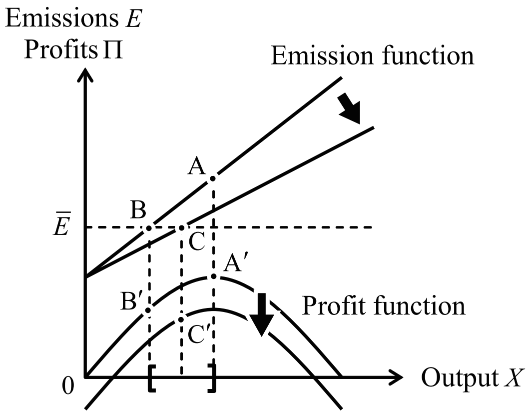

Figure 3.1: Illustration of cap-and-trade policy

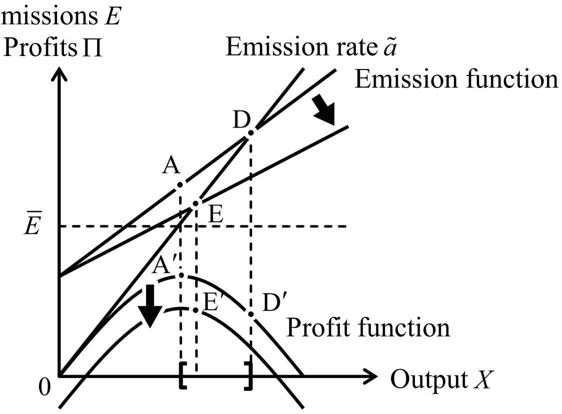

Figure 3.2: Illustration of rate-based policy

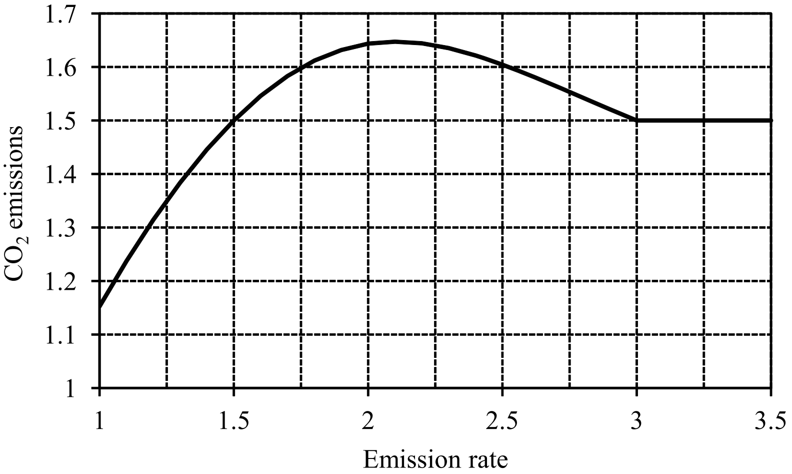

Figure 3.3: Relationship between the emission rate settings and CO_2 emissions

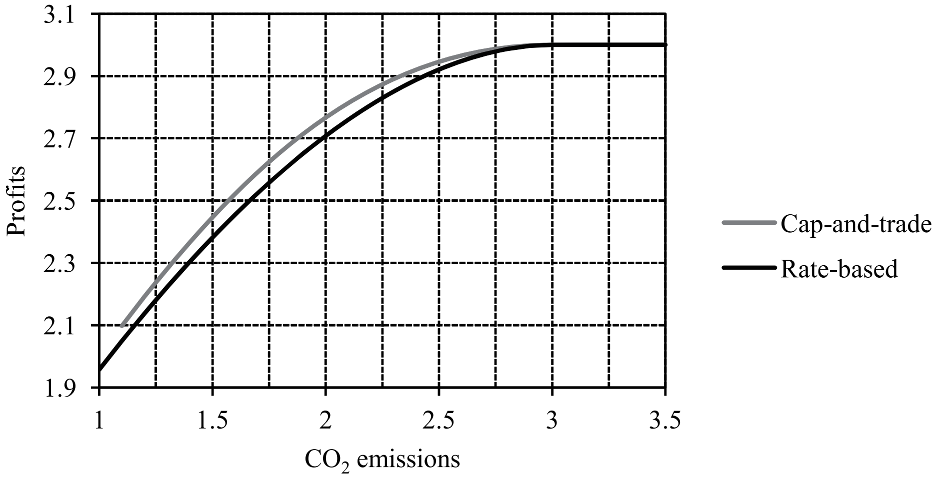

Figure 3.4: Comparison of profits under the cap-and-trade and rate-based policies

Chapter 4

Introduction of rate-based policy in Japan: A CGE analysis

4.1 Introduction

Although global efforts toward climate change mitigation have tended to focus on total emission amounts, some countries have set emission targets relative to their GDP. For example, China and India, which are likely to be major arbiters of global climate change in the next century, have set such targets. The Chinese government seeks to reduce carbon dioxide emissions as a proportion of GDP in 2020 by 40–45% compared to the 2005 proportion. India has a similar policy to decrease its carbon intensity in 2020 by 20–25% compared to that in 2005.

The effects on carbon emissions of linking emissions to GDP values (herein referred to as the emission rate) cannot be determined, as revealed in Fisher (2003) and Boom and Dijkstra (2009). These theoretical studies investigate the effects of a rate-based policy that aims to attain a particular emission rate under the emissions trading scheme. Fischer (2003) shows that the total amount of emissions tends to increase with the rate-based policy compared to the case where a cap-and-trade policy and the rate-based policy are used together. Boom and Dijkstra (2009) show that the amount of output in the rate-based policy increases compared to that in the cap-and-trade policy in the short term and long term. While these studies suggest that a rate-based policy cannot restrict total emissions and does not suppress economic growth, the extent of such a policy's impact has not been scrutinized empirically and quantitatively.

This study investigates the impact of a rate-based policy in Japan using computable general equilibrium (CGE) analysis. While Japan's target for greenhouse gas emissions are based on the total emission amount, introducing a rate-based target similar to those of China and India is a topic of discussion. As it allows an increase in production, the introduction of a rate-based policy is preferred by industries and trade unions likely to be affected by the government's climate policy. A report by the Japanese Ministry of the Environment on the introduction of the domestic cap-and-trade policy also included to the possibility of introducing a rate-based policy (Japanese Ministry of the Environment 2010).

The results of this study suggest that within the framework of the CGE analysis, the rate-based policy can reduce firms' emissions at a greater emission rate than that specified by regulation in the short run. However, in the long run we show that because of the effects of technological progress and capital accumulation, there is a possibility that with the introduction of the rate-based policy, emission and production may increase compared to the case with no regulations. In addition, we show that the rate-based policy tends to reduce the rate of production more evenly across sectors. In contrast, the cap-and-trade policy can increase the output of sectors that emit less carbon dioxide and thereby promote a structural shift in the economy.

The remaider of this chapter is organized as follows. Section 4.2 introduces the model. Section 4.3 explains the data used and the method of calibration. Section 4.4 presents simulation results for the assumption that the rate-based policy is introduced to attain a 25% reduction in the emission rate from that in the base case and compares the rate-based policy and the cap-and-trade-policy using the static model. Section 4.5 examines the effect of the rate-based policy in the long-run on output and emissions by using dynamic CGE analysis. Section 4.6 presents our concluding remarks.

4.2 Model

4.2.1 Static model

We develop a static CGE model for the Japanese economy based on 2005 data. The model is composed of 34 sectors, which are listed in Table 4.1.

It is assumed that three sectors—crude petroleum, coking coal, and natural gas (foss), petroleum and coal products (p_c) and gas and heat supply (ghs)—produce energy goods and that other sectors produce non-energy goods. Firms emit carbon dioxide from their production process as they use energy goods, while households emit carbon dioxide from their consumption of energy goods.

The model has three economic agents: a household, firms and the government. In this analysis, a representative household that owns exogenously given capital and labor is assumed. The household provides capital and labor to firms and, using the income obtained, it saves money and purchases goods. It saves at a constant rate and gains utility from the consumption of goods.

Figure 4.1 shows that the household gains utility from the consumption of energy and non-energy goods. The number in Figure 4.1 denotes the elasticity of substitution, which is assumed to equal 1. The household determines its consumption of goods so as to maximize its utility under budget constraints.

Figure 4.2 shows the production structure of firms. A firm produces a primary production factor by using capital and labor, then produces a secondary production factor by using energy goods, and finally produces a final product by using non-energy goods. It is assumed that carbon dioxide emissions occur because of the use of energy goods. To maximize profits, firms determine the production quantity in this production structure.

Then, the final products are transformed into domestic goods and export goods. The domestic goods are transformed into Armington composite goods in combination with imported goods (Takeda 2007). The assumption about imperfect substitution between imported and domestic goods is called Armington's assumption (Armington 1969). The elasticity of substitution between domestic goods and imported goods and the elasticity of transformation between domestic goods and export goods are set at 4. The value of the elasticity of substitution in our model comes from the reference value in Takeda (2007).

In addition, the government is supposed to collect three types of tax: production tax, tariff, and tax on household income. It is assumed that the government consumes or saves the tax revenue at a constant rate.

For simplicity, a small country is assumed. As a result, the foreign currency prices of imported and exported goods are constant. As for the balance of payments, the amount of the current account imbalance is constant. In addition, the current account deficit is interpreted as foreign savings.

From the above settings, government spending, household consumption, and the current account deficit are determined, and as a result, the total amount of savings is determined. The total amount of savings is spent on investment goods at a constant rate.

4.2.2 Dynamic model

In this paper, we use a recursive dynamic model. Each economic agency optimizes its behavior in each period and does not foresee events such as policy changes. Therefore, they would not decide their behavior in the current time period according expectations of future events. While the basic structure of the dynamic model is the same as that of the static model, we add a capital accumulation term:

$$K_{t+1} = (1 - \delta)K_t + \theta I_t$$

where K_{t+1} is capital accumulation in period $t+1$, δ is the depreciation rate of capital, and I_t is investment in period t. Here, θ is a parameter for adjusting the divergence of the capital accumulation so that K_t matches the actual amounts of capital accumulation listed in the input-output tables. There are several reasons for such adjustments. Capital in this study is obtained by summing the capital consumption allowances and operating surplus in the input–output tables. However, it merely represents the rental cost of capital in one year, so this amount is undervalued compared to the actual capital accumulation. For these reasons, it is necessary to use θ in the CGE model. By dividing the amount of capital accumulation in the input–output table by the real amount, we can calculate θ and match the scale. We use a depreciation rate of 0.064, which was estimated by Takeda (2007).

4.3 Data and calibration

In CGE analysis, data are taken from a base year and a simulation is performed using these benchmark data. The benchmark data are made up of economic data and emissions data.

In the present study, the data comprise economic data and emissions data. The economic data comprise data on intermediate inputs, final consumption, investment, government expenditure, and exports and imports taken from *2005 Input–output Tables for Japan* (Statistics Bureau, Japanese Ministry of Internal Affairs and Communications 2009). In addition, we use data on government savings from *Income and Outlay Accounts Classified by Institutional Sector in 2005* (Economic and Social Research Institute 2007). We construct a social accounting matrix from these data for the CGE analysis. Emissions data are taken from the consumption and input of energy goods from the 3EID database (Nansai et al. 2012).

In addition, three data sets are used in the model: the capital accumulation amount in 2005, the real GDP as a target for 2020, and carbon dioxide emissions in 2020 under the business-as-usual (BaU) scenario.

The value of the capital accumulation in 2005 was 1,446 trillion yen (RIETI 2012). This value is used to determine theta.

The real GDP and carbon dioxide emissions in 2020 under the BaU scenario are used to derive the path of the benchmark in the dynamic model. We adjust the rates of technological progress and population growth so as to attain the real GDP and carbon dioxide emissions in 2020. This will be described in more detail in the next section. The data for the real GDP in 2020 were obtained from the annual GDP (ESRI 2013). We use a 2% real GDP growth rate averaged through to 2020, which the Abe administration has set as a growth strategy. The amount of the real GDP in 2020 is 608.9 trillion yen. In addition, we assume carbon dioxide emissions under the BaU scenario in 2020 to be 1,076 million tons (Ban 2013).

In a CGE analysis, calibration refers to a model estimation method that exactly reproduces the initial equilibrium of the estimated model. From the social accounting matrix, we can obtain the parameters for the production function, utility function, saving rate, tax rate, income, and emissions coefficient.

As data in the social accounting matrix are only expressed in terms of the value added, we must separate the value data into quantity and price data. For convenience, it is assumed that labor is the numeraire good, and the price for all production factors and all products take a value of one in the base year. Numerical computation is done with GAMS (General Algebraic Modeling System) and its solver, PATH.

4.4 Static CGE analysis

4.4.1 Impacts of rate-based policy

Using the CGE model, we analyze the characteristics of emission regulations with the rate-based policy. When emissions trading under the rate-based policy is introduced, the profit function of the representative firm in the sector is represented as follows:

$$\max_{y_1, y_2} \quad P_x x - \{P_{y_1} y_1 + P_{y_2} y_2 + P_{CO_2}(h_{y_2} y_2 - \alpha x)\} \tag{4.1}$$

where x is the output, y_1 is the input of non-energy goods, y_2 is the input of energy goods, h_{y_2} is the emission coefficient, and α is the emission rate. P_x, P_{y_1}, P_{y_2}, and P_{CO_2} represent the prices of x, y_1, y_2, and emission permits, respectively. We assume that emission regulations are imposed only on firms and not on the household. A firm's carbon dioxide emissions are represented by $h_{y_2} y_2$, while αx denotes the initially allocated emission permits. When the amount of emissions is larger than that allowed under the allocated emission permits ($h_{y_2} y_2 - \alpha x > 0$), the firm must be a buyer of permits at the permit price P_{CO_2}. In contrast, when the amount of emissions is smaller than the allocated emission permits ($h_{y_2} y_2 - \alpha x < 0$), the firm must be a seller of permits. Under the rate-based policy, the price of permits is determined by the demand and supply for emission permits as follows:

$$\sum_i h_{y_{2i}} y_{y_{2i}} = \sum_i \alpha_i x_i \tag{4.2}$$

where i is the index of the firm. The LHS of (4.2) denotes the total demand for emission permits and the RHS denotes the total supply. P_{CO_2} is determined so as to satisfy this equation. In the rate-based policy simulation, the business-as-usual (BaU) emission rate is calculated by dividing the BaU emissions by the BaU output. A rate-based policy is expressed by multiplying the BaU emission rate by an amount less than one. For example, a rate-based policy that requires a 10% reduction in the emission rate is expressed by multiplying the BaU emission rate by 0.9. This means that the firm must reduce emissions by 10% from the BaU emissions when it maintains its output at the BaU level.

Table 4.2 shows the results of a simulation for a 25% reduction in the emission rate. Note that the policy requires a 25% reduction from the BaU emission rate. Since the BaU data are for the Japanese economy in 2005, the policy refers to emissions and output in 2005. After a 25% reduction in the emission rate, emissions from firms are reduced by more than 25%, with the actual value being −26.6%. Because the rate-based policy in this simulation is imposed only on firms, the emission reduction from the household is small, 0.59%. As a result, the total emission of carbon dioxide is reduced by 22.9%.

The total supply of emission permits is $\sum_i \alpha_i x_i$. By requiring α_i to be reduced by 25%, the output also becomes less than the BaU output, and emissions are reduced by 26.6%—that is, at a rate greater than that required by the rate-based policy. Even though the rate-based policy seems to allow firms to increase emissions and output, such increases are not possible in the short run. Because capital and labor are limited, the economy does not grow beyond the BaU. Thus, emissions from firms are reduced by 26.6%—that is, at a rate greater than the emission rate (25%) required by the rate-based policy in this analysis.

The impact of requiring a lower emission rate on carbon dioxide emissions and on the permit price are shown in Figures 4.3 and 4.4, respectively. By requiring a lower emission rate, emissions are reduced and the permit price increases because of an increase in the marginal abatement cost.

Figure 4.5 shows the realized emission rate in each sector after a 25% reduction in the emission rate. Although the reduction in the total emission rate is 25%, such reduction varies across sectors. This rate is significantly reduced in sectors such as pulp, paper, and wood products (pulp), ceramic, stone, and clay products (nmm), and iron and steel (iron). This suggests that the marginal cost of reducing the emission rate is relatively lower in these sectors.

4.4.2 Comparison of cap-and-trade policy and rate-based policy

In this section, we compare the rate-based policy with the cap-and-trade policy, assuming that both policies reduce the total amount of emission by 25% from the 1990 levels. The policy settings in this section differ from those in the previous section. The reference year of policies examined in this section is 1990, while that in the previous section is 2005. Policies in this section target the total amount of emission, while that in the previous section focus on firms' emissions. However, as before, we assume that emission regulations are imposed only on firms and not on the household in both policies.

When emissions trading using the cap-and-trade policy is introduced, the profit function of the firm is represented as follows:

$$\max_{x} \quad P_x x - (P_{y_1} y_1 + P_{y_2} y_2 + P_{CO_2} h_{y_2} y_2) \tag{4.3}$$

We assume that emission permits are auctioned by the government and that the household receives the auction revenue. Under the cap-and-trade policy, the permit price P_{CO_2} is determined by the demand and supply of emission permits using the following equation:

$$\sum_i h_{y_2 i} y_{2i} = \bar{E} \tag{4.4}$$

where $\bar{E}$ is the total supply of permits offered by the government. The LHS of (4.4) denotes the total demand for emission permits and the RHS denotes its total supply. P_{CO_2} is determined according to this equation.

Table 4.3 shows the results. As shown in this table, in order to achieve the same target of total emissions, the real GDP under the rate-based policy is lower than that under the cap-and-trade policy. This means that the rate-based policy is inefficient. The permit price and the marginal abatement cost are higher under the rate-based policy than under the cap-and-trade policy. Although the target in this section is the reduction of total emissions, the rate-based policy focuses on the emission rate. Since the rate-based policy is a mixture of policies on emissions and output, it induces an inefficient allocation of resources to attain the total emission target.

The reduction of emissions by 25% compared to 1990 levels means a reduction of 28.8% compared to 2005 emission levels. That is, total emissions from firms and the household are regulated to be 28.8% lower than the 2005 levels. Emissions from firms are reduced by 32.9% with the cap-and-trade policy and by 33.4% with the rate-based policy. Emissions from the household are reduced by 4.6% with the cap-and-trade policy and by 1.1% with the rate-based policy. Although the household is not required to reduce emissions, its emissions decrease because its consumption decreases because of the reduction of the output of firms.

Figures 4.6 and 4.7 show the changes in output for each sector under the cap-and-trade policy and the rate-based policy, respectively. Under both policies, the output of the three sectors that produce energy goods, crude petroleum, coking coal and natural gas (foss), petroleum and coal products (p_c) and gas and heat supply (ghs), are significantly and negatively affected. In contrast, the output of iron and steel (iron) and electricity (ely) are reduced significantly with the cap-and-trade policy, whereas they are reduced to a lesser extent with the rate-based policy. Under the rate-based policy, large sectors such as iron and steel and electricity can obtain many permits free of charge from the government according to their BaU emission rate, and hence, the drop in their output is small. In this way, industry must reduce output under the cap-and-trade policy, but it does not significantly reduce output under the rate-based policy.

Reductions in output are more evenly distributed among sectors with the rate-based policy than with the cap-and-trade policy. Comparing Figures 4.6 and 4.7, it is apparent that the decrease in output with the rate-based policy is smaller than that with the cap-and-trade policy. This can be understood by arranging equation 4.1 as follows:

$$\max_{x} \quad (P_x + \alpha P_{CO_2})x - (P_{y_1}y_1 + P_{y_2}y_2 + P_{CO_2}h_{y_2}y_2). \tag{4.5}$$

Since αP_{CO_2} in the first term of equation (4.5) is positive, the rate-based policy has the features of a subsidy for output while imposing a tax on emissions. For this reason, the reduction rate of output under the rate-based policy can be smaller in many sectors than that under the cap-and-trade policy.

In three sectors, information and communication electronics equipment (iteq), electronic components (semi), and precision instruments (preq), output increases under the cap-and-trade policy but decreases under the rate-based policy. Carbon dioxide emissions from these sectors are very small. Of the total emissions in Japan in 2005, the share of iteq is 0.03%, semi is 0.25%, and preq is 0.03%. Therefore, with the introduction of the cap-and-trade policy, demand for these products increases. This suggests the possibility of changes in the industrial structure toward a low-carbon economy. The cap-and-trade policy can promote growth in sectors related to information technology while the rate-based policy does not have such an effect.

We summarize our results as follows. The decrease in output tends to be more evenly distributed under the rate-based policy than under the cap-and-trade policy. Regarding the sectors with lower carbon dioxide emission (iteq, semi, and preq), output increases with the cap-and-trade policy but decreases with the rate-based policy. Since the rate-based policy aims to reduce emissions by setting the emission rate, it is thus inefficient in reducing emissions. As a result, the real GDP under the rate-based policy is smaller than that under the cap-and-trade policy.

4.4.3 Sensitivity analysis

We conduct a sensitivity analysis to check the robustness of the results. We change the elasticity of substitution $\sigma_E = 0.5$ in the input of energy goods to $\sigma_E = 0.3$ or 0.7 and analyze the change in the static analysis results.

Table 4.4 shows the result in the case of a 25% reduction of the emission rate. From this table, we can see that emissions fall by more than 25% regardless of the value of σ_E. Thus, the results in Section 4 are robust to a change in the elasticity of substitution. When the elasticity of substitution σ_E is large, the real GDP is large and the emission reduction is small. This is because production efficiency increases.

Table 4.5 shows the comparison of the cap-and-trade policy and the rate-based policy when σ_E changes. From Table 4.5, we note that the reduction in the real GDP under the rate-based policy is higher than that under the cap-and-trade policy regardless of the value of σ_E. Thus, this result is the same as that in Section 4.5. Further, when σ_E is large, the real GDP becomes larger. This is the same result as that in Table 4.4. The lower permit price indicates that the marginal abatement cost is lower because of the increase in production efficiency. The permit price changes significantly according to σ_E, suggesting that technological change would have a significant impact on the cost of climate change mitigation.

4.5 Dynamic CGE analysis

4.5.1 Business as usual

In this subsection, we develop a recursive dynamic model without emission regulation (BaU scenario). First, we determine the real GDP and emissions in 2020 in the BaU scenario.

The real GDP of the BaU in 2020 is calculated as follows. By using the real GDP in 2012 obtained from the ESRI (2013) and the "growth strategy" of the Abe administration in Japan, the real GDP in 2020 is calculated such that the average real GDP growth rate is 2% up to 2020. As a result, the real GDP in 2020 is estimated as 608.9 million yen.

A figure of 1,076 million tons of CO_2 emissions in 2020 under the BaU scenario is sourced from Ban (2012). A model is created so that these values are realized in 2020. In CGE analysis, it is assumed that technological progress includes increases in labor productivity and the input efficiency of energy goods, and we create a dynamic model to fit the BaU scenario (Jacoby et al. 2004; Sue Wing 2010). Therefore, the rate of increase in labor productivity λ_L and the parameter φ that relates to the input efficiency of energy goods are introduced into the model.

By expressing labor productivity as an increase in the endowment of labor L_t, we can formulate the following:

$$L_{t+1} = (1 + \lambda_L)L_t$$

Moreover, the input efficiency of energy goods is included in the production function as follows:

$$x = a\left[\beta_1 y_1^{\frac{\sigma-1}{\sigma}} + \beta_2(\varphi y_2)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

where a, β_1, and β_2 are the parameters in the CES production function, y_1 is the input of non-energy goods, y_2 is the input of energy goods, and σ is the elasticity of substitution. φ changes according to the following equation:

$$\varphi_{t+T} = (1 + \lambda_E)^T \varphi_t$$

where φ_t is φ in year 2005 and it is assumed that $\varphi_t = 1$. Then, after T years it is φ_{t+T}. In this way, we derive Figure 4.8, which shows that the real GDP is 608.9 trillion yen and emissions are 1,076 million tons of CO_2 in 2020 when λ_L is 0.24% and λ_E is 4.6%.

4.5.2 Comparison of cap-and-trade policy and rate-based policy

In this subsection, we compare emissions trading under the cap-and-trade policy and under the rate-based policy using the dynamic model developed in the previous subsection. The steps of the analysis are as follows:

Step 1 Under the cap-and-trade policy, we calculate the reduction rate of emission allowances to achieve the 25% emissions reduction from 1990 levels in 2020.

Step 2 Under the rate based policy, the reduction rate obtained in Step 1 is used as the reduction rate of the emission rate for each sector.

Step 3 We compare the emissions, permit price and real GDP attained under both policies.

In Step 1, it is calculated that the reduction rate of emissions should be 34.8% compared to 2005 in order to achieve the 25% emissions reduction from 1990 levels in 2020. It is assumed that the emission reduction in each year is the same. This value is higher than 25% because the emission target aims to reduce total emissions including emissions from households, while the regulation is applied only to firms. In Step 2, each sector applies the value obtained in Step 1, 34.8%, to the decrease in the emission rate in 2020. It is assumed that the reduction of the emission rate in each year is the same. In other words, the emission rate of each sector is reduced by 34.8% compared to 2005. We show the transition of emissions, permit price and real GDP from 2005 to 2020 in Figures 4.9, 4.10, and 4.11, respectively.

Figure 4.9 shows that it is possible to achieve the goal of a 25% reduction from 1990 levels in 2020 under the cap-and-trade policy, but it is difficult to attain this under the rate-based policy. Under the rate-based policy, emissions are reduced more than in the BaU scenario but not as much as under the cap-and-trade policy. Figure 4.10 suggests that the permit price is low under the rate-based policy, since the incentive to reduce emissions is weak and the demand for permits is low. Figure 4.11 suggests that the rate-based policy does not reduce the real GDP greatly. On the other hand, the real GDP falls significantly under the cap-and-trade policy. This is considered to be the reason for the belief that rate-based regulation does not suppress economic growth.

4.5.3 Effects of technological progress in rate-based policy

In the previous subsection, we did not consider technological progress in the BaU scenario. In this subsection, we suppose that technological progress follows from environmental regulations. This means that we consider the introduction of the rate-based policy to induce the improvement of labor productivity or input efficiency.

Under the BaU scenario, the rate of increase in labor productivity λ_L is set to 0.24% per year, and the parameter λ_E relating to the input efficiency of energy goods is set to 4.6%. Figures 4.12 and 4.13 show that varying λ_L and λ_E under the rate-based policy leads to different emissions paths.

In Figure 4.12, we exogenously change the rate of technological progress in labor productivity from 0.24% to 2%. When labor productivity increases, the production cost decreases and output increases. As a result, emissions increase, and therefore the graph shows an upward trend. When λ_L is more than 0.53% in spite of the introduction of the rate-based policy, emissions increase more than in the BaU scenario. This feature is not seen under the cap-and-trade policy. Under the cap-and-trade policy, even if similar technological progress occurs, a 25% emission reduction is realized because a cap is put on total emissions.

In Figure 4.13, we analyzed the case where the parameter for the input efficiency of energy goods was increased from 4.6% to 20%. As this parameter is increased, it becomes increasingly possible to produce more goods from less energy. Therefore, the increase of λ_E decreases emissions. When λ_E is more than 8.7%, a 25% emission reduction can be achieved. Improvement in λ_L and in λ_E have different effects on emissions under the rate-based policy: the former increases emissions, while the latter reduces emissions.

4.6 Conclusion

This study simulated the introduction of emissions trading in Japan by the rate-based policy. In the static CGE analysis, it is shown that emissions from firms are reduced by 25% or more when the emission rate is required to be reduced by 25% from the base year. This result is explained by the fact that the reduction of the emission rate and output occur simultaneously. In the short run, technological innovation is not considered and the emission reduction effect is large.

Furthermore, we compared the rate-based policy with the cap-and-trade policy assuming identical levels of emissions reduction. The result suggests that the rate-based policy reduces the real GDP to a greater extent than the cap-and-trade policy. This is because the rate-based policy forces a reduction in emissions even in the high marginal abatement cost sector.

The rate-based policy does not promote a reduction in emissions for sectors with a higher BaU emission rate even though these sectors are large and have a relatively low marginal abatement cost. In contrast, the cap-and-trade policy forces a significant emission reduction for sectors that have a low marginal abatement cost. Our results suggest that the rate-based policy is inferior in terms of efficiency, but is favorable in terms of ensuring that the burden of emission reduction is shared equally among sectors.

When considering capital accumulation, technological progress (e.g., the improvement of labor productivity and the input efficiency of energy goods), output and emissions can increase since the rate-based policy does not restrict total emissions. In this paper, we found that there is a possibility that emissions would increase with the introduction of the rate-based policy even if the rate of increase of labor productivity is set at a relatively low level.

Table 4.1: Sector identifiers (34 sectors)

Identifier	Sector description
agr	Agriculture, forestry, and fishery
foss	Crude petroleum, coking coal, and natural gas*
omn	Other mining
food	Beverages and foods
tex	Textile products
pulp	Pulp, paper, and wooden products
chem	Chemical products
p_c	Petroleum and coal products*
nmm	Ceramic, stone and clay products
iron	Iron and steel
nfm	Non-ferrous metals
fmp	Metal products
mch	General machinery
eleq	Electrical products
iteq	Information and communication electronic equipment
semi	Electronic components
treq	Transportation equipment
preq	Precision instruments
omf	Other industrial products
cns	Construction
ely	Electricity
ghs	Gas and heat supply*
wat	Water supply and waste disposal services
trd	Commerce
fin	Finance and insurance
dwe	Real estate
trp	Transport
itc	Information and communications
pubs	Public administration
edu	Education and research
mhs	Medical service, health, social security, and nursing care
opub	Other public services
bsrv	Business services
psrv	Personal services

Note: * indicates energy goods.

Table 4.2: Emissions with a −25% emission rate

Total CO_2	Emissions (firm)	Emissions (household)	Permit price	Real GDP
−22.9%	−26.6%	−0.59%	1,327 yen	−0.45%

Note: Comparison with the actual 2005 values.

Table 4.3: Comparison of cap-and-trade policy and rate-based policy

	Emissions (firm)	Emissions (household)	Permit price	Real GDP
Cap-and-trade	−32.9%	−4.6%	1,434 yen	−0.64%
Rate-based	−33.4%	−1.1%	2,096 yen	−0.74%

Note: Real GDP indicates the change from that under the BaU.

Table 4.4: Sensitivity analysis: −25% emission rate

Elasticity of substitution	$\sigma_E = 0.3$	$\sigma_E = 0.5$	$\sigma_E = 0.7$
Emissions (firm)	−27.6%	−26.6%	−26.3%
Real GDP	−0.84%	−0.45%	−0.34%

Note: Comparison with the actual 2005 values.

Table 4.5: Sensitivity analysis: comparison of policies

	Cap-and-trade policy			Rate-based policy		
	$\sigma_E = 0.3$	$\sigma_E = 0.5$	$\sigma_E = 0.7$	$\sigma_E = 0.3$	$\sigma_E = 0.5$	$\sigma_E = 0.7$
Real GDP	−0.89%	−0.64%	−0.52%	−1.35%	−0.74%	−0.54%
Permit price	2,659 yen	1,434 yen	943 yen	6,020 yen	2,096 yen	1,202 yen

Note: Real GDP indicates the change from that under the BaU.

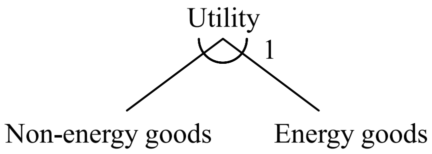

Figure 4.1: Consumption structure

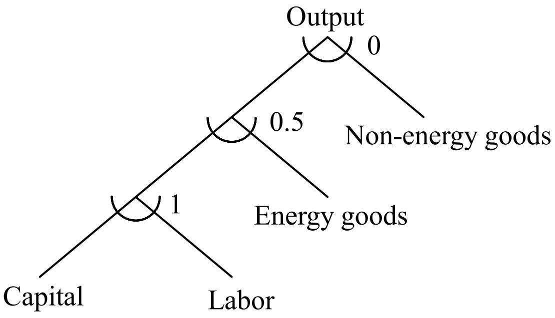

Figure 4.2: Production structure

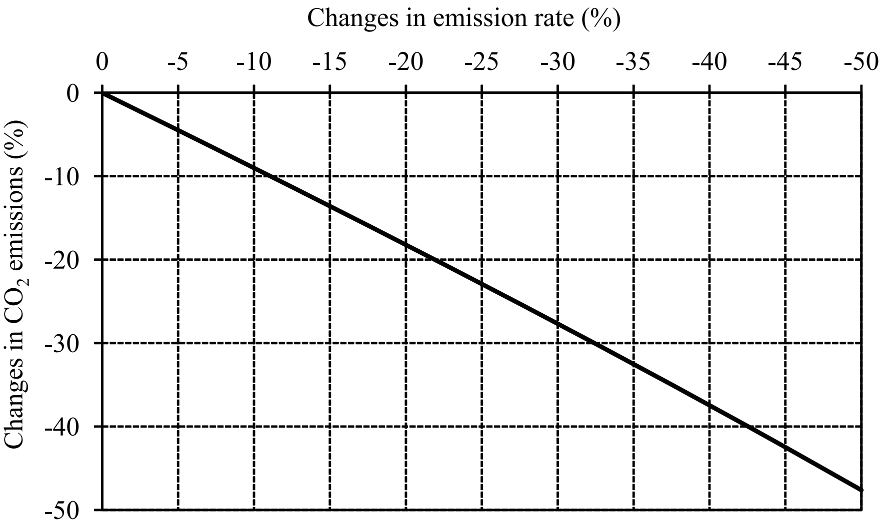

Figure 4.3: Changes in emission rate and CO_2 emissions

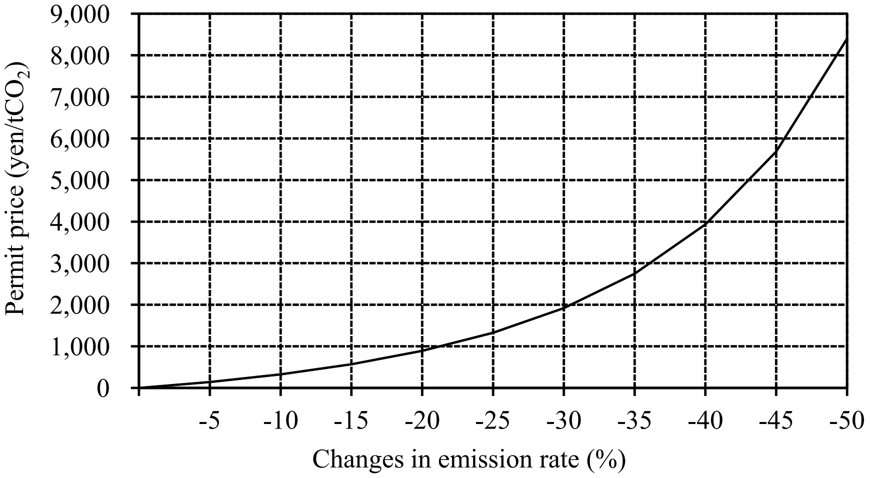

Figure 4.4: Changes in emission rate and permit price

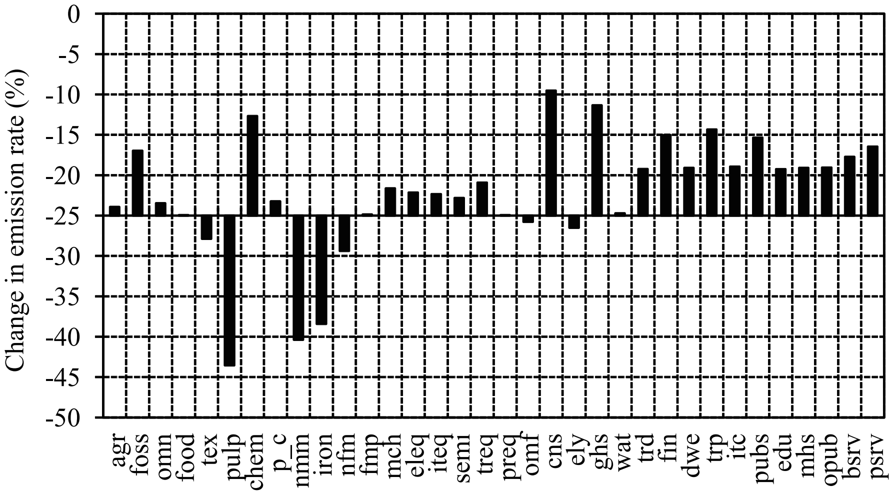

Figure 4.5: Changes in realized emission rates (−25% emission rate)

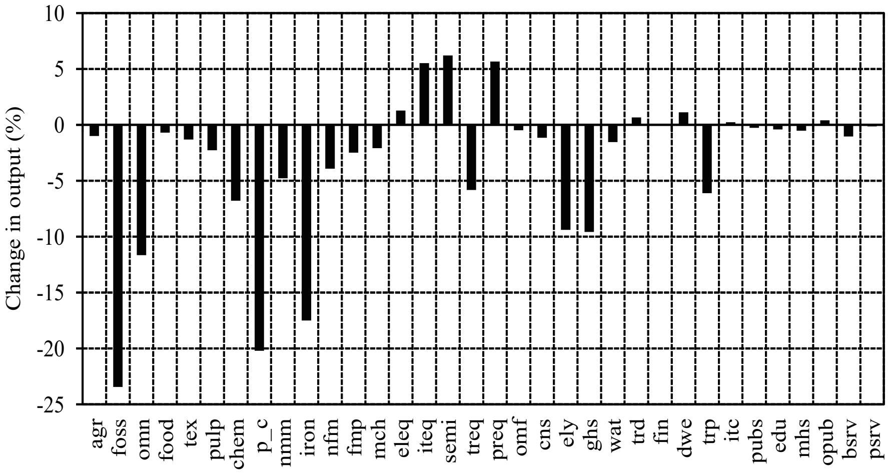

Figure 4.6: Changes in output under cap-and-trade policy (−25% total emissions)

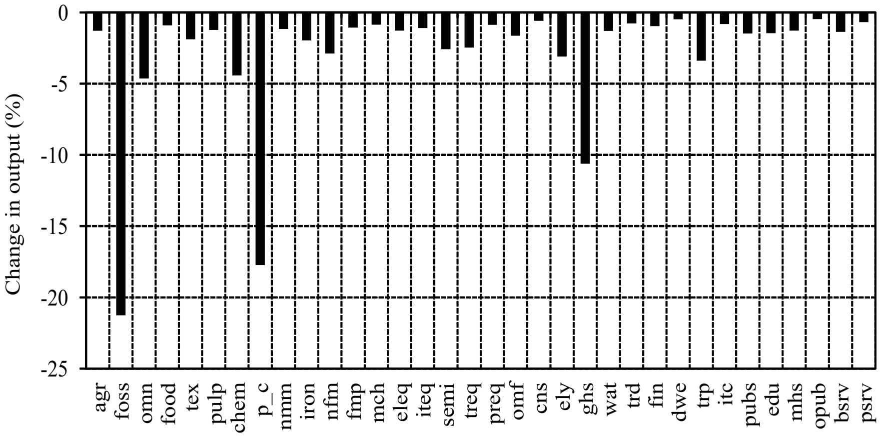

Figure 4.7: Changes in output under rate-based policy (−25% total emissions)

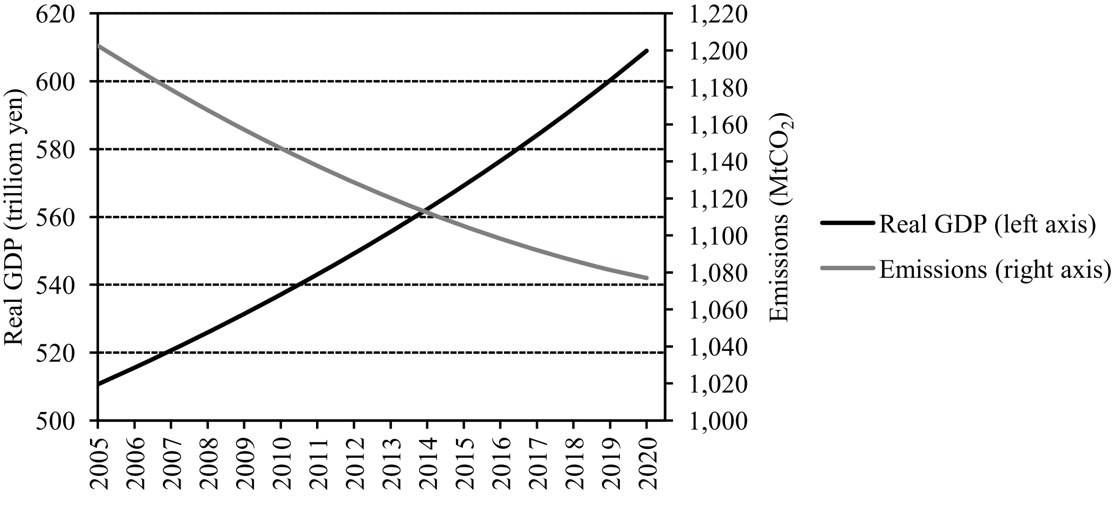

Figure 4.8: The real GDP and CO_2 emissions in BaU

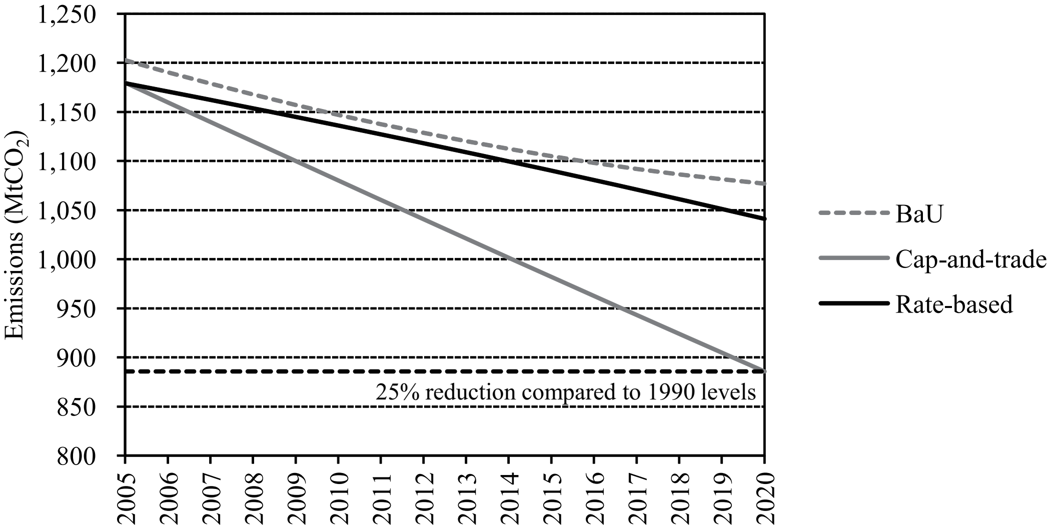

Figure 4.9: Comparison of CO_2 emissions between cap-and-trade policy and rate-based policy

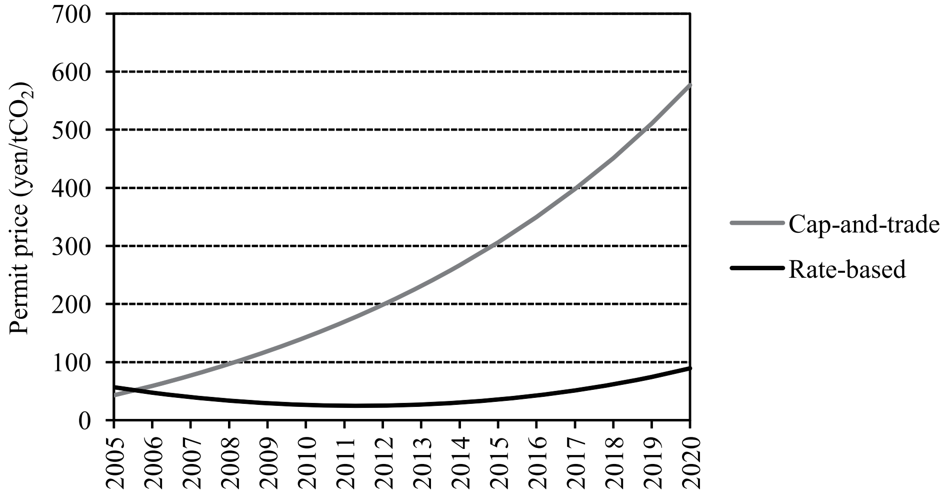

Figure 4.10: Comparison of permit price between cap-and-trade policy and rate-based policy

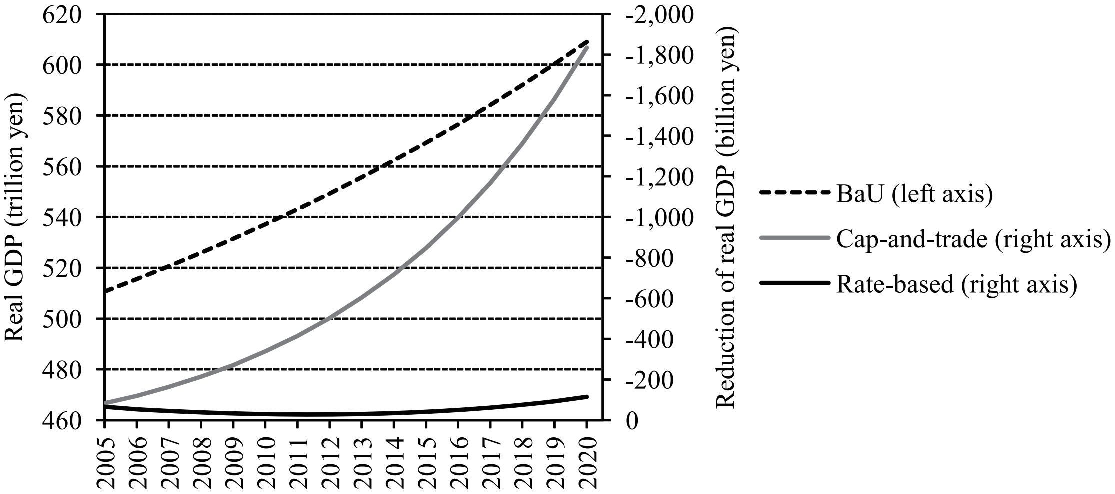

Figure 4.11: Comparison of the real GDP between cap-and-trade policy and rate-based policy

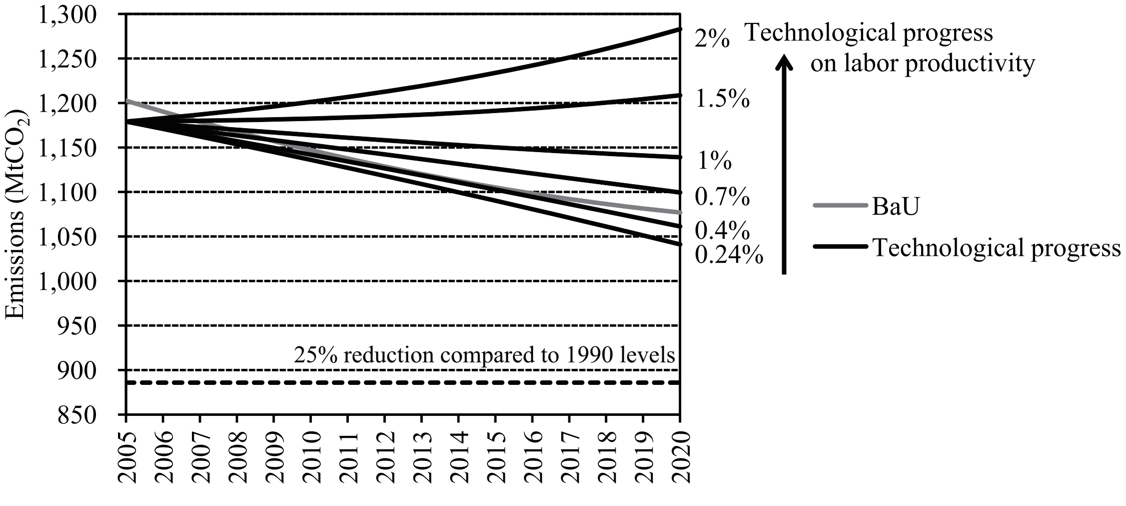

Figure 4.12: Effects of technological progress on labor productivity (rate-based policy)

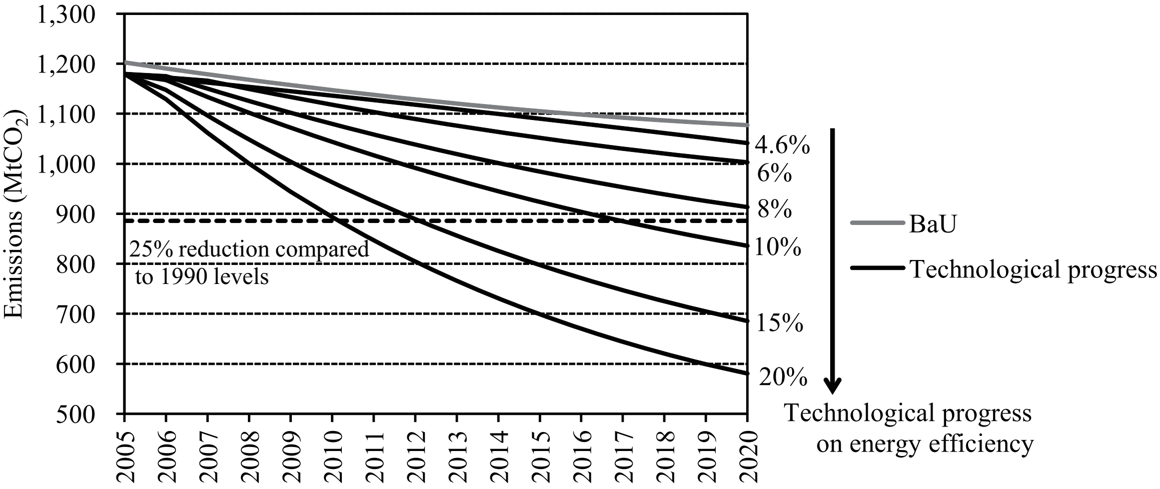

Figure 4.13: Effects of technological progress on energy efficiency (rate-based policy)

Chapter 5

Conclusion

In Chapter Two, we investigated the cost incurred when an incorrect target is set for direct rate-based regulation. An incorrect target is considered to be anything other than the optimal emission rate. First, we estimated the marginal abatement cost function for four industries, iron and steel; chemical; ceramic, stone, and clay; and pulp and paper, which account for most of the carbon dioxide emissions in Japan. Using the marginal abatement cost function that we obtained, we analyzed the introduction of emissions trading using the cap-and-trade policy in these industries. In addition, we calculated the emission rate as the ratio of emissions to the value added of each industry. When the government can directly regulate such emission rates, it is possible to achieve optimal resource allocation so that marginal abatement costs are equalized. However, in practice, it would be difficult for the government to accurately estimate the marginal abatement cost of each industry. Therefore, we analyzed cases in which the government sets the wrong emission rate to determine how much loss would occur for these four industries. Throughout Chapter Two, we noted that there is a possibility of generating additional costs using direct rate-based regulation.

In Chapter Three, we compared the cap-and-trade policy with the rate-based policy for emissions trading. Under the assumption that there is a linear relationship between output and emissions, we showed that there is a tendency for output and emissions to increase after the rate-based policy is implemented. This indicates that there is a possibility that emission targets will not be achieved using the rate-based policy. However, by setting a more severe emission rate, it was shown that it is possible to achieve the emission rate targets. In order to achieve the same emissions targets, we found that the profit in the rate-based policy is less than in the cap-and-trade policy.

In Chapter Four, we analyzed a feature of the rate-based policy and the difference between it and the cap-and-trade policy. It was noted that rate-based regulation has characteristics that make it difficult to suppress economic growth, and there is a possibility the emissions will increase. However, we also showed that emissions can be reduced more in the short term. Furthermore, we found that because of the effects of technological progress and capital accumulation in the long run, output and emissions are not reduced significantly with the introduction of the rate-based policy or that there is a possibility that output and emissions would increase more than before regulation. In addition, since there is a tendency to equalize the output reduction rate of each sector, we noted that the rate-based policy is desirable from the viewpoint of fairness.

The conclusion of this thesis is as follows. While it is relatively easy to introduce direct regulation using the emission rate for each industry, there is a possibility that there will be additional costs compared to the cap-and-trade policy, as it dependent on the emission rate target, which has to be set carefully (Chapter Two). When this regulation is compared to the cap-and-trade policy, we find that economic efficiency is lower (Chapters Three and Four), but it is desirable from the viewpoint of equity among industries (Chapter Four). Although environmental regulation using emission rates does not hinder economic growth, it is difficult for such regulation to reduce greenhouse gas emissions in the long run (Chapter Four).

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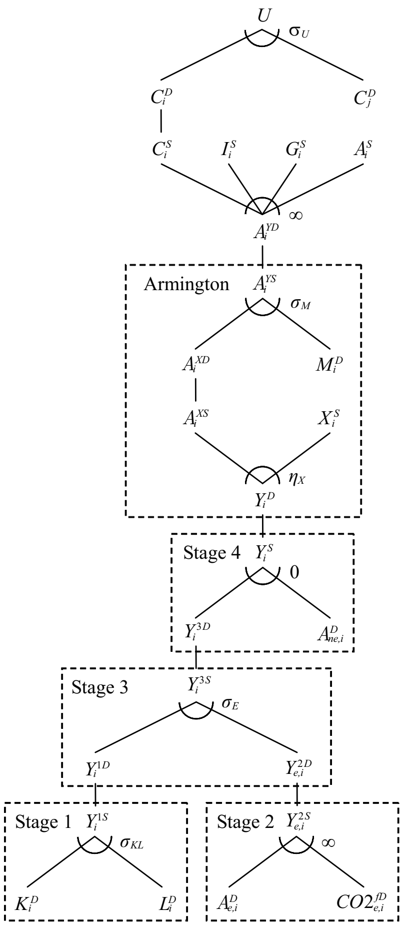
Appendix

1. Description of the static CGE model

1.1 Overview



1.2 Description

- In this model, we use the CES function for the utility and production functions.
- It is assumed that the optimizing behavior of economic agents will be displayed (utility maximization and profit maximization).
- In all scenarios using CGE analysis, we assume the following three points:
  - The household receives emissions trading revenue from the government.
  - Emissions regulations are imposed only on firms (only firms buy and sell emission permits).
  - The emission rate in the BaU scenario is considered to be the emission rate in a base year.

1.3 Notation

Indices for sectors and goods

Notation	Description	Program
i, j	Sectors and goods	`i,j`
e, f	Energy goods	`e,f`
ne, nf	Non-energy goods	`ne,nf`

Endogenous variables

Notation	Description	Program
K_i^D	Factor demand for capital	`K_D(i)`
L_i^D	Factor demand for labor	`L_D(i)`
Y_i^{1S}	Composite factor supply in stage 1	`Y_1S(i)`
Y_i^{1D}	Composite factor demand in stage 1	`Y_1D(i)`
$Y_{e,i}^{2S}$	Composite factor supply in stage 2	`Y_2S(e,i)`
$Y_{e,i}^{2D}$	Composite factor demand in stage 2	`Y_2D(e,i)`
Y_i^{3S}	Composite factor supply in stage 3	`Y_3S(i)`

Y_i^{3D}	Composite factor demand in stage 3	`Y_3D(i)`
Y_i^S	Goods supply (output)	`Y_S(i)`
Y_i^D	Goods demand	`Y_D(i)`
X_i^S	Export good	`X_S(i)`
M_i^D	Import good	`M_D(i)`
A_i^{XS}	Supply of domestic good	`A_XS(i)`
A_i^{XD}	Demand for domestic good	`A_XD(i)`
A_i^{YS}	Supply of composite good	`A_YS(i)`
A_i^{YD}	Demand for composite good	`A_YD(i)`
A_i^S	Supply of intermediate good	`A_S(i)`
$A_{i,j}^D$	Demand for intermediate good	`A_D(i,j)`
C_i^S	Supply of consumption good	`C_S(i)`
C_i^D	Household consumption	`C_D(i)`
I_i^S	Supply of investment good	`I_S(i)`
I_i^D	Demand for investment good	`I_D(i)`
G_i^S	Composite goods supply for government	`G_S(i)`
G_i^D	Government expenditure	`G_D(i)`
U	Utility	-
$CO2_e^{hD}$	CO_2 emissions by the household	`CO2_hD(e)`
$CO2_{e,i}^{fD}$	CO_2 emissions by firms	`CO2_fD(e,i)`
r	Rental price of capital	`r`
w	Wage (numeraire)	`w`
p_i^{Y1}	Price of composite factor Y_i^1	`p_Y1(i)`
$p_{e,i}^{Y2}$	Price of composite factor $Y_{e,i}^2$	`p_Y2(e,i)`
p_i^{Y3}	Price of composite factor Y_i^3	`p_Y3(i)`
p_i^Y	Price of goods Y_i	`p_Y(i)`
p_i^X	Price of export good X_i	`p_X(i)`
p_i^M	Price of import good M_i	`p_M(i)`
p_i^{XA}	Price of domestic good A_i^X	`p_XA(i)`
p_i^{AY}	Price of composite good A_i^Y	`p_AY(i)`
p_i^A	Price of intermediate good A_i	`p_A(i)`
p_i^C	Price of consumption good C_i	`p_C(i)`
p_i^I	Price of investment good I_i	`p_I(i)`
p_i^G	Demand price by government	`p_G(i)`
p^{CO2}	Price of emissions permit	`p_CO2`
ε	Exchange rate	`epsilon`
I	Total income	`I_H`

B	Disposal income	B
S	Total savings	S
S^H	Household savings	S_H
S^G	Government savings	S_G
T	Total tax	T
T^D	Direct tax	T_D
T_i^Y	Production tax	T_Y(i)
T_i^M	Import tariff	T_M(i)

Elasticity parameters (exogeneous variables)

Notation	Description	Program
σ_{KL}	Elasticity of substitution between capital and labor (= 1)	-
σ_E	Elasticity of substitution between energy good and composite factor (= 0.5)	sigmma_E
η_X	Elasticity of transformation between domestic good and export good (= 4)	eta_X
σ_M	Elasticity of substitution between domestic good and import good (= 4)	sigmma_M
σ_U	Elasticity of substitution between consumption goods (= 1)	-

Parameters in the CES function, etc. (exogeneous variables)

Notation	Description	Program
β_i^{K1}	Share coefficient for capital	beta_K1(i)
β_i^{L1}	Share coefficient for labor	beta_L1(i)
a_i^1	Total factor productivity in stage 1	a_1(i)
$a_{e,i}^{fE}$	Emission coefficient	a_fE(e,i)
β_i^{Y3}	Parameter in stage-3 CES function	beta_Y3(i)
$\beta_{e,i}^{A3}$	Parameter in stage-3 CES function	beta_A3(e,i)
a_i^3	Parameter in stage-3 CES function	a_3(i)

a_i^Y	Input requirement coefficient of Y_i^{3D} for a unit output	`a_Y(i)`
$a_{i,j}^A$	Input requirement coefficient of $Y_{i,j}^D$ for a unit output	`a_A(i,j)`
β_i^{XA}	Parameter in transformation function	`beta_XA(i)`
β_i^X	Parameter in transformation function	`beta_X(i)`
a_i^X	Scaling coefficient in transformation function	`a_X(i)`
β_i^{MA}	Parameter in Armington composite good production function	`beta_MA(i)`
β_i^M	Parameter in Armington composite good production function	`beta_M(i)`
a_i^M	Scaling coeffiecient in Armington composite good production function	`a_M(i)`
γ_i^H	Share coefficient in utility function	`gamma_H(i)`
a_e^{hE}	Emission coefficient in consumption	`a_hE(e)`
γ_i^I	Expenditure share of total investment	`gamma_I(i)`
γ_i^G	Share of government expenditure	`gamma_G(i)`

Tax rate and savings rate (exogeneous variables)

Notation	Description	Program
t_i^{tY}	Production tax rate	`t_tY(i)`
t_i^{tM}	Import tariff rate	`t_tM(i)`
t^{tD}	Direct tax rate	`t_tD`
s^{sH}	Average propensity for savings by the household	`s_sH(i)`
s^{sG}	Average propensity for savings by the government	`s_sG`

Other exogeneous variables

Notation	Description	Program
K	Endowments of capital	`KZ`
L	Endowments of labor	`LZ`
S^F	Current account deficits in foreign currency terms	`S_F`
p_i^{WX}	Price of exported good in terms of foreign currency (= 1)	`p_WX(i)`
p_i^{WM}	Price of imported good in terms of foreign currency (= 1)	`p_WM(i)`

$CO2^S$	Total supply of emission permits (cap-and-trade policy)	`CO2_S`
α_i	Emission rate set (rate-based policy)	`alpha(i)`

1.4 Model

- Firm

[Stage 1]

$$K_i^D = \frac{\beta_i^{K1} p_i^{Y1} Y_i^{1S}}{r} \qquad \{K_i^D\}$$

$$L_i^D = \frac{\beta_i^{L1} p_i^{Y1} Y_i^{1S}}{r} \qquad \{L_i^D\}$$

$$Y_i^{1S} = a_i^1 (K_i^D)^{\beta_i^{K1}} (L_i^D)^{\beta_i^{L1}} \qquad \{Y_i^{1S}\}$$

[Stage 2]

$$A_{e,i}^D = Y_{e,i}^{2S} \qquad \{A_{e,i}^D\}$$

$$CO2_{e,i}^{fD} = a_{e,i}^{fE} Y_{e,i}^{2S} \qquad \{CO2_{e,i}^{fD}\}$$

$$p_{e,i}^{Y2} Y_{e,i}^{2S} - (p_e^A A_{e,i}^D + p^{CO2} CO2_{e,i}^{fD}) = 0 \qquad \{Y_{e,i}^{2S}\}$$

[Stage 3]

$$Y_i^{1D} = \left[\frac{(a_i^3)^{\frac{\sigma_E - 1}{\sigma_E}} \beta_i^{Y3} p_i^{Y3}}{p_i^{Y1}} \right]^{\sigma_E} Y_i^{3S} \qquad \{Y_i^{1D}\}$$

$$Y_{e,i}^{2D} = \left[\frac{(a_i^3)^{\frac{\sigma_E - 1}{\sigma_E}} \beta_i^{A3} p_i^{Y3}}{p_{e,i}^{Y2}} \right]^{\sigma_E} Y_i^{3S} \qquad \{Y_{e,i}^{2D}\}$$

$$Y_i^{3S} = a_i^3 \left[\beta_i^{Y3} (Y_i^{1D})^{\frac{\sigma_E - 1}{\sigma_E}} + \sum_e \beta_{e,i}^{A3} (Y_{e,i}^{2D})^{\frac{\sigma_E - 1}{\sigma_E}} \right]^{\frac{\sigma_E}{\sigma_E - 1}} \qquad \{Y_i^{3S}\}$$

[Stage 4]

$$Y_i^{3D} = a_i^Y Y_i^S \qquad \{Y_i^{3D}\}$$

$$A_{ne,i}^D = a_{ne,i}^A Y_i^S \qquad \{Y_{ne,i}^D\}$$

□ Cap-and-trade policy

$$(1 - t_i^{tY}) p_i^Y Y_i^S - \left[p_i^{Y3} Y_i^{3D} + \sum_{ne} p_{ne,i}^A A_{ne,i}^D \right] = 0 \qquad \{Y_i^S\}$$

□ Rate-based policy

$$\left[(1 - t_i^{tY}) p_i^Y + \alpha_i p^{CO2} \right] Y_i^S - \left[p_i^{Y3} Y_i^{3D} + \sum_{ne} p_{ne,i}^A A_{ne,i}^D \right] = 0 \qquad \{Y_i^S\}$$

- Armington structure

[Export side]

$$A_i^{XS} = \left[\frac{(a_i^X)^{\frac{\sigma_X+1}{\sigma_X}} \beta_i^{XA} p_i^Y}{p_i^{XA}} \right]^{-\sigma_X} Y_i^D \qquad \{A_i^{XS}\}$$

$$X_i^S = \left[\frac{(a_i^X)^{\frac{\sigma_X+1}{\sigma_X}} \beta_i^X p_i^Y}{p_i^X} \right]^{-\sigma_X} Y_i^D \qquad \{X_i^S\}$$

$$Y_i^D = a_i^X \left[\beta_i^{XA} (A_i^{XS})^{\frac{\sigma_X+1}{\sigma_X}} + \beta_i^X (X_i^S)^{\frac{\sigma_X+1}{\sigma_X}} \right]^{\frac{\sigma_X}{\sigma_X+1}} \qquad \{Y_i^D\}$$

[Import side]

$$A_i^{XD} = \left[\frac{(a_i^M)^{\frac{\sigma_M-1}{\sigma_M}}\beta_i^{MA}p_i^{AY}}{p_i^{XA}}\right]^{\sigma_M} A_i^{YS} \qquad \{A_i^{XD}\}$$

$$M_i^D = \left[\frac{(a_i^M)^{\frac{\sigma_M-1}{\sigma_M}}\beta_i^{M}p_i^{AY}}{(1+t_i^{tM})p_i^M}\right]^{\sigma_M} A_i^{YS} \qquad \{M_i^D\}$$

$$A_i^{YS} = a_i^M\left[\beta_i^{MA}(A_i^{XD})^{\frac{\sigma_M-1}{\sigma_M}} + \beta_i^M(M_i^D)^{\frac{\sigma_M-1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M-1}} \qquad \{A_i^{YS}\}$$

- Goods market

$$p_i^C = p_i^{AY} \qquad \{C_i^S\}$$

$$p_i^I = p_i^{AY} \qquad \{I_i^S\}$$

$$p_i^G = p_i^{AY} \qquad \{G_i^S\}$$

$$p_i^A = p_i^{AY} \qquad \{A_i^S\}$$

$$A_i^{YD} = C_i^S + I_i^S + G_i^S + A_i^S \qquad \{A_i^{YD}\}$$

- Household

$$C_i^D = \frac{\gamma_i^H B}{p_i^C} \qquad \{C_i^D\}$$

  - Cap-and-trade policy

$$rK + wL + p^{CO2}CO2^S = I \qquad \{I\}$$

  - Rate-based policy

$$rK + wL = I \qquad \{I\}$$

$$S^H = s^{sH}I \qquad \{S^H\}$$

$$T^D = t^{tD}I \qquad \{T^D\}$$

$$I - (S^H + T^D) = B \qquad \{B\}$$

$$CO2_e^{hD} = \mathrm{a}_e^{hE}\mathrm{C}_e^D \qquad \{CO2_e^{hD}\}$$

- Investment

$$I_i^D = \frac{\gamma_i^I S}{p_i^I} \qquad \{I_i^D\}$$

$$S = S^H + S^G + \varepsilon S^F \qquad \{S\}$$

- Government

$$G_i^D = \frac{\gamma_i^G (T - S^G)}{p_i^G} \qquad \{G_i^D\}$$

$$T_i^Y = t_i^{tY} p_i^Y Y_i^S \qquad \{T_i^Y\}$$

$$T_i^M = t_i^{tM} p_i^M M_i^D \qquad \{T_i^M\}$$

$$T = T^D + \sum_i T_i^Y + \sum_i T_i^M \qquad \{T\}$$

$$S^G = s^{sG} T \qquad \{S^G\}$$

- International price

$$p_i^X = \varepsilon p_i^{WX} \qquad \{p_i^X\}$$

$$p_i^M = \varepsilon p_i^{WM} \qquad \{p_i^M\}$$

- Market-clearing conditions

$$\sum_i K_i^D = K \qquad \{r\}$$

$$\sum_i L_i^D = L \qquad \{w\}$$

$$Y_i^{1D} = Y_i^{1S} \qquad \{p_i^{Y1}\}$$

$$Y_{e,i}^{2D} = Y_{e,i}^{2S} \qquad \{p_{e,i}^{Y2}\}$$

$$Y_i^{3D} = Y_i^{3S} \qquad \{p_i^{Y3}\}$$

$$Y_i^D = Y_i^S \qquad \{p_i^Y\}$$

$$\sum_j A_{i,j}^D = A_i^S \qquad \{p_i^A\}$$

$$A_i^{XD} = A_i^{XS} \qquad \{p_i^{XA}\}$$

$$A_i^{YD} = A_i^{YS} \qquad \{p_i^{AY}\}$$

$$C_i^D = C_i^S \qquad \{p_i^C\}$$

$$I_i^D = I_i^S \qquad \{p_i^I\}$$

$$G_i^D = G_i^S \qquad \{p_i^G\}$$

$$\sum_i p_i^{WM} M_i^D = \sum_i p_i^{WX} M_i^S + S^F \qquad \{\varepsilon\}$$

□ Cap-and-trade policy

$$\sum_i \sum_e CO2_{e,i}^{fD} = CO2^S \qquad \{p^{CO2}\}$$

□ Rate-based policy

$$\sum_i \sum_e CO2_{e,i}^{fD} = \sum_i \alpha_i Y_i^S \qquad \{p^{CO2}\}$$

2. Description of the dynamic CGE model

2.1 Overview

The overview is the same as that of the static CGE model.

2.2 Description

- This model is a recursive dynamic model formed by adding the capital accumulation equation to the static model.
- For the capital accumulation equation, we add parameters for adjusting the divergence of the capital accumulation amount and the actual amount of capital accumulation that is listed in the input–output table.
- For technological progress to be introduced, we assume the following two points:

  - □ An increase in labor productivity (the same as in the population growth model).
  - □ An increase in the input efficiency of energy goods.

2.3 Notation

- Variables added (exogeneous variables)

Notation	Description	Program
θ	Adjustment parameter in capital accumulation equation	`theta`
δ	Depreciation rate	`delta`
λ_L	The rate of increase in labor productivity	`lambda_L`
λ_E	The rate of increase in the input efficiency of energy goods	`lambda_E`
φ	Parameter representing the input efficiency of energy goods	`phi`

2.4 Model

We add the following to the static model:

- Capital accumulation equation

$$K_{t+1} = (1-\delta)K_t + \theta \sum_i I_{i,t}^D$$

- Technological progress on labor productivity

$$L_{t+1} = (1+\lambda_L)L_t$$

We modify part of the static model as shown below.

- Technological progress on the input efficiency of energy goods

$$Y_i^{3S} = a_i^3 \left[\beta_i^{Y3} (Y_i^{1D})^{\frac{\sigma_E - 1}{\sigma_E}} + \sum_e \beta_{e,i}^{A3} (\varphi Y_{e,i}^{2D})^{\frac{\sigma_E - 1}{\sigma_E}} \right]^{\frac{\sigma_E}{\sigma_E - 1}} \qquad \{Y_i^{3S}\}$$

$$Y_{e,i}^{2D} = \left[\frac{(a_i^3)^{\frac{\sigma_E - 1}{\sigma_E}} \beta_i^{A3} p_i^{Y3}}{p_{e,i}^{Y2}} \right]^{\sigma_E} \varphi^{\sigma_E - 1} Y_i^{3S} \qquad \{p_{e,i}^{2D}\}$$

$$\varphi_{t+T} = (1 + \lambda_E)^T \varphi_t$$

2.5 GAMS program (dynamic model under the rate-based policy in Subsection 4.5.2)

```
$Title Dynamic CGE Model with Rate-based Regulation

Set u          /agr,foss,omn,food,tex,pulp,chem,p_c,nmm,iron
                nfm,fmp,mch,eleq,iteq,semi,treq,preq,omf,cns
                ely,ghs,wat,trd,fin,dwe,trp,itc,pubs,edu
                mhs,opub,bsrv,psrv
                CAP,LAB,IDT,TRF,HOH,GOV,INV,EXT/
    i(u)       /agr,foss,omn,food,tex,pulp,chem,p_c,nmm,iron
                nfm,fmp,mch,eleq,iteq,semi,treq,preq,omf,cns
                ely,ghs,wat,trd,fin,dwe,trp,itc,pubs,edu
                mhs,opub,bsrv,psrv/
    e(i)       /foss,p_c,ghs/
    ne(i)      /agr,omn,food,tex,pulp,chem,nmm,iron,nfm,fmp
                mch,eleq,iteq,semi,treq,preq,omf,cns,ely,wat
                trd,fin,dwe,trp,itc,pubs,edu,mhs,opub,bsrv
                psrv/
;

Alias (u,v),(i,j),(e,f),(ne,nf);

Table SAM(u,v)

        agr       foss      omn       food      tex
agr     1643.017  0.332     0.172     7111.018  35.881
foss    0         0.126     0         0.063     0.027
omn     0.626     0         2.893     0         0.01
food    1244.658  0         0         5369.035  13.1
tex     57.427    0.363     4.208     42.653    1148.899
pulp    183.143   0.538     1.902     570.337   34.215
chem    573.052   0.194     8.073     326.655   481.198
p_c     260.168   0.394     15.275    159.907   32.434
nmm     17.577    0.157     0.039     137.336   2.235
iron    1.038     1.05      0.762     0         0.22
nfm     0         0.15      0.109     52.627    0.161
fmp     14.747    3.814     17.39     629.438   8.335
mch     0.234     0.234     4.165     0.002     0
eleq    3.221     0.001     0.31      0.11      0
iteq    0.086     0         0.02      0.185     0.107
semi    0.005     0         0         0.088     0.007
treq    67.599    0         0.04      0         0
preq    2.786     0.016     0.017     0.113     0.08
```

omf	131.441	1.042	8.321	981.769	124.945
cns	65.697	0.733	5.785	57.602	16.915
ely	99.738	8.397	26.078	364.564	69.994
ghs	0.314	0.045	0.057	72.639	7.699
wat	12.729	0.65	3.74	119.959	17.746
trd	543.366	2.079	23.874	2888.79	346.162
fin	226.281	7.145	62.863	330.764	195.251
dwe	4.52	2.858	4.971	51.378	15.435
trp	633.183	5.642	270.375	1211.601	114.824
itc	37.206	3.169	8.098	139.738	41.28
pubs	0	0	0	0	0
edu	10.891	2.389	2.156	224.374	27.141
mhs	0.859	0	0	0	0
opub	3.252	0.508	1.719	27.758	5.237
bsrv	184.088	9.605	39.093	1125.631	130.624
psrv	180.256	2.516	7.92	206.543	21.996
CAP	5082.506	21.743	109.842	5177.591	216.812
LAB	1435.01	34.609	203.114	5070.029	1112.775
IDT	433.854	12.472	52.029	3439.053	153.046
TRF	149.278	1219.45	86.489	1042.176	393.023
HOH					
GOV					
INV					
EXT	2092.569	12324.51	1729.781	4625.095	3205.556

+	pulp	chem	p_c	nmm	iron
agr	413.493	31.173	0.609	0.856	0.002
foss	38.882	66.038	10108.895	54.779	217.274
omn	11.851	70.422	-2.246	422.656	717.782
food	21.723	120.839	0.064	3.474	0.022
tex	87.547	23.589	3.693	22.27	11.743
pulp	3455.155	395.63	0.322	149.913	16.805
chem	407.462	9007.825	30.394	192.188	99.921
p_c	61.702	2049.077	661.698	141.097	623.266
nmm	79.344	154.053	7.262	574.809	147.12
iron	126.419	1.201	-0.008	64.916	13290.958
nfm	28.663	120.038	0.106	40.183	198.534
fmp	170.957	242.158	10.859	76.615	20.079
mch	17.727	0.769	0.091	22.233	8.63
eleq	1.731	0.443	0	0.033	0
iteq	0.158	1.897	0.041	0.181	0.125
semi	0.141	0.211	0.015	0.008	0.042
treq	0	0	0	0	0
preq	0.688	0.6	0.006	0.386	0.07
omf	383.204	530.064	11.594	98.581	254.718

cns	84.255	178.017	16.22	100.221	153.842
ely	378.234	618.391	108.425	181.769	677.477
ghs	9.624	36.194	0.929	26.125	84.535
wat	48.945	197.94	8.522	37.968	50.057
trd	1090.315	1177.229	194.258	329.827	1023.014
fin	243.197	414.955	94.525	192.43	237.889
dwe	36.937	79.979	6.388	23.63	41.572
trp	541.976	708.525	464.441	466.479	569.473
itc	89.248	404.359	17.462	73.785	91.03
pubs	0	0	0	0	0
edu	79.967	2022.341	38.019	255.602	193.713
mhs	0.021	0.366	0	0	0.048
opub	9.374	44.505	6.574	7.819	21.655
bsrv	376.205	1383.206	82.875	380.67	397.971
psrv	83.852	61.356	6.877	70.965	120.761
CAP	1516.709	3437.378	373.713	1141.603	2928.599
LAB	2521.838	3270.582	304.251	1696.896	2463.19
IDT	412.016	635.6	4363.296	304.962	652.113
TRF	125.715	227.213	147.462	28.191	52.492
HOH					
GOV					
INV					
EXT	1911.727	3807.771	2591.158	504.382	897.012

+	nfm	fmp	mch	eleq	iteq
agr	0.274	0	0	0	0
foss	2.643	0.263	0.454	0.269	0.063
omn	911.355	0.617	1.052	0	0
food	0	0	0	0	0
tex	10.793	16.431	40.731	49.745	18.392
pulp	30.638	56.296	54.599	116.664	73.695
chem	84.233	104.615	171.716	198.184	81.407
p_c	36.16	32.574	40.425	14.959	4.204
nmm	56.388	44.051	165.854	126.719	21.541
iron	11.401	2678.153	2450.737	597.523	82.749
nfm	2884.344	807.55	619.779	1020.074	273.674
fmp	18.097	745.261	1126.294	392.976	169.983
mch	3.675	25.218	6152.528	243.52	36.462
eleq	0.317	12.225	762.289	1630.728	245.726
iteq	0.143	0.388	17.224	1.66	355.948
semi	1.849	42.574	866.882	1606.785	3728.46
treq	0	0	3.875	0	0
preq	0.053	0.369	155.237	14.217	25.62
omf	185.518	103.956	724.335	655.097	493.596
cns	39.049	109.33	88.024	62.443	28.035

ely	161.477	180.473	265.148	135.783	64.805
ghs	10.114	21.209	14.966	18.374	3.649
wat	13.317	18.123	71.935	23.022	8.25
trd	354.572	667.424	1933.937	1084.816	780.859
fin	126.216	208.774	425.658	151.325	105.731
dwe	12.04	45.926	82.649	47.858	23.9
trp	262.096	384.07	620.683	326.601	215.122
itc	55.042	148.54	359.357	256.92	205.202
pubs	0	0	0	0	0
edu	152.626	118.247	986.641	1252.244	770.294
mhs	0	0	0	0	0
opub	2.526	15.406	53.207	11.152	14.973
bsrv	177.447	432.587	1294.374	753.692	510.155
psrv	32.402	61.407	223.219	75.468	35.579
CAP	521.084	1077.67	3012.913	1335.596	728.701
LAB	959.785	3920.946	7007.883	3382.241	1737.888
IDT	212.333	403.775	583.885	245.434	166.961
TRF	132.934	34.909	134.34	135.632	211.942
HOH					
GOV					
INV					
EXT	2474.045	630.672	2648.703	2429.477	4101.871

+	semi	treq	preq	omf	cns
agr	0	0.057	0	204.87	87.905
foss	0.313	3.608	0	0.315	0.009
omn	0	0	0.043	10.675	502.655
food	0	0	0	24.435	0
tex	58.995	99.688	5.507	114.725	182.19
pulp	100.489	76.596	23.382	1023.329	2929.128
chem	274.366	530.011	24.56	3228.057	275.895
p_c	29.35	108.325	3.501	46.662	704.416
nmm	474.242	402.557	89.909	87.362	3623.305
iron	73.058	2454.127	47.635	76.416	1458.233
nfm	496.266	1022.919	95.039	192.419	497.465
fmp	273.103	519.881	76.117	229.324	6190.568
mch	56.826	531.441	34.111	63.384	417.882
eleq	369.089	1364.437	63.127	7.145	493.668
iteq	2.97	401.148	0.117	1.566	105.975
semi	4988.634	394.172	626.405	108.884	13.526
treq	0	24604.589	0	0	0
preq	6.922	34.049	77.386	5.013	6.54
omf	441.127	2044.834	177.444	4287.057	1047.942
cns	89.032	68.037	14.631	92.3	143.85
ely	305.356	429.778	38.766	388.776	210.831

ghs	28.435	78.1	3.729	19.017	45.386
wat	42.801	59.246	8.559	43.208	148.729
trd	682.884	2553.585	220.555	1780.332	4123.288
fin	162.307	404.587	96.922	453.468	937.841
dwe	24.785	42.728	10.253	75.21	160.378
trp	304.665	886.901	72.008	1170.495	3343.445
itc	166.076	193.154	32	212.414	757.075
pubs	0	0	0	0	0
edu	1654.923	1823.954	235.196	457.185	79.319
mhs	0	0	0	0.039	0.02
opub	10.812	16.471	2.443	20.402	60.666
bsrv	726.556	1577.766	173.114	925.597	4957.399
psrv	40.256	80.18	10.717	123.07	538.934
CAP	955.029	2524.89	377.004	2644.641	4031.753
LAB	3144.015	6899.095	985.003	6738.348	23268.06
IDT	228.074	785.407	97.51	738.708	1893.048
TRF	181.345	130.609	70.142	262.174	0
HOH					
GOV					
INV					
EXT	3626.958	2674.069	1414.262	3182.179	0

+	ely	ghs	wat	trd	fin
agr	0	0	0	9.311	0
foss	2331.866	975.105	0.245	0	0
omn	-0.214	0	0	0	0
food	0	0	0	16.52	0
tex	2.443	1.119	12.093	375.143	66.539
pulp	32.599	1.938	26.298	806.118	189.829
chem	7.665	8.424	117.245	0.883	1.184
p_c	942.934	123.29	118.105	224.977	18.48
nmm	0.927	0.257	21.48	36.241	0.77
iron	0	0	2.913	0	0
nfm	13.149	0	1.153	1.42	0
fmp	10.4	3.842	5.265	332.702	2.552
mch	0	0.165	32.927	0.777	0
eleq	0.111	0	0.674	28.918	0.242
iteq	0.143	0.048	0.365	14.634	2.864
semi	0.249	0.016	0.075	4.14	2.831
treq	0	0	0	0	0
preq	0	0	0.672	156.441	2.81
omf	124.946	37.277	247.882	1119.446	867.455
cns	844.756	201.494	231.683	651.679	164.048
ely	561.061	61.331	357.877	1428.977	108.006
ghs	12.825	43.284	15.236	273.498	25.721

wat	116.853	14.52	493.129	337.432	112.246
trd	288.481	90.74	173.704	1826.085	252.847
fin	602.405	33.048	74.613	5707.629	4478.944
dwe	119.762	41.963	18.237	2879.732	569.767
trp	362.879	135.775	289.057	5458.445	819.735
itc	278.256	63.284	255.263	4223.835	2328.652
pubs	0	0	0	0	0
edu	396.234	41.213	1.231	327.863	19.473
mhs	0	0.023	0.206	2.129	1.134
opub	19.499	9.148	53.817	52.324	103.13
bsrv	1378.967	134.381	596.623	6035.146	4674.937
psrv	62.41	12.191	77.212	1130.577	270.936
CAP	4231.709	403.822	2044.296	24623.782	13054.601
LAB	1914.977	453.536	2807.223	44454.926	12657.01
IDT	1125.075	2.565	229.672	3732.782	790.042
TRF	0	0	0	0	0
HOH					
GOV					
INV					
EXT	1.079	0.183	1.716	704.6	499.171

+	dwe	trp	itc	pubs	edu
agr	0.081	1.939	0	2.14	34.205
foss	0	0.057	0	0.031	5.111
omn	0	0	0	0.398	0
food	0	8.619	0.009	9.467	30.59
tex	1.582	87.075	59.419	93.891	16.443
pulp	34.957	298.732	874.319	78.586	204.035
chem	1.113	20.499	93.291	29.467	187.027
p_c	32.472	5205.624	47.257	334.11	272.335
nmm	2.533	1.98	0.466	7.705	63.175
iron	0	13.822	0	0.928	0
nfm	0	0.546	1.994	6.439	1.601
fmp	17.331	75.088	12.668	174.282	4.203
mch	0	4.831	0.414	12.027	0
eleq	0.647	10.369	8.756	66.606	14.23
iteq	1.519	3.639	6.348	79.591	1.67
semi	0	0.172	73.69	134.571	53.174
treq	0	737.675	0	764.324	1.568
preq	0.303	1.798	17.101	30.745	0.562
omf	29.435	231.861	1475.13	982.398	872.116
cns	3047.681	505.823	233.419	588.219	453.558
ely	178.753	682.572	292.9	402.545	691.598
ghs	15.579	23.302	21.768	43.846	92.711
wat	25.486	262.486	165.49	818.929	390.269

trd	72.325	1665.151	714.522	581.473	702.208
fin	3798.522	2220.168	636.153	126.344	314.064
dwe	378.002	749.394	897.579	36.347	284.839
trp	150.947	5919.613	1106.699	1195.672	705.266
itc	137.929	604.955	4763.584	1338.661	1095.032
pubs	0	0	0	0	0
edu	0.17	99.285	503.975	6.396	85.024
mhs	0.09	2.612	2.107	0.322	0.336
opub	20.495	58.113	48.368	0.253	50.553
bsrv	1385.73	6605.944	5725.66	2091.211	1863.246
psrv	303.604	373.667	1025.92	110.953	677.274
CAP	50656.597	6667.041	10902.527	11556.133	4429.425
LAB	2310.99	15596.181	14628.841	16726.239	22452.818
IDT	3601.062	2003.767	1595.583	106.628	242.912
TRF	0	0	6.127	0	0
HOH					
GOV					
INV					
EXT	1.463	3667.297	707.962	0	641.415

+	mhs	opub	bsrv	psrv	CAP
agr	225.434	8.564	1.006	1038.617	
foss	0.408	0	0.275	1.411	
omn	0	0	0	-0.458	
food	706.339	6.492	0.5	5392.041	
tex	165.954	98.446	125.784	245.273	
pulp	274.72	84.212	221.657	1019.272	
chem	6476.823	10.848	239.539	460.743	
p_c	185.324	27.186	115.337	372.96	
nmm	59.501	3.764	70.715	144.205	
iron	0.388	0.024	7.778	47.623	
nfm	61.574	0.812	19.814	51.347	
fmp	16.119	8.893	85.875	136.533	
mch	0	0	1758.344	117.807	
eleq	2.83	0	438.304	21	
iteq	1.035	0.45	127.339	6.466	
semi	0.062	0	701.535	40.667	
treq	0	0	1833.918	3.091	
preq	444.924	0.122	44.82	17.469	
omf	336.818	252.709	1443.848	834.134	
cns	293.525	13.406	175.208	301.196	
ely	520.92	12.658	277.226	897.281	
ghs	126.409	7.787	13.493	368.789	
wat	537.219	15.385	73.84	1226.996	
trd	2835.627	183.921	1708.624	3917.266	

fin	660.311	88.074	2533.832	3137.201	
dwe	307.729	94.826	322.496	748.569	
trp	870.549	138.163	949.123	1861.913	
itc	751.008	337.643	5906.722	1316.431	
pubs	0	0	0	1109.667	
edu	7.595	0	98.904	163.932	
mhs	893.38	0.053	0.439	3.33	
opub	57.901	0	129.787	209.056	
bsrv	2276.151	369.527	5963.626	1955.312	
psrv	962.798	49.154	476.684	906.602	
CAP	5669.808	366.078	14046.623	10361.201	
LAB	24491.127	2825.959	22014.076	16130.737	
IDT	-8.913	25.478	1822.059	2942.157	
TRF	0	0	1.203	1.245	
HOH	0	0	0	0	196229.42
GOV					
INV					
EXT	2.07	33.851	1040.258	3536.191	0

+	LAB	IDT	TRF	HOH	GOV
agr				3563.257	0
foss				0.023	0
omn				-15.077	0
food				27746.44	327.785
tex				3895.92	0
pulp				592.863	1.684
chem				2823.92	0
p_c				5887.602	0
nmm				256.201	0
iron				-32.731	0
nfm				108.25	0
fmp				351.236	0.508
mch				92.02	0.038
eleq				2910.042	0
iteq				4968.416	0
semi				240.602	0
treq				5567.891	0
preq				918.244	0.088
omf				3556.985	4.297
cns				0	0
ely				4566.142	0
ghs				1327.889	0
wat				2134.662	634.473
trd				48570.364	6.873
fin				11941.943	0

```
dwe                                   57908.362 37.145
trp                                   15403.112 -74.768
itc                                   11191.24  35.886
pubs                                  786.643   36641.567
edu                                   7608.327  16803.455
mhs                                   12683.196 36622.546
opub                                  3895.555  0
bsrv                                  4617.297  0
psrv                                  51609.133 0
CAP
LAB
IDT
TRF
HOH     275620.198 0        0         0         0
GOV     0         34024.445 4774.091  55562.241 0
INV     0         0         0         118611.408 3319.2
EXT

+       INV       EXT
agr     919.745   62.464
foss    -141.747  0.125
omn     35.666    30.974
food    249.404   265.065
tex     181.004   545.653
pulp    477.699   354.708
chem    92.943    4850.314
p_c     -159.602  884.805
nmm     58.251    748.471
iron    33.521    2772.68
nfm     91.421    1227.366
fmp     334.458   642.078
mch     15062.868 8460.183
eleq    4418.276  5521.593
iteq    5081.438  4139.533
semi    8.732     6380.855
treq    6877.258  15359.168
preq    1843.296  1397.534
omf     1236.943  2698.936
cns     54117.611 0
ely     0         30.339
ghs     0         0.705
wat     0         13.326
trd     12967.223 8620.512
fin     0         654.576
dwe     0         19.254
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```
trp     877.505   5669.407
itc     8397.087  333.423
pubs    0         0
edu     0         384.294
mhs     0         0.211
opub    0         20.027
bsrv    2810      668.198
psrv    0         1011.884
CAP
LAB
IDT
TRF
HOH
GOV
INV     0         -6059.608
EXT
;

Table CO2_f(e,i)
        agr         foss        omn         food        tex
foss                0.003023707             0.001398241 0.00059965
p_c     15.11480196 0.014716884 0.870048916 10.48892293 2.509503587
ghs     0.009624573 0.000765591 0.001747094 3.242726682 0.29515513

+       pulp        chem        p_c         nmm         iron
foss    9.947160758 8.027987232 0.360089881 14.68953407 34.45642805
p_c     4.868708083 31.17368038 38.50358157 13.86762782 113.9203237
ghs     0.254997431 1.408511129 0.037674243 1.174474108 3.847621829

+       nfm         fmp         mch         eleq        iteq
foss    0.341012334 0.011375438 0.011112384 0.006584837 0.001541553
p_c     2.944239534 2.137828956 1.949684024 0.811467061 0.223153748
ghs     0.445156282 0.950559483 0.675667058 0.819164457 0.16421927

+       semi        treq        preq        omf         cns
foss    0.00766251  0.088322047             0.069970492 0.001997891
p_c     1.71506244  5.12064975  0.248450308 3.067167803 10.45820312
ghs     1.237584452 3.504357035 0.154617325 0.304336565 1.439058398

+       ely         ghs         wat         trd         fin
foss    343.0940969 0.074633808 0.05441636
p_c     61.28226058 0.575549063 7.231292682 11.65560348 0.692538345
ghs     0.357986392 1.376810759 0.461769229 5.655177467 0.266765093

+       dwe         trp         itc         pubs        edu
```

```
foss                0.012656766             0.006882776 1.135312997
p_c     1.455156552 184.8284919 2.059285165 10.33578022 9.450675937
ghs     0.277556909 0.577788322 0.286515832 0.674036877 1.693516521

+       mhs         opub        bsrv        psrv
foss    0.090621649             0.059721755 0.313410516
p_c     8.503008162 1.163536151 4.114261523 14.70968552
ghs     2.306506944 0.141154426 0.182150316 6.636040022
;

Table CO2_h(e,*)
        HOH
foss    0.005106454
p_c     148.4764964
ghs     22.29710153
;

Parameter K_DZ(i),KZ,L_DZ(i),LZ,Y_1DZ(i),Y_1SZ(i),Y_2DZ(e,i),Y_2SZ(e,i)
          Y_3DZ(i),Y_3SZ(i),A_DZ(i,j),A_SZ(i),Y_DZ(i),Y_SZ(i),A_XDZ(i)
          A_XSZ(i),A_YDZ(i),A_YSZ(i),G_DZ(i),G_SZ(i),I_DZ(i),I_SZ(i)
          C_DZ(i),C_SZ(i),C_CDZ(e),C_CSZ(e),CO2_hDZ(e),CO2_fDZ(e,i)
          M_DZ(i),X_SZ(i),I_HZ,BZ,SZ,S_HZ,S_GZ,TZ,T_DZ,T_YZ(i),T_MZ(i)
          S_F,p_WM(i),P_WX(i),alpha(i);

K_DZ(i)      = SAM("CAP",i);
KZ           = SAM("HOH",'CAP');
L_DZ(i)      = SAM("LAB",i);
LZ           = SAM("HOH",'LAB');
Y_1DZ(i)     = K_DZ(i)+L_DZ(i);
Y_1SZ(i)     = Y_1DZ(i);
Y_2DZ(e,i)   = SAM(e,i);
Y_2SZ(e,i)   = Y_2DZ(e,i);
Y_3DZ(i)     = Y_1DZ(i)+sum(e,Y_2DZ(e,i));
Y_3SZ(i)     = Y_3DZ(i);
A_DZ(i,j)    = SAM(i,j);
A_SZ(i)      = sum(j,A_DZ(i,j));
Y_DZ(i)      = Y_3DZ(i)+sum(ne,A_DZ(ne,i))+SAM("IDT",i);
Y_SZ(i)      = Y_DZ(i);
A_XDZ(i)     = Y_DZ(i)-SAM(i,"EXT");
A_XSZ(i)     = A_XDZ(i);
A_YDZ(i)     = A_XDZ(i)+SAM("EXT",i)+SAM("TRF",i);
A_YSZ(i)     = A_YDZ(i);
G_DZ(i)      = SAM(i,"GOV");
G_SZ(i)      = G_DZ(i);
I_DZ(i)      = SAM(i,"INV");
```

```
I_SZ(i)       = I_DZ(i);
C_DZ(i)       = SAM(i,"HOH");
C_SZ(i)       = C_DZ(i);
C_CDZ(e)      = SAM(e,"HOH");
C_CSZ(e)      = C_CDZ(e);
CO2_hDZ(e)    = CO2_h(e,"HOH");
CO2_fDZ(e,i) = CO2_f(e,i);
M_DZ(i)       = SAM("EXT",i);
X_SZ(i)       = SAM(i,"EXT");
I_HZ          = KZ+LZ;
BZ            = I_HZ-SAM("INV","HOH")-SAM("GOV","HOH");
SZ            = SAM("INV","HOH")+SAM("INV","GOV")+SAM("INV","EXT");
S_HZ          = SAM("INV","HOH");
S_GZ          = SAM("INV","GOV");
TZ            = SAM("GOV","HOH")+sum(i,SAM("IDT",i))+sum(i,SAM("TRF",i));
T_DZ          = SAM("GOV","HOH");
T_YZ(i)       = SAM("IDT",i);
T_MZ(i)       = SAM("TRF",i);
S_F           = SAM("INV","EXT");
p_WM(i)       = 1;
p_WX(i)       = 1;
alpha(i)      = sum(e,CO2_fDZ(e,i))/Y_SZ(i);

Display K_DZ,KZ,L_DZ,LZ,Y_1DZ,Y_1SZ,Y_2DZ,Y_2SZ,Y_3DZ,Y_3SZ,A_DZ,A_SZ,Y_DZ
        Y_SZ,A_XDZ,A_XSZ,A_YDZ,A_YSZ,G_DZ,G_SZ,I_DZ,I_SZ,C_DZ,C_SZ,C_CDZ
        C_CSZ,CO2_hDZ,CO2_fDZ,M_DZ,X_SZ,I_HZ,BZ,SZ,S_HZ,S_GZ,TZ,T_DZ,T_YZ
        T_MZ,S_F,p_WM,P_WX,alpha;

Parameter sigmma_E,sigmma_M,eta_X;

sigmma_E = 0.5;
sigmma_M = 4;
eta_X    = 4;

Display sigmma_E,sigmma_M,eta_X;

Parameter gamma_H(i),a_hE(e),s_sH,t_tD,gamma_G(i),s_sG,gamma_I(i),beta_K1(i)
          beta_L1(i),a_1(i),a_fE(e,i),a_3(i),beta_Y3(i),beta_A3(e,i),a_Y(i)
          a_A(i,j),a_X(i),beta_XA(i),beta_X(i),a_M(i),beta_MA(i),beta_M(i)
          t_tM(i),t_tY(i),CO2Z_f,CO2Z_all,CO2Z_each(i),phi(e,i);

gamma_H(ne)  = C_DZ(ne)/BZ;
gamma_H(e)   = C_CDZ(e)/BZ;
a_hE(e)      = CO2_hDZ(e)/C_CSZ(e);
s_sH         = S_HZ/I_HZ;
```

```
t_tD         = T_DZ/I_HZ;
gamma_G(i)   = G_DZ(i)/(TZ-S_GZ);
s_sG         = S_GZ/TZ;
gamma_I(i)   = I_DZ(i)/SZ;
beta_K1(i)   = K_DZ(i)/Y_1SZ(i);
beta_L1(i)   = L_DZ(i)/Y_1SZ(i);
a_1(i)       = Y_1SZ(i)/(K_DZ(i)**beta_K1(i)*L_DZ(i)**beta_L1(i));
a_fE(e,i)    = (CO2_fDZ(e,i)/Y_2SZ(e,i))$Y_2SZ(e,i);
beta_Y3(i)   = Y_1DZ(i)**(1/sigmma_E)/(Y_1DZ(i)**(1/sigmma_E)
               +sum(e,Y_2DZ(e,i)**(1/sigmma_E)));
beta_A3(e,i) = Y_2DZ(e,i)**(1/sigmma_E)/(Y_1DZ(i)**(1/sigmma_E)
               +sum(f,Y_2DZ(f,i)**(1/sigmma_E)));
a_3(i)       = Y_3SZ(i)/(beta_Y3(i)*Y_1DZ(i)**((sigmma_E-1)
               /sigmma_E)+sum(e,beta_A3(e,i)*Y_2DZ(e,i)
               **((sigmma_E-1)/sigmma_E)))**(sigmma_E/(sigmma_E-1));
a_Y(i)       = Y_3DZ(i)/Y_SZ(i);
a_A(ne,i)    = A_DZ(ne,i)/Y_SZ(i);
beta_XA(i)   = A_XSZ(i)**(-1/eta_X)/(A_XSZ(i)**(-1/eta_X)
               +(X_SZ(i)**(-1/eta_X))$X_SZ(i));
beta_X(i)    = (X_SZ(i)**(-1/eta_X))$X_SZ(i)/(A_XSZ(i)**(-1/eta_X)
               +(X_SZ(i)**(-1/eta_X))$X_SZ(i));
a_X(i)       = Y_DZ(i)/(beta_XA(i)*A_XSZ(i)**((eta_X+1)/eta_X)+beta_X(i)
               *X_SZ(i)**((eta_X+1)/eta_X))**(eta_X/(eta_X+1));
t_tM(i)      = (T_MZ(i)/M_DZ(i))$M_DZ(i);
beta_MA(i)   = A_XDZ(i)**(1/sigmma_M)/(A_XDZ(i)**(1/sigmma_M)
               +(1+t_tM(i))*M_DZ(i)**(1/sigmma_M));
beta_M(i)    = (1+t_tM(i))*M_DZ(i)**(1/sigmma_M)/(A_XDZ(i)
               **(1/sigmma_M)+(1+t_tM(i))*M_DZ(i)**(1/sigmma_M));
a_M(i)       = A_YSZ(i)/(beta_MA(i)*A_XDZ(i)**((sigmma_M-1)
               /sigmma_M)+beta_M(i)*M_DZ(i)**((sigmma_M-1)
               /sigmma_M))**(sigmma_M/(sigmma_M-1));
t_tY(i)      = T_YZ(i)/Y_SZ(i);
CO2Z_f       = sum(e,sum(i,CO2_fDZ(e,i)));
CO2Z_all     = sum(e,CO2_hDZ(e))+sum(e,sum(i,CO2_fDZ(e,i)));
CO2Z_each(i) = sum(e,CO2_fDZ(e,i));
phi(e,i)     = 1;

Display gamma_H,a_hE,s_sH,t_tD,gamma_G,s_sG,gamma_I,beta_K1,beta_L1,a_1
        a_fE,a_3,beta_Y3,beta_A3,a_Y,a_A,a_X,beta_XA,beta_X,a_M,beta_MA
        beta_M,t_tM,t_tY,CO2Z_f,CO2Z_all,CO2Z_each,phi;


Variable K_D(i),L_D(i),Y_1D(i),Y_1S(i),Y_2D(e,i),Y_2S(i,j),Y_3D(i),Y_3S(i)
         A_D(i,j),A_S(i),Y_D(i),Y_S(i),A_XD(i),A_XS(i),A_YD(i),A_YS(i)
         G_D(i),G_S(i),I_D(i),I_S(i),C_D(i),C_S(i),C_CD(e),C_CS(i)
```

```
         CO2_hD(e),CO2_fD(e,i),M_D(i),X_S(i),r,w,p_Y1(i),p_Y2(e,i),p_Y3(i)
         p_A(i),p_Y(i),p_XA(i),p_AY(i),p_G(i),p_I(i),p_C(i),p_CC(e)
         p_CO2,epsilon,I_H,B,S,S_H,S_G,T,T_D,T_Y(i),T_M(i),P_M(i),P_X(i);

Equation EQK_D(i),EQL_D(i),EQY_1D(i),EQY_1S(i),EQY_2D(e,i),EQY_2S(e,i)
         EQY_3D(i),EQY_3S(i),EQA_D(i,j),EQA_S(i),EQY_D(i),EQY_S(i)
         EQA_XD(i),EQA_XS(i),EQA_YD(i),EQA_YS(i),EQG_D(i),EQG_S(i)
         EQI_D(i),EQI_S(i),EQC_D(i),EQC_S(i),EQC_CD(e),EQC_CS(e)
         EQCO2_hD(e),EQCO2_fD(e,i),EQM_D(i),EQX_S(i),EQr,EQw
         EQp_Y1(i),EQp_Y2(e,i),EQp_Y3(i),EQp_A(i),EQp_Y(i)
         EQp_XA(i),EQp_AY(i),EQp_G(i),EQp_I(i),EQp_C(i),EQp_CC(e)
         EQp_CO2,EQepsilon,EQI_H,EQB,EQS,EQS_H,EQS_G,EQT,EQT_D,EQT_Y(i)
         EQT_M(i),EQp_M(i),EQp_X(i);

EQK_D(i)..         K_D(i)    =e= beta_K1(i)*p_Y1(i)*Y_1S(i)/r;
EQL_D(i)..         L_D(i)    =e= beta_L1(i)*p_Y1(i)*Y_1S(i)/w;
EQY_1D(i)..        Y_1D(i)   =e= (a_3(i)**((sigmma_E-1)/sigmma_E)*beta_Y3(i)
                                 *p_Y3(i)/p_Y1(i))**sigmma_E*Y_3S(i);
EQY_1S(i)..        Y_1S(i)   =e= a_1(i)*K_D(i)**beta_K1(i)*L_D(i)**beta_L1(i);
EQY_2D(e,i)..      Y_2D(e,i) =e= (a_3(i)**((sigmma_E-1)/sigmma_E)
                                 *beta_A3(e,i)*p_Y3(i)/p_Y2(e,i))
                                 **sigmma_E*Y_3S(i)*phi(e,i)**(sigmma_E-1);
EQY_2S(e,i)..      p_Y2(e,i)*Y_2S(e,i)-(p_A(e)*A_D(e,i)+p_CO2*CO2_fD(e,i))=e= 0;
EQY_3D(i)..        Y_3D(i)   =e= a_Y(i)*Y_S(i);
EQY_3S(i)..        Y_3S(i)   =e= a_3(i)*(beta_Y3(i)*Y_1D(i)**((sigmma_E-1)
                                 /sigmma_E)+sum(e$Y_2DZ(e,i),beta_A3(e,i)
                                 *(phi(e,i)*Y_2D(e,i))**((sigmma_E-1)/sigmma_E)))
                                 **(sigmma_E/(sigmma_E-1));
EQA_D(j,i)..       A_D(j,i)  =e= Y_2S(j,i)$e(j)+(a_A(j,i)*Y_S(i))$ne(j);
EQA_S(i)..         p_A(i)    =e= p_AY(i);
EQY_D(i)..         Y_D(i)    =e= a_X(i)*(beta_XA(i)*A_XS(i)**((eta_X+1)/eta_X)
                                 +(beta_X(i)*X_S(i)**((eta_X+1)/eta_X))
                                 $X_SZ(i))**(eta_X/(eta_X+1));
EQY_S(i)..         (1-t_tY(i))*p_Y(i)*Y_S(i)+alpha(i)*p_CO2*Y_S(i)
                   -(p_Y3(i)*Y_3D(i)+sum(ne,p_A(ne)*A_D(ne,i))) =e= 0;
EQA_XD(i)..        A_XD(i)   =e= (a_M(i)**((sigmma_M-1)/sigmma_M)
                                 *beta_MA(i)*p_AY(i)/p_XA(i))**sigmma_M*A_YS(i);
EQA_XS(i)..        A_XS(i)   =e= (a_X(i)**((eta_X+1)/eta_X)*beta_XA(i)*p_Y(i)
                                 /p_XA(i))**(-eta_X)*Y_D(i);
EQA_YD(i)..        A_YD(i)   =e= C_S(i)+G_S(i)+I_S(i)+A_S(i);
EQA_YS(i)..        A_YS(i)   =e= a_M(i)*(beta_MA(i)*A_XD(i)**((sigmma_M-1)
                                 /sigmma_M)+(beta_M(i)*M_D(i)**((sigmma_M-1)
                                 /sigmma_M))$M_DZ(i))**(sigmma_M/(sigmma_M-1));
EQG_D(i)..         G_D(i)    =e= gamma_G(i)*(T-S_G)/p_G(i);
EQG_S(i)..         p_G(i)    =e= p_AY(i);
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```
EQI_D(i)..         I_D(i)    =e= gamma_I(i)*S/p_I(i);
EQI_S(i)..         p_I(i)    =e= p_AY(i);
EQC_D(i)..         C_D(i)    =e= (gamma_H(i)*B/p_C(i))$ne(i)+C_CS(i)$e(i);
EQC_S(i)..         p_C(i)    =e= p_AY(i);
EQC_CD(e)..        C_CD(e)   =e= gamma_H(e)*B/p_CC(e);
EQC_CS(e)..        p_CC(e)*C_CS(e)-p_C(e)*C_D(e) =e= 0;
EQCO2_hD(e)..      CO2_hD(e) =e= a_hE(e)*C_CS(e);
EQCO2_fD(e,i)..    CO2_fD(e,i) =e= a_fE(e,i)*Y_2S(e,i);
EQM_D(i)..         M_D(i)    =e= (a_M(i)**((sigmma_M-1)/sigmma_M)
                                 *beta_M(i)*p_AY(i)/((1+t_tM(i))*p_M(i)))
                                 **sigmma_M*A_YS(i);
EQX_S(i)..         X_S(i)    =e= ((a_X(i)**((eta_X+1)/eta_X)*beta_X(i)
                                 *p_Y(i)/p_X(i))**(-eta_X))$beta_X(i)*Y_D(i);
EQr..              sum(i,K_D(i)) =e= KZ;
EQw..              sum(i,L_D(i)) =e= LZ;
EQp_Y1(i)..        Y_1D(i)   =e= Y_1S(i);
EQp_Y2(e,i)..      Y_2D(e,i) =e= Y_2S(e,i);
EQp_Y3(i)..        Y_3D(i)   =e= Y_3S(i);
EQp_A(i)..         sum(j,A_D(i,j)) =e= A_S(i);
EQp_Y(i)..         Y_D(i)    =e= Y_S(i);
EQp_XA(i)..        A_XD(i)   =e= A_XS(i);
EQp_AY(i)..        A_YD(i)   =e= A_YS(i);
EQp_G(i)..         G_D(i)    =e= G_S(i);
EQp_I(i)..         I_D(i)    =e= I_S(i);
EQp_C(i)..         C_D(i)    =e= C_S(i);
EQp_CC(e)..        C_CD(e)   =e= C_CS(e);
EQp_CO2..          sum(i,alpha(i)*Y_S(i)) =g= sum(e,sum(i,CO2_fD(e,i)));
EQepsilon..        sum(i,p_WM(i)*M_D(i))  =e= sum(i,p_WX(i)*X_S(i))+S_F;
EQI_H..            r*KZ+w*LZ =e= I_H;
EQB..              I_H-(S_H+T_D) =e= B;
EQS..              S         =e= S_H+S_G+epsilon*S_F;
EQS_H..            S_H       =e= s_sH*I_H;
EQS_G..            S_G       =e= s_sG*T;
EQT..              T         =e= T_D+sum(i,T_Y(i))+sum(i,T_M(i));
EQT_D..            T_D       =e= t_tD*I_H;
EQT_Y(i)..         T_Y(i)    =e= t_tY(i)*p_Y(i)*Y_S(i);
EQT_M(i)..         T_M(i)    =e= t_tM(i)*p_M(i)*M_D(i);
EQp_M(i)..         p_M(i)    =e= epsilon*p_WM(i);
EQp_X(i)..         p_X(i)    =e= epsilon*p_WX(i);

K_D.l(i)      = K_DZ(i);
L_D.l(i)      = L_DZ(i);
Y_1D.l(i)     = Y_1DZ(i);
Y_1S.l(i)     = Y_1SZ(i);
Y_2D.l(e,i)   = Y_2DZ(e,i);
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```
Y_2S.l(e,i)    = Y_2SZ(e,i);
Y_3D.l(i)      = Y_3DZ(i);
Y_3S.l(i)      = Y_3SZ(i);
A_D.l(i,j)     = A_DZ(i,j);
A_S.l(i)       = A_SZ(i);
Y_D.l(i)       = Y_DZ(i);
Y_S.l(i)       = Y_SZ(i);
A_XD.l(i)      = A_XDZ(i);
A_XS.l(i)      = A_XSZ(i);
A_YD.l(i)      = A_YDZ(i);
A_YS.l(i)      = A_YSZ(i);
G_D.l(i)       = G_DZ(i);
G_S.l(i)       = G_SZ(i);
I_D.l(i)       = I_DZ(i);
I_S.l(i)       = I_SZ(i);
C_D.l(i)       = C_DZ(i);
C_S.l(i)       = C_SZ(i);
C_CD.l(e)      = C_CDZ(e);
C_CS.l(e)      = C_CSZ(e);
CO2_hD.l(e)    = CO2_hDZ(e);
CO2_fD.l(e,i) = CO2_fDZ(e,i);
M_D.l(i)       = M_DZ(i);
X_S.l(i)       = X_SZ(i);
r.l            = 1;
w.l            = 1;
p_Y1.l(i)      = 1;
p_Y2.l(e,i)    = 1;
p_Y3.l(i)      = 1;
p_A.l(i)       = 1;
p_Y.l(i)       = 1;
p_XA.l(i)      = 1;
p_AY.l(i)      = 1;
p_G.l(i)       = 1;
p_I.l(i)       = 1;
p_C.l(i)       = 1;
p_CC.l(e)      = 1;
p_CO2.l        = 0;
epsilon.l      = 1;
I_H.l          = I_HZ;
B.l            = BZ;
S.l            = SZ;
S_H.l          = S_HZ;
S_G.l          = S_GZ;
T.l            = TZ;
T_D.l          = T_DZ;
```

```
T_Y.l(i)       = T_YZ(i);
T_M.l(i)       = T_MZ(i);
p_M.l(i)       = 1;
p_X.l(i)       = 1;

r.lo           = 0.001;
w.lo           = 0.001;
p_Y1.lo(i)     = 0.001;
p_Y2.lo(e,i)   = 0.001;
p_Y3.lo(i)     = 0.001;
p_A.lo(i)      = 0.001;
p_Y.lo(i)      = 0.001;
p_XA.lo(i)     = 0.001;
p_AY.lo(i)     = 0.001;
p_G.lo(i)      = 0.001;
p_I.lo(i)      = 0.001;
p_C.lo(i)      = 0.001;
p_CC.lo(e)     = 0.001;
p_CO2.lo       = 0;
epsilon.lo     = 0.001;
p_M.lo(i)      = 0.001;
p_X.lo(i)      = 0.001;

Y_1D.lo(i)     = 1e-6;
Y_2D.lo(e,i)   = 1e-6;

w.fx           = 1;

Model dynamic_rate_based_mcp

      /EQK_D.K_D,EQL_D.L_D,EQY_1D.Y_1D,EQY_1S.Y_1S,EQY_2D.Y_2D,EQY_2S.Y_2S
       EQY_3D.Y_3D,EQY_3S.Y_3S,EQA_D.A_D,EQA_S.A_S,EQY_D.Y_D,EQY_S.Y_S
       EQA_XD.A_XD,EQA_XS.A_XS,EQA_YD.A_YD,EQA_YS.A_YS,EQG_D.G_D,EQG_S.G_S
       EQI_D.I_D,EQI_S.I_S,EQC_D.C_D,EQC_S.C_S,EQC_CD.C_CD,EQC_CS.C_CS
       EQCO2_hD.CO2_hD,EQCO2_fD.CO2_fD,EQM_D.M_D,EQX_S.X_S,EQr.r,EQw.w
       EQp_Y1.p_Y1,EQp_Y2.p_Y2,EQp_Y3.p_Y3,EQp_A.p_A,EQp_Y.p_Y,EQp_XA.p_XA
       EQp_AY.p_AY,EQp_G.p_G,EQp_I.p_I,EQp_C.p_C,EQp_CC.p_CC,EQp_CO2.p_CO2
       EQepsilon.epsilon,EQI_H.I_H,EQB.B,EQS.S,EQS_H.S_H,EQS_G.S_G,EQT.T
       EQT_D.T_D, EQT_Y.T_Y,EQT_M.T_M,EQp_M.p_M,EQp_X.p_X/;

dynamic_rate_based_mcp.iterlim = 10000;
Solve dynamic_rate_based_mcp using mcp;

Set time /2005*2020/;
```

```
Parameter l_GDP,l_CO2,roc_GDP,roc_CO2,dp_CO2,dCO2_,GDPZ_,GDP_,dGDP_
          KZ0,LZ0,alpha0(i),lambda_L,lambda_E;

KZ0       = KZ;
LZ0       = LZ;
alpha0(i) = alpha(i);
lambda_L  = 0.00237;
lambda_E  = 0.04555;

Parameter l_CO2_f;

l_CO2_f(e,i)          = yes;
l_CO2_f("foss","p_c") = no;

Display l_co2_f;

Loop(time,

     Solve dynamic_rate_based_mcp using mcp;

     dCO2_(time,"bau") = ((sum(e,CO2_hD.l(e))+sum(e,sum(i,CO2_fD.l(e,i))))
                         /CO2Z_all-1)*100;
     GDPZ_(time,"bau") = sum(ne,C_DZ(ne))+sum(e,C_CDZ(e))+sum(i,I_DZ(i))
                         +sum(i,G_DZ(i))+sum(i,X_SZ(i))-sum(i,M_DZ(i));
     GDP_(time,"bau")  = sum(ne,C_D.l(ne))+sum(e,C_CD.l(e))+sum(i,I_D.l(i))
                         +sum(i,G_D.l(i))+sum(i,X_S.l(i))-sum(i,M_D.l(i));
     dGDP_(time,"bau") = (GDP_(time,"bau")/GDPZ_(time,"bau")-1)*100;
     l_CO2(time,"bau") = sum(e,CO2_hD.l(e))+sum(e,sum(i,CO2_fD.l(e,i)));
     roc_CO2(time,"bau")$l_CO2(time-1,"bau")
                       = 100*(l_CO2(time,"bau")/l_CO2(time-1,"bau")-1);
     l_GDP(time,"bau") = GDP_(time,"bau");
     roc_GDP(time,"bau")$l_GDP(time-1,"bau")
                        = 100*(l_GDP(time,"bau")/l_GDP(time-1,"bau")-1);
     dp_CO2(time,'bau') = p_CO2.l;
     KZ  = (1-0.064)*KZ+KZ/1446904*sum(i,I_D.l(i));
     LZ  = (1+lambda_L)*LZ;
     phi(e,i)$l_CO2_f(e,i) = (1+lambda_E)*phi(e,i);

);

Display l_CO2,l_GDP,roc_CO2,roc_GDP,dp_CO2,dCO2_,GDPZ_,GDP_,dGDP_;

KZ       = KZ0;
LZ       = LZ0;
phi(e,i) = 1;
```

```
Loop(time,

     alpha(i) = alpha(i)-(alpha0(i)-0.6523287*alpha0(i))/16;

    Solve dynamic_rate_based_mcp using mcp;

     dCO2_(time,"lim") = ((sum(e,CO2_hD.l(e))+sum(e,sum(i,CO2_fD.l(e,i))))
                         /CO2Z_all-1)*100;
     GDPZ_(time,"lim") = sum(ne,C_DZ(ne))+sum(e,C_CDZ(e))+sum(i,I_DZ(i))
                         +sum(i,G_DZ(i))+sum(i,X_SZ(i))-sum(i,M_DZ(i));
     GDP_(time,"lim")  = sum(ne,C_D.l(ne))+sum(e,C_CD.l(e))+sum(i,I_D.l(i))
                         +sum(i,G_D.l(i))+sum(i,X_S.l(i))-sum(i,M_D.l(i));
     dGDP_(time,"lim") = (GDP_(time,"lim")/GDPZ_(time,"lim")-1)*100;
     l_CO2(time,"lim") = sum(e,CO2_hD.l(e))+sum(e,sum(i,CO2_fD.l(e,i)));
     roc_CO2(time,"lim")$l_CO2(time-1,"lim")
                       = 100*(l_CO2(time,"lim")/l_CO2(time-1,"lim")-1);
     l_GDP(time,"lim") = GDP_(time,"lim");
     roc_GDP(time,"lim")$l_GDP(time-1,"lim")
                        = 100*(l_GDP(time,"lim")/l_GDP(time-1,"lim")-1);
     dp_CO2(time,’lim’) = p_CO2.l;
     KZ  = (1-0.064)*KZ+KZ/1446904*sum(i,I_D.l(i));
     LZ  = (1+lambda_L)*LZ;
     phi(e,i)$l_CO2_f(e,i) = (1+lambda_E)*phi(e,i);

);

Display l_CO2,l_GDP,roc_CO2,roc_GDP,dp_CO2,dCO2_,GDPZ_,GDP_,dGDP_;

Execute_unload "results_dynamic_rate_based_mcp.gdx", l_CO2,l_GDP,dp_CO2;
```