Economic Growth and Carbon Emissions with Endogenous Carbon Taxes

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Abstract

In this paper, we explore the effects of the further economic growth on carbon emissions. Our approach has the following two features. First, we employ a multi-sector, multi-region recursive CGE model. Second, we explicitly consider the dependence of carbon regulations on income levels. We incorporate into the model the positive relationship between the level of carbon tax and per capita income, and make the level of carbon tax determined endogenously. Our main finding is summarized as follows. Although economic growth raises per capita income and, therefore, carbon taxes are strengthened in all regions, emissions increase significantly in all regions. This is because the estimated responsiveness of carbon taxes to income changes is too weak to restrain emissions. We test this finding by doing some sensitivity analysis and found that the above results are unchanged. Thus, our conclusion is that carbon emissions are likely to increase throughout the world with further economic growth even if we take account of the dependence of carbon regulation on income level.

Keywords: Computable general equilibrium model; the environmental Kuznets curve; carbon emissions; carbon tax; endogenous regulation; economic growth.

JEL Classification: O13; Q56.

1 Introduction

It is widely known that emissions of GHGs from anthropogenic activities have been increasing dramatically and at an unprecedented rate over recent decades. This has lead to a rapid increase in atmospheric GHG concentration, which has begun to affect the global climate (IPCC, 2001b). Much evidence suggests that these climate changes have had adverse effects on physical, biological, and human systems (see IPCC, 2001a). Moreover, there is a widespread concern that continuing global climate change is likely to have a significant influence on the global environment, which could be irreversible and hazardous.

To assess the future trends of global climate change, it is necessary to project future GHG emissions. Projections of future GHG emissions are made by many institutions and researchers (for example, IPCC, 2000; EIA, 2001). Most forecasters project that global GHG emissions will continue to rise with world economic growth. However, it is often pointed out that some types of

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emissions or pollutants have not necessarily increased with economic growth, and there is empirical evidence of a quadratic relationship between emissions and economic growth. That is, emissions (or pollutants) increase with income growth at low levels of per capita income but then decrease at higher levels of per capita income. This relationship between emissions and per capita income is known as the *inverted-U relationship* or the environmental Kuznets curve (hereafter, EKC). The following empirical studies derive the EKC between emissions and per capita income: Grossman and Krueger (1993, 1995), Selden and Song (1994), Gale and Mendez (1998), and Antweiler et al. (2001). Most of these studies investigate the relationship between air or water pollutants and economic growth (or increases in income).

So-called *scale* and *technique* effects are often used to explain the existence of the EKC (for example, Grossman and Krueger 1993, Antweiler et al. 2001). The argument is as follows. On the one hand, economic growth causes an expansion of production and consumption activities, which tends to increase emissions. This is the scale effect. On the other hand, economic growth raises per capita income. The increase in per capita income raises people's concerns over environmental quality, which produces stricter environmental regulations through the political process. Therefore emissions tend to decrease as a result of increases in per capita income. This latter effect is called the technique effect because stricter regulations typically lead to the adoption of cleaner technology[1]. These two offsetting effects explain the observed EKC. At low per capita incomes, the scale effect dominates the technique effect, and thus, emissions increase along with per capita income. However, as per capita income increases, the technique effect strengthens, eventually offsetting the scale effect to produce decreasing emissions as per capita income increases further.

To sum up, the argument of the EKC views economic growth in relation to the endogenous nature of environmental regulations. This endogeneity (or dependence on income) of environmental regulations could be crucial for designing policies for environmental protection because it means that restraining economic growth may harm the environment in the long run.

From the same point of view, Holtz-Eakin and Selden (1995) have investigated the relationship between carbon emissions and per capita income. Their approach and results are summarized as follows. They estimated a reduced-form equation in which per capita carbon emissions are the dependent variable and income per capita is an explanatory variable, using panel data on 130 countries from 1951 to 1985.[2] Furthermore, they projected future carbon emissions using the estimated equation. Their findings are summarized as follows. (i) There is an EKC between per capita income and per capita carbon emissions. (ii) The value of per capita income at the turning point is very high (US$35,428 in 1985) and lies outside the range of incomes in their sample (their largest income value is US$15,000). (iii) Global carbon emissions are likely to continue to rise in the coming decades because the per capita incomes of most growing countries remain below the turning-point income and, at the same time, the population in these regions will continue to rise.

Their approach is the standard one commonly employed in studies on the EKC, but has the following shortcomings. First, the estimated equation is a reduced-form equation and does not have a rigorous theoretical foundation. Although one may be able to interpret the relationship between per capita carbon emissions and per capita income in terms of the two effects mention above, it is unclear from their analysis whether such an interpretation is appropriate. Moreover, their analysis provides no detail of what economic growth brings to economies. For example, if emissions increase in a region with economic growth, there are many possible reasons for this, including changes in technology, changes in energy composition, and changes in patterns of production and consumption. Their analysis provides no answer to this question.

The second problem relates to the data used in their analysis. As pointed out above, the EKC is usually interpreted in terms of scale and technique effects. It is reasonable to suppose that

[1]The term "technique effect" may indicate that the effect is related to purely technological aspect and not related to people's preference. But it is not true bacause cleaner technology is adopted only if people's concerns over environments has grown.

[2]The estimated equation is:

$$c_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 y_{it}^2 + \gamma_t + f_i + \varepsilon_{it} \tag{1}$$

where i and t are country and time indices respectively, c_{it} is per capita carbon emissions, y_{it} is per capita income, and γ_t, f_i, and the βs are parameters to be estimated.

the technique effect is due to stricter emission regulations because it is implausible that citizens and firms voluntarily adopt cleaner technologies or decrease their consumption of polluting goods. However, no regulations on carbon emissions were adopted by any of the countries during the period covered by their data, 1951–1985. This means that there is no reason to expect an EKC for this period. Nevertheless, they estimated an EKC but offer no explanation for it. Moreover, they projected ahead using the estimated equation. It follows that their projections do not incorporate any policy effects (technique effects) because no policy was adopted during the period covered by the data used for estimation. To take account of the fact that the regulations on carbon emissions, such as the one embodied in the Kyoto Protocol, are likely to be adopted in the near future (UNFCCC, 1997), it seems inappropriate to project into the future without considering policy interventions.

In this paper, we also investigate the relationship between carbon emissions and economic growth. Our approach has the following characteristics. First, we employ the multisector, multiregion CGE models that are widely used in analyses of carbon emissions — for example, Jorgenson and Wilcoxen (1993), Bernstein et al. (1999), McKibbin et al. (1999), Paltsev (2000a,b), Böhringer (2000), and Babiker and Rutherford (2001). The multisector, multiregion CGE model has a number of advantages. First, we can investigate in detail changes associated with economic growth, such as changes in energy composition and energy intensity. Moreover, we can clarify the effects of regulations on emissions. This advantage is noteworthy in comparison with econometric methods in which reduced-form equations are estimated, because this latter approach is not suitable for policy analysis.

The second feature of this paper is that we explicitly consider the dependence of carbon regulations on income levels. In previous studies of the EKC including the one by Holtz-Eakin and Selden (1995), regulations on emissions have not been considered explicitly. Moreover, it is often the case that they do not distinguish scale and technique effects although they use the technique effect (regulations) in interpreting the estimation results. By contrast, we explicitly consider the dependence of regulations on income levels and incorporate it into the model. This approach enables evaluation of the details of the consequences of economic growth not only in terms of the direct scale effects but also in terms of the indirect technique effects, as well as evaluation of the strength of both effects separately.

The key aspect of our analysis is the method of incorporating the endogeneity of emission regulations into the model — that is, how regulations depend on income levels. As has already been pointed out, no regulations have so far been adopted (except for minor carbon taxes in several developed countries since the 1990s). Therefore, since we cannot determine any meaningful relationship from past data, we must take another approach. The approach we employ is to make use of the fact that Kyoto Protocol-type emission regulations are likely to be adopted in the near future. We presume that Kyoto Protocol-type emission regulations are imposed on economies in 2010 and then derive the relationship between income and the regulations from the consequences of such a policy intervention.

The main objective of our analysis is to clarify the impact of economic growth on carbon emissions when emission regulations are determined endogenously. In particular, we aim to answer the question of whether economic growth increases carbon emissions. Our numerical analyses yield the following results. Although economic growth raises per capita income and, therefore, emission regulations are strengthened in all regions, emissions increase significantly in all regions. This means that the EKC between income and carbon emissions is not likely to arise even if we take account of the fact that large scale emission regulations will be implemented in the near future. The reason for this result is that the responsiveness of regulations to income changes, which is inferred from the Kyoto Protocol-type regulations, is too weak to restrain emissions; in other words, the technique effects are much smaller than the scale effects. We test this finding by doing some sensitivity analysis on the responsiveness of the regulations, and find that the above results are unchanged. Thus, our conclusion is that although the EKC argument suggests that economic growth does not necessarily damage the environment, the argument is unlikely to apply to carbon emissions.

The remainder of the paper is organized as follows. Section 2 describes the model. Section 3 and

Table 1: The list of regions and sectors in the model.

Figure 1: The nesting structure of Fossil fuel sector.

4 describe the dataset, parameters, and the method of deriving the relationship between income and the regulations. Section 5 presents the numerical results of the simulation and interprets them, and Section 6 conducts sensitivity analysis. Finally, Section 7 provides concluding remarks.

2 The Model

In this section, we present the structure of the model used for the simulation. The detailed description of the model is provided the supplementary paper available from the author. The model is a multisector, multiregion recursive dynamic model. The periods range from 1997 (the benchmark year) to 2020. The structure of the model within a period is based on the GTAP–EG (Rutherford and Paltsev, 2000) and the GTAP standard model (Hertel, 1997).

The world is divided into 13 regions, and each economy has eight production sectors. The lists of regions and sectors of the model are provided in Table 1. Regions are chosen to be compatible with those employed in *International Energy Outlook 2001* (EIA, 2001, hereafter, EIA dataset). There are six Annex I regions and seven non-Annex I regions. Note that we assume that US is included in Annex I regions. Since the US government declared that he will not ratify Kyoto Protocol, this assumption may not be realistic. However, even if the US government will not ratify Kyoto Protocol, it is likely that he will take some measures to reduce carbon emissions. Thus, in the base case, we assume that US joins Annex I regions. In the sensitivity analysis, we also consider the case where US does not join Annex I regions.

2.1 Production Structure

Production structure and the specification of elasticity parameters are almost the same as Rutherford and Paltsev (2000). It is assumed that all production sectors have a nested CES type structure. We also assume that goods produced for the domestic market and goods produced for the export market are differentiated and that there is a constant elasticity of transformation (CET) relationship between domestic and exported goods. The production sectors are divided into two types, fossil fuel and non-fossil fuel sectors, and we assume that these have different production structures.

First, let us consider fossil fuel sectors. Fossil fuel production activities include the extraction of crude oil (CRU), natural gas (GAS), and coal (COL). Its production structure is presented in Fig. 1, where a value or a sigma represent an elasticity of substitution (see Section 3 for the values of elasticity of substitution). Fossil fuel output is produced as an CES aggregate of a resource input and a non-resource input composite. The non-resource input for production is a fixed coefficient (Leontief) composite of labor and non-resource intermediate inputs. The elasticity of substitution between non-resource intermediates and labor is equal to zero. Fossil fuel resource inputs are assumed to be sector-specific, and thus their rates of return vary across sectors.

On the other hand, non-fossil fuel production (including electricity and refined oil) has a different structure from that of the fossil fuel sectors. Fig. 2 illustrates the nesting and elasticities of substitution employed in non-fossil production sectors. Non-fossil fuel output is produced with fixed coefficient (Leontief) aggregation of non-energy intermediates and an energy-primary factor composite. The energy composite and primary factor composite are aggregated through a CES function with an elasticity of σ_{PFE}. The primary factor composite is a CES aggregation of labor and capital stock with an elasticity of σ_{PF}. The energy composite is a CES aggregation of electricity and a non-electric energy input composite with an elasticity of substitution of σ_E. The non-electric energy is a CES aggregation of coal and liquid energy composites. The liquid energy composite is a CES aggregation of gas and refined oil.

Figure 2: The nesting structure of non-fossil fuel sector.

Figure 3: Utility function.

2.2 International trade

To explain bilateral cross-hauling in goods trade, we use the so-called Armington assumption: goods produced in different regions are qualitatively distinct (Armington, 1969). We assume that goods produced in different regions are aggregated through a CES function. This aggregation is conducted in two stages. First, imports from different regions are aggregated into an import composite. Second, an import composite and domestic goods are aggregated into a composite (Armington composite). The Armington composite is used for both final consumption and intermediate input in production.

2.3 Final Demand Structure

The representative agent's utility has the structure depicted in Fig. 3, in which utility is a nested Cobb–Douglas aggregation of savings and final goods consumption. The Cobb–Douglas specification means that the shares of savings and expenditure on goods in total expenditure are constant. Final consumption is a CES aggregation of a non-energy composite and an energy composite with an elasticity of substitution of σ_C. The non-energy composite is a Cobb–Douglas aggregate of non-energy goods, and the energy composite is a Cobb–Douglas aggregate of final energy (refined oil, gas, and coal) and electricity.

The representative agent makes decisions to maximize utility subject to the budget constraint. The agent's income is derived from (i) factor income (capital, labor, and fossil fuel resources), and (ii) tax revenues (from output taxes, intermediate inputs taxes, consumption taxes, and trade taxes). We assume that endowments of primary factors are exogenously constant within a period.[3]

2.4 Investment and Dynamic Structure

Since we assume that money can freely move across regions, investment and savings in a region need not be equalized. As already described, savings are determined through utility maximization of a representative agent. On the other hand, we assume that regional investment (investment in a region) is determined in the same way as the standard GTAP model. That is, regional investment is determined so that the expected rate of return from capital stock is equalized across regions.[4] Regional investment is collected into the global investment sector and converted to saving goods and allocated to each region.

Our model is a recursive one and solved successively for each period. The time span for our analysis is 24 periods (from 1997 to 2020). In each period, given the beginning-of-period capital stock, the static model is solved and the level of investment in that period is determined. Then, we can derive the beginning-of-period capital stock in the next period by adding net investment (gross investment less depreciation) to the current capital stock. Following the same procedure, equilibria in subsequent periods are solved successively.

2.5 Government

We assume that government expenditure is included in final consumption (final demand) of a representative agent and that all tax revenues are transferred to a representative agent through lump-sum fashion. Thus, government does not appear in the model explicitly.

[3] Note that endowments of capital and labor change over time.

[4] In the standard GTAP model, there is another type of investment decision. That is, regional investment is determined so that share of each region's capital stock is fixed. In this paper, we do not employ this approach.

2.6 Carbon Emissions and Carbon Tax

Carbon emissions are assumed to be generated from consumption (intermediate inputs and final consumption) of fossil fuels (OIL, GAS, and COL). This means that carbon emissions from fossil fuel sectors and international transport sector are not taken into account. The carbon tax in our model is a specific tax on carbon emissions.

3 Benchmark Datasets and Parameters

For the benchmark dataset, we use a global economic-energy dataset, GTAP–EG provided by Rutherford and Paltsev (2001). GTAP–EG is the data set in which the global economic dataset, GTAP version 5.3 (see Hertel, 1997) and the International Energy Agency (IEA) energy datasets are combined (see Rutherford and Paltsev, 2000, for details).[5] We aggregate the GTAP–EG dataset to sectors and regions in this paper, using the aggregation routine program provided by GTAP–EG. The benchmark year for the data is 1997.

Next, we explain the specification of parameters. Parameters here mean variables which are not determined endogenously in the model. Most of the parameters are given exogenously, but some of them are calibrated. Parameters presented here are (1) population, (2) labor growth rate, (3) technology growth rate, and (4) elasticity parameters.

Population

In the simulation later, we consider per capita income in each region. To derive per capita income, it is necessary to project population of each region. For this, we use the population projection in EIA dataset.[6]

Labor and Technology Growth

Since we employ a recursive dynamic model, regions in the model grow over time through accumulation of the capital stock. In addition to capital accumulation, we add two sources of economic growth into the model, namely, (1) increase in labor endowment, and (2) technology improvement.

As to labor endowment, we assume that the growth rate of labor endowment is equal to population growth rate. As to technology improvement, we assume that it has a form of labor–capital augmented technology change and that this technology improvement occurs only in non-fossil fuel sectors.[7] The rate of technology growth is determined so that the GDP growth rates derived from the model become close to the GDP growth rates projected in EIA dataset (EIA, 2001).[8]

Elasticity of substitution

Table 2 presents values of elasticity of substitution. Most of them are taken from Rutherford and Paltsev (2000). As to σ_{NEL} (elasticity of substitution between coal and liquidity energy) and σ_{LQD} (elasticity of substitution between oil and gas), we use slightly higher values than the original values. They are adjusted so that emission shares of final energy derived from our model become close to projected shares in EIA dataset. As to these elasticity parameters, we conduct sensitivity analysis in Section 6.

[5] The GTAP datasets are widely used in numerical analyses, primarily of trade policy. See the GTAP web site.

[6] For the population data, see the supplementary paper.

[7] Although there are various types of technology improvement, we assume a quite simple form. This is because complicated technology specification requires much data in our global model.

[8] We do not take account of technology improvement for energy inputs. However, it does not mean that energy efficiency (energy required to produce one dollar of outputs) is not improved because labor–capital augmented technology improvement raises energy efficiency indirectly.

Table 2: Value of elasticity parameters

Elasticity of subsection between fossil fuel resources and other inputs

Elasticity of substitution between fossil fuel resources and other inputs in fossil fuel sectors ($\sigma_{R,i}$, i = CRU, COL, GAS) is calibrated from a benchmark value of the fossil fuel supply elasticity (ε_i^S). The values of the fossil fuel supply elasticity is determined so that carbon emissions of each regions become close to projected emissions in EIA dataset. As the benchmark supply elasticity, we assume 0.6 for CRU, 2.2 for COL, and 0.1 for GAS.

4 Endogenous carbon tax

In this section, we explain the approach used to derive the relationship between per capita income and carbon tax. The key aspect of our analysis is the method used to endogenize carbon regulations (carbon tax). At least two approaches to this immediately suggest themselves:

Approach 1: to assume, as do standard theoretical models that deal with endogenous regulations,[9] that government sets carbon tax to maximize an objective. For example, to assume that government determines the level of carbon tax so as to maximize social welfare.

Approach 2: to assume a relationship between carbon regulation and income level and then estimate it from past data. For example, assume that the level of carbon tax is a linear function of income level and estimate parameters from past data of carbon tax and income level.

Although carbon tax does not directly depend on income level in approach 1, a positive relation between carbon tax and income level is usually derived from it. In this sense, we can regard it as an approach that connects carbon tax with income level. In this paper, we do not employ these two approaches. Before presenting the approach in this paper, we explain reasons why we do not use the above approaches. Let us start with Approach 1.

Approach 1

An assumption that the government chooses the optimal level of carbon tax means that he takes account of externality caused by increase in carbon emissions. As types of externality, we can consider at least the following two types: externality on production function and externality on utility function. First, let us assume that carbon emissions affect production function. Since many researches predict that climate change can have substantial impacts on some industries such as agriculture and travel industry, this is a plausible assumption. However, even if the assumption is true, in order to incorporate it into simulation, we need to numerically specify how carbon emissions affect production. In particular, for our model with multi-regions and multi-sectors, we need to specify externality for all sectors in all regions. Needless to say, it is very difficult to do.

In addition, even if it is possible to predict impacts from climate change on production correctly, there is little point in incorporating such effects into this model because the time span considered in the model covers only 1997 to 2020. It may be true that climate change can have large impacts in the long run, but it seems likely that influences in the next 15 years are very small. If externality effects are small, it is meaningless to consider such effects.

Next, let us consider externality which affects utility in stead of production. Two interpretations are possible for this type of externality: (a) climate change affects utility directly. For example, the case that increase in temperature or precipitation decreases utility. Second, (b) although utility of the current generation is not directly affected by climate change, it depends on utility of future generation who can suffer from climate change. In this case, increase in carbon emissions, which raises the possibility of climate change, decreases utility of the current generation indirectly.

[9]See, for example, Copeland and Taylor (1994, 1995).

Suppose that interpretation (a) is adopted. Then, the same difficulty as in externality for production arises. That is, externality which is large enough to directly affect utility is not likely to occur in our model which covers only 1997–2020. On the other hand, in interpretation (b) where the current generation takes account of losses the future generation suffers from, increase in carbon emissions can lower utility of the current generation significantly. However, it is still difficult to specify numerically how how carbon emissions affect utility.

Up to this point, we have explained the difficulties of incorporating externality of carbon emissions into production and utility. However, there is another serious problem. Even if we can specify externality correctly, Approach 1 has the following problem.

As many theoretical models do, Approach 1 assumes that the government optimizes a certain objective. As objective functions, we can consider the following two types: (a) a social welfare function, and (b) an objective function which takes account of political-economic aspects. In terms of simplicity and tractability, type (a) is superior to type (b). However, many researchers are suspicious of the assumption that the government pursues social welfare maximization, and that is why researches on political economic aspects have been done widely. On the other hand, type (b) may reflect the reality more precisely, but results from the simulation can be significantly subject to the way in which political economic aspects are introduced into the model, and there is no consensus about the appropriate approach for modeling political economic aspects. In addition, even if an approach turns out to be appropriate, it is very difficult to specify an objective function numerically.

Finally, there is a problem attributable to the multi-region nature. If the model includes only one region, there is just one optimizing government and thus it may be easy to derive his optimized policy. However, if the model includes many regions and there are multiple optimizing governments, the solution of the model is a Nash equilibrium where each government chooses his optimal policy given other governments' policies. Such a Nash equilibrium may be derived without difficulty in a simplified analytical model, but in a large–scale CGE model, it is extremely difficult to derive it. In fact, as far as the author knows, there is no CGE analyses which try to derive a Nash equilibrium where multiple governments set their optimal policies.

We have presented various problems related to the approach that endogenizes carbon tax from governments' optimizing behavior. As explained above, there are many problems and most of them cannot be resolved easily. From the theoretical point of view, the sophisticated approach based on government optimizing behavior may be desirable. However, that approach is very difficult to incorporate into a large–scale CGE model and thus not suited to the model in this paper.

Approach 2

Next, let us examine the validity of Approach 2, that is, the approach in which a relation between carbon tax and income level is assumed *a priori* and then is estimated from the past data. There can be various problems also in this approach, but the most serious problem is that large–scale emission regulations have rarely been implemented in the past.

For example, suppose that carbon tax in each region is a linear function of its income level. It is usually possible to determine parameters by estimating the equation with the past data and to evaluate the validity of the equation. However, since carbon tax have rarely been implemented in the past, there is little point in estimating the equation from the past data.

Since some developed countries have imposed carbon taxes since the 1990s, it may be possible to use the data of developed countries to estimate the equation. However, there is a problem also in that case. Since carbon taxes imposed in developed countries are very modest, it is likely that significant relation between carbon tax and income level cannot be derived or that carbon tax turns out to have little to do with income level. Taking account of the fact that many countries accept large–scale emission regulations embodied in Kyoto Protocol, the use of developed data in 1990's is likely to underestimate the relation between carbon tax and income level.

The approach in this paper

As explained above, both Approach 1 and 2 have various problems. Thus, this paper uses the alternative approach in order to endogenize carbon tax. The approach is explained as follows. First, like Approach 2, we assume a relation between carbon tax and income level. Specifically, we assume that carbon tax is determined as a linear function of income per capita. Up to this point, the procedure is the same as Approach 2. The difference lies in the way for determining parameters, that is, we use the predicted data rather than the past data to estimate parameters. To be precise, we suppose that emission regulation embodied in Kyoto Protocol is implemented in Annex I regions and then estimate parameters by using carbon taxes and income level realized under the regulation. The detailed procedure is as follows:

[1] First, we assume that in 2010 Annex I regions will restrain carbon emissions to the level determined in Kyoto Protocol by imposing carbon taxes.

[2] Let t_r^C and y_r denote the level of carbon tax and per capita income in region r realized under the regulation described in [1]. Then, we assume that the following relation holds between t_r^C and y_r:

$$t_r^C = a + by_r \tag{2}$$

That is, we assume that the level of carbon tax in region r is determined as a linear function of per capita income in region r.

[3] Next, we estimate a and b in Eq. (2) by OLS, using the values of t_r^C and y_r derived in [1]. Since we consider eight regions, the number of pairs of t_r^C and y_r used for estimation is also eight. Note that we use the pairs of t_r^C and y_r also of non-Annex I regions where emission regulations are not imposed and thus carbon taxes are zero.

[4] Let $\hat{a}$ and $\hat{b}$ denote estimates of a and b respectively, and let $\hat{e}_r$ denote the residual. Then, the following relation holds:

$$t_r^C = \hat{a} + \hat{b}y_r + \hat{e}_r \tag{3}$$

In periods after 2010, we incorporate this equation into the model as an equilibrium condition so that each region changes its carbon tax endogenously according to this relationship.

It is necessary to offer some interpretation of equation (3) (and (2)). Since the estimate of $\hat{b}$ turns out to be positive, we provide an interpretation assuming a positive value for $\hat{b}$. The first interpretation is straightforward. Eq. (3) shows that countries with a higher per capita income impose higher carbon taxes. In other words, richer countries impose stricter regulations than poorer countries. Second, since the carbon tax in each region is equal to the marginal abatement cost in each region, and since the marginal abatement cost is an index that represents the burdens borne by countries, Eq. (3) implies that rich countries are willing to bear heavier burdens than poor countries. In the context of these interpretations, the magnitude of b measures the responsiveness of regulations to income, or the willingness to accept the burden of abatement. Although our specification of (3) may be ad-hoc, it is a good starting point for endogenizing emission regulations.[10]

In (2), we assume the linear relation. The reason for this is that the linear relation is the simplest form. The equation used here is not based on rigorous theoretical foundation and but on conjecture that emission regulation and income level has a certain relation. Thus, we can use other types of equations. However, since we want to analyze the simplest case in the first place, we assume the linear relation of (2). In Section 6, we analyze also the case that carbon tax is a quadratic function of per capita income.

[10] Note that we estimate the equation, using the data which include non-Annex I regions without carbon taxes in 2010. As will be shown later, per capita income in these non-Annex I regions is relatively low. We can infer that no emission regulation in these regions is attributable to low per capita income. Since this exactly reveals the relation between carbon tax and income, we include the data of non-Annex I regions to estimate the equation.

Table 3: GDP and carbon emissions in BAU scenario.

5 The Results from Simulations

In this section, we present results from the numerical analyses. The numerical analysis is conducted according to the following procedure.

[1] First, we drive the Business-As-Usual (BAU) equilibrium from 1997 to 2020 where no emission tax is imposed.

[2] Second, we derive the equilibrium prevailing in 2010 with the Kyoto Protocol-type regulations.

[3] Third, we derive the relationship between per capita income and carbon tax based on the results in [2].

[4] Finally, we incorporate the estimated relationship between income and carbon tax (3) into the model and derive the equilibrium from 2010 to 2020 where carbon tax changes endogenously according to (3).

Numerical computation is done with GAMS (general algebraic modeling system) and its solver PATH.[11] For details of GAMS, see the GAMS web site `<http://www.gams.com/>`. In the following, we mainly focus on change in carbon emissions. However, all other results of the simulation are available from the author upon request.

5.1 Derivation of BAU equilibrium

In this section, we describe the economies under BAU equilibrium where no emission regulation is introduced. Table 3 represents the path of GDP and carbon emissions in each region under BAU scenario. It shows that the world total GDP grows from 26.5 trillion US$ in 1997 to 39.9 trillion US$ in 2010 and to 54.3 trillion US$ in 2020. In particular, non-Annex I regions which include developing countries exhibit higher GDP growth than Annex I regions which mainly include developed countries.

The table also shows that carbon emissions increase significantly with economic growth. For example, world total carbon emissions increase from 6 BtC in 1997 to 7.73 BtC in 2010 and to 9.82 BtC in 2020. In particular, they increase at high rates in rapidly growing economies such as China, India, and other Asian countries. As a result of this, non-Annex I regions as a whole exhibit a higher growth in carbon emissions than do Annex I regions as a whole.

5.2 The Economies in 2010

Next, we derive the relationship between per capita income and carbon tax by imposing emission regulation on the economies in 2010. Table 4 describes the characteristics of the emission regulations imposed on the economies in 2010. The numbers in column (A) indicate the rates of reduction in carbon emissions under the Kyoto Protocol. Annex I regions must reduce their carbon emissions at these rates to below the 1990 levels in 2010. The numbers in column (B) indicate the associated limits on carbon emissions. Since non-Annex I regions have no reduction targets, the cells associated with them are empty. The numbers in column (C) are the effective rates of reduction prevailing in 2010. The reduction rates in column (A) are set in terms of 1990 emission levels. However, since most Annex I regions (except EFS) have experienced increases in emissions since 1990, the effective rates of reduction in 2010 are higher than those shown in column (A).

[11] To write programs for the simulation in this paper, the author has greatly benefited from various GAMS programs created by Thomas F. Rutherford and his coauthors. The author would like to express acknowledgment to them. GAMS codes for the simulation in this paper is available from the author upon request.

Table 4: Emission in 2010.

Table 5: Per capita income and endogenous carbon tax.

Table 6: Carbon emissions under endogenous carbon taxes (BtC).

Note that the effective reduction rate for EFS is negative, which means that the emission limit for EFS exceeds the actual emissions in 2010.

Column (D) shows the carbon emissions in each region when carbon taxes are imposed. Except for EFS, which has hot air, the emission constraints on all Annex I regions are binding, and emissions are reduced to the target levels. Note that emissions from non-Annex I regions increase when we impose emission limits on Annex I regions (compare the value in Table 4 with the one in Table **??**). In other words, *the carbon leakage* occurs as a result of the regulations (the leakage rate is about 29%). However, the world as a whole generates less emissions because of the drastic emission reductions in Annex I regions (from 7.73 BtC without carbon tax to 7.14 BtC with carbon tax).

Column (E) and (F) in table 4 present combinations of per capita incomes and carbon taxes in all regions when carbon taxes are imposed on Annex I regions. Using these values, we can estimate a relationship between per capita income and carbon tax of (3). In all non-Annex I regions and in EFS where emission restrictions are not binding, carbon taxes are zero. As the table shows, per capita incomes of all Annex I regions on which emission regulations are imposed tend to be higher than those of non-Annex I regions. In other words, a region with higher per capita income tends to impose stricter regulations.

The estimated values of $\hat{a}$ and $\hat{b}$ are -28.67 and 8.5 respectively. The sign of $\hat{b}$ is positive as expected. Its magnitude represents the responsiveness of the regulations to income or the willingness to accept the burden of abatement. In the remainder of the paper, we incorporate equation (3) into the model and assume that government in each region sets carbon taxes according to (3).

5.3 Endogenous carbon tax

In this section, we derive the equilibrium from 2010 to 2020 where carbon tax is determined endogenously. Our main purpose is to make clear whether carbon emissions decrease when carbon tax rises according to per capita income.

Table 5 reports per capita income (thousand $) and the level of endogenous carbon tax ($ per tons of carbon). In all regions, per capita income increases with economic growth from 2010 to 2020. In particular, less developed country (LDC) regions display relatively high growth. In the LDC regions, the growth rates of total income are much higher than those of per capita income because the growth rates of population are also high in these regions. Given the increases in per capita income, all regions impose the higher carbon taxes according to equation (3).

Table 6 reports carbon emissions under endogenous carbon tax. It immediately shows that the volume of carbon emissions under endogenous carbon tax (Column B) is lower than that in BAU scenario (Column A), but that carbon emissions increases from 7.14 BtC in 2010 to 7.51 BtC in 2015 and to 7.92 BtC in 2020. That is, carbon emissions increase with economic growth even if carbon taxes are raised with increase in per capita income. This means that the responsiveness of regulations to income changes or to changes in the willingness to accept the burden of abatement $\hat{b}$ is too low to restrain emissions.

This is confirmed by looking at Column (C) in Table 6. It presents carbon emissions in 2015 and 2020 when carbon taxes are kept constant at 2010 level. The difference in carbon emissions between endogenous tax case and constant carbon tax case indicates the amount of carbon emissions reduced by the rise in carbon tax. The table shows that the amount of carbon emissions in endogenous carbon tax case is less than that in constant carbon tax case only by a few percents. This indicates that the rise in carbon tax induced by increase in per capita income is very small and therefore the amount of carbon emissions reduced is also small.

To sum up, we can conclude that, given the policy responsiveness or the willingness to accept the burden of abatement estimated on the basis of imposing the Kyoto Protocol-type regulations, world carbon emissions are likely to increase with economic growth even if emission regulations are determined endogenously.

6 Sensitivity Analysis

In this section, we conduct five sensitivity analyses and see whether the results obtained in the previous section alter or not. We consider the following points: the specification of (3), supply elasticity of fossil fuel, elasticities of substitution related to energy goods, and trade elasticity. In addition to this, we consider the case where US is not included in Annex I regions. In the following, the case assumed in the previous sections is called the base case.

Our specification of (3) may be a good starting point for endogenizing emission regulations, and the parameters in (3) are estimated by imposing the Kyoto Protocol-type regulations that are likely to be adopted in the near future. However, the specification is somewhat *ad hoc*. Therefore, it is worth examining its robustness. For this, we conduct the following two sensitivity analyses: (i) changing the linear form to the quadratic form, (ii) changing the value of estimated $\hat{b}$.

Although a lot of alternative specifications are possible, we change the specification to the following quadratic equation:

$$t_r^C = a + b_1 y_r + b_2 y_r^2 \tag{4}$$

Using the same procedure in Section 4, parameter a, b_1, and b_2 are estimated. The estimated values are $\hat{a} = -6.0$, $\hat{b}_1 = 1.11$, and $\hat{b}_2 = 0.21$ respectively. Since the coefficient for y_r^2 is positive, the effect of rise in per capita income on carbon tax becomes stronger as per capita income becomes higher. Table 7 compares carbon taxes and carbon emissions in both cases. From the table, we can see that world carbon emissions are almost the same in both cases.

Table 7: Carbon taxes and carbon emissions in 2020 under the quadratic specification.

Next, we change the estimated value of $\hat{b}$ and examine whether the results alter or not. Since we found that the responsiveness of regulations $\hat{b}$ is too *low* to reduce emissions, we increase the value of $\hat{b}$. We consider the following two cases: (i) doubling $\hat{b}$ and (ii) tripling $\hat{b}$. The results are shown in Table 8, in which carbon taxes and carbon emissions in each case are presented. As the table shows, carbon taxes rise to a significantly higher level in these two cases than in the base case. Nevertheless, carbon emissions increase in comparison to those in 2010. This result means that our previous finding is robust to some extent.

Next, we conduct a sensitivity analysis of supply elasticity of fossil fuels ($\varepsilon_i^S, i = \mathrm{CRU}, \mathrm{OIL}, \mathrm{GAS}$). The high value of supply elasticity of fossil fuels means the large response of supply against price change. Since economic growth increases demand for fossil fuels and raises demand price of fossil fuels, if ε^S is high, economic growth is likely to increase supply of fossil fuels in a large amount and thus lead to large increase in carbon emissions. The benchmark values of fossil fuel supply elasticity are 0.6 for crude oil (CRU), 2.2 for gas (GAS), and 0.1 for coal (COL). Here we consider two other cases: (i) $\varepsilon_i^S \times 0.5$, and (ii) $\varepsilon_i^S \times 2$.

Row (B) in Table 9 presents carbon emissions (BtC) in each case. The table shows that according to the value of ε_i^S, the amount of carbon emissions differ significantly and that as pointed out above, the higher ε_i^S is, the more carbon emissions are in all cases. However, even in the case of $\varepsilon_i^S \times 0.5$ in which the rise in carbon emissions is the smallest, the result that carbon emissions increase as a result of economic growth remains unchanged.

Next, we see the sensitivity of trade elasticities (σ_A and σ_M). The high value of trade elasticities means that shocks to a region will have large ripple effects on other regions through trade in goods.

Table 8: The sensitivity to estimated b: Carbon tax and carbon emissions in 2020.

Table 9: Sensitivity of various parameters and assumptions. Carbon emissions (BtC)

In our model, it means that economic growth or rise in carbon tax in a region will have large effects on other regions. We consider two cases other than the base case: doubling and halving trade elasticities. The results are shown in Row (C) in Table 9. The table shows that as trade elasticities are higher, emissions from all regions increase. However, carbon emissions increase over time in all cases.

Production functions of non-fossil fuel sectors and utility function include many elasticities of substitution between energy inputs: σ_E, σ_{NEL}, σ_{LQD}, and σ_{CE}. The values of these elasticities could significantly affect the effects of carbon taxes on economies. Thus, we examine the sensitivity of these elasticities. Row (D) in Table 9 presents carbon emissions (BtC) in each case. It shows that the result that carbon emissions increase as a result of economic growth remains unchanged in all cases.

We have so far included US in Annex I regions. However, the current US government declared that he would not ratify Kyoto Protocol and thus it is not clear whether US would join Annex I in the future. Therefore, we examine the assumption that US is included in Annex I regions. Intuitively, the effect of excluding US from Annex I regions is clear. If a high income region like US does not join Annex I regions, the estimate of $\hat{b}$ comes to have a lower value and thus the possibility that economic growth decreases carbon emissions becomes smaller. Row (E) in Table 9 shows that this indeed holds. That is, the volume of world carbon emissions is larger when US is not included in Annex I regions. So, our conclusion that economic growth increases carbon emissions remains the same.

7 Concluding Remarks

In this paper, we have explored the impact of economic growth on carbon emissions. Our approach is summarized as follows. First, we employed a multisector, multiregion recursive CGE model with 13 regions and eight sectors. The 13 regions comprise six Annex regions and seven non-Annex regions, and the eight sectors comprise five energy goods sectors and three non-energy goods sectors. Moreover, the model allows for different production structures for fossil fuel sectors and non-fossil fuel goods sectors, and incorporates differences in substitutability between various energy and non-energy inputs.

The second feature of our analysis is that we explicitly consider the dependence of emission regulations on income. As the well known environmental Kuznets curve argument suggests, rich countries tend to impose stricter regulations than poor countries, and thus one needs to consider this interaction between income levels and emission regulations to project the future trend of carbon emissions accurately. However, previous studies have projected future carbon emissions under the assumption that no abatement policies are adopted. By contrast, we explicitly incorporate into the model the interaction between income levels and regulations. As far as the author knows, this is a first attempt to consider such an interaction.

Based on the above model and assumptions, we have derived the following insights. Economic growth leads to a substantial increase in carbon taxes because all regions, especially less developed ones, enjoy rising per capita incomes. Nevertheless, carbon emissions increase as a result of economic growth. This is because the responsiveness of carbon tax regulations to income, which is estimated from Kyoto Protocol-type regulations, is too low to limit the increase in carbon emissions. Thus, our conclusion is that carbon emissions are likely to increase throughout the world with further increases in economic growth. Although the environmental Kuznets curve argument suggests that economic growth does not necessarily damage the environment, our results show that this argument is unlikely to apply to carbon emissions. To test the robustness of our results, we conducted several sensitivity analyses and found that the above results remain unchanged.

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Table 1: The list of regions and sectors.

Identifier	Region	Identifier	Sector
USA	United States*	Y	Other manufactures and services
CAN	Canada*	EIS	Energy-intensive sectors
WEU	Western Europe*	COL	Coal
JPN	Japan*	OIL	Petroleum and coal products (refined)
AUS	Australia and New Zealand*	CRU	Crude oil
EFS	Eastern Europe and Former Soviet Unic	GAS	Natural gas
MEX	Mexico	ELE	Electricity
CHN	China	CGD	Saving goods (investment goods)
IND	India		
ASI	Other Asian countries		
MIE	Middle East and Turkey		
CSA	Central and Southern America		
ROW	Rest of the world		

Note: asterisk indicates Annex I regions.

Table 2: Value of elasticity parameters.

Notation	Description	Value
η	EOT between domestic supply and export supply	4
σ_C	EOS between energy and non-energy consumption goods	0.5
σ_{PFE}	EOS between primary factor-energy composite	0.5
σ_{PF}	EOS between primary factors	1
σ_E	EOS between electricity and non-electricity	0.1
σ_{NEL}	EOS between coal and liquidity energy	1.5
σ_{LQD}	EOS between oil and gas	4
$\sigma_{R,i}$	EOS between fossil fuel resources and other inputs in fossil fuel sectors†	
σ_A	EOS between domestic and import goods	4
σ_M	EOS between imports from different regions	8

Note: EOS is elasticity of substitution and EOT is elasticity of transformation.

$\dagger\sigma_{R,i}$ is calibrated from fossil fuel supply elasticity.

Table 3: GDP and carbon emissions in BAU scenario.

	GDP (trillion US$)						Carbon emissions (BtC)					
	1997	2000	2005	2010	2015	2020	1997	2000	2005	2010	2015	2020
USA	7.92	8.70	10.16	11.81	13.70	15.85	1.48	1.55	1.68	1.80	1.94	2.10
CAN	0.55	0.59	0.67	0.76	0.86	0.97	0.14	0.14	0.16	0.17	0.19	0.21
WEU	7.44	7.97	8.95	10.01	11.18	12.46	0.90	0.93	0.99	1.05	1.13	1.22
JPN	3.64	3.86	4.19	4.47	4.70	4.95	0.33	0.33	0.34	0.35	0.36	0.37
AUS	0.41	0.45	0.52	0.59	0.67	0.75	0.09	0.09	0.10	0.10	0.11	0.12
EFS	0.79	0.88	1.06	1.28	1.55	1.87	0.75	0.78	0.85	0.93	1.03	1.15
MEX	0.34	0.39	0.49	0.62	0.79	1.02	0.09	0.09	0.11	0.13	0.15	0.18
CHN	0.84	1.06	1.52	2.13	2.93	3.97	0.82	0.89	1.01	1.17	1.39	1.70
IND	0.35	0.42	0.56	0.74	0.96	1.24	0.23	0.26	0.30	0.36	0.43	0.53
ASI	1.39	1.64	2.12	2.68	3.33	4.07	0.39	0.44	0.52	0.62	0.73	0.86
MIE	0.63	0.70	0.86	1.07	1.33	1.65	0.28	0.30	0.34	0.39	0.45	0.52
CSA	1.47	1.65	2.02	2.48	3.03	3.69	0.22	0.24	0.27	0.32	0.36	0.42
ROW	0.75	0.84	1.02	1.24	1.51	1.84	0.29	0.30	0.32	0.35	0.39	0.45
Annex I	20.74	22.45	25.54	28.92	32.66	36.86	3.68	3.83	4.10	4.40	4.76	5.17
Non-Annex I	5.77	6.71	8.59	10.95	13.88	17.48	2.32	2.52	2.88	3.32	3.90	4.65
World	26.51	29.16	34.13	39.87	46.54	54.34	6.00	6.35	6.98	7.73	8.66	9.82

Table 4: Emissions in 2010.

	(A) Reduction rate (%)	(B) Limits on emissions (BtC)	(C) Effective reduction rate	(D) Emissions in 2010 (BtC)	(E) Per capita income*	(F) Carbon tax†
USA	7.0	1.25	30.70	1.25	35.5	218.7
CAN	6.0	0.12	30.90	0.12	23.2	191.3
WEU	7.9	0.86	18.30	0.86	25.8	159.5
JPN	6.0	0.25	27.30	0.25	33.6	382.1
AUS	-7.2	0.09	6.20	0.09	19.8	44.4
EFS	1.5	1.32	-41.60	1.00	3	0
MEX				0.13	5.6	0
CHN				1.25	1.6	0
IND				0.39	0.7	0
ASI				0.67	2.3	0
MIE				0.41	3.6	0
CSA				0.34	5	0
ROW				0.38	1.3	0
Annex I	5.0	3.89	11.60	3.58		
Non-Annex I				3.56		
World				7.14		

* thousand dollars.

† a US dollar per tons of carbon.

Table 5: Per capita income and endogenous carbon tax.

	Per capita income*			Carbon tax†		
	2010	2015	2020	2010	2015	2020
USA	35.5	37.6	39.7	218.7	236.3	254.6
CAN	23.2	24.1	25	191.3	199	207.1
WEU	25.8	27.9	30.1	159.5	177.1	196.1
JPN	33.6	34.4	35.1	382.1	388.8	394.8
AUS	19.8	20.4	21.1	44.4	49.5	54.8
EFS	3	3.5	4.1	0	4.1	8.8
MEX	5.6	5.9	6.4	0	3.2	6.8
CHN	1.6	1.8	2.1	0	2.2	4.7
IND	0.7	0.7	0.8	0	0.4	0.8
ASI	2.3	2.4	2.4	0	0.6	1.2
MIE	3.6	3.8	4	0	1.8	3.8
CSA	5	5.3	5.6	0	2.3	4.8
ROW	1.3	1.3	1.3	0	0.2	0.5

* thousand dollars.

† a US dollar per tons of carbon.

Table 6: Carbon emissions under endogenous carbon tax (BtC).

	(A) BAU			(B) END			(C) CONST	
	2010	2015	2020	2010	2015	2020	2015	2020
USA	1.80	1.94	2.10	1.25	1.32	1.39	1.35	1.45
CAN	0.17	0.19	0.21	0.12	0.12	0.13	0.13	0.13
WEU	1.05	1.13	1.22	0.86	0.88	0.91	0.90	0.94
JPN	0.35	0.36	0.37	0.25	0.25	0.26	0.25	0.26
AUS	0.10	0.11	0.12	0.09	0.10	0.10	0.10	0.10
EFS	0.93	1.03	1.15	1.00	1.06	1.13	1.07	1.15
MEX	0.13	0.15	0.18	0.13	0.14	0.15	0.14	0.15
CHN	1.17	1.39	1.70	1.25	1.33	1.42	1.34	1.45
IND	0.36	0.43	0.53	0.39	0.41	0.43	0.41	0.43
ASI	0.62	0.73	0.86	0.67	0.70	0.73	0.70	0.73
MIE	0.39	0.45	0.52	0.41	0.44	0.48	0.44	0.48
CSA	0.32	0.36	0.42	0.34	0.36	0.38	0.36	0.38
ROW	0.35	0.39	0.45	0.38	0.40	0.42	0.40	0.42
Annex I	4.40	4.76	5.17	3.58	3.74	3.91	3.79	4.02
Non-Annex I	3.32	3.90	4.65	3.56	3.78	4.02	3.78	4.04
World	7.73	8.66	9.82	7.14	7.51	7.92	7.57	8.05

BAU is BAU scenario, END is endogenous carbon tax scenario, and CONST is constant carbon tax scenario.
Carbon emissions in 2010 of CONST is omitted because they are the same as those of END.

Table 7: Carbon taxes and carbon emission in 2020 under quadratic specification.

	Carbon taxes ($/tC).		Carbon emission (BtC)	
	L	Q	L	Q
USA	254.6	292.2	1.39	1.34
CAN	207.1	212.8	0.13	0.13
WEU	196.1	216.9	0.91	0.89
JPN	394.8	406.3	0.26	0.25
AUS	54.8	56.8	0.10	0.10
EFS	8.8	2.8	1.13	1.15
MEX	6.8	3.0	0.15	0.15
CHN	4.7	1.1	1.42	1.45
IND	0.8	0.1	0.43	0.43
ASI	1.2	0.3	0.73	0.73
MIE	3.8	1.2	0.48	0.48
CSA	4.8	2.0	0.38	0.38
ROW	0.5	0.1	0.42	0.43
Annex I			3.91	3.86
Non-Annex I			4.02	4.06
World			7.92	7.91

L indicates the base case (linear specification) and Q indicates the case of quadratic specification..

Table 8: The sensitivity of estimated b. Carbon tax and carbon emissions in 2020.

	Carbon tax ($/tC)			Carbon emissions (BtC)		
	B	x 2	x 3	B	x 2	x 3
USA	254.6	289.8	324.2	1.39	1.34	1.30
CAN	207.1	222.4	237.3	0.13	0.13	0.13
WEU	196.1	232.4	268.2	0.91	0.88	0.86
JPN	394.8	407.6	420.4	0.26	0.25	0.25
AUS	54.8	64.8	74.4	0.10	0.10	0.09
EFS	8.8	17.7	26.4	1.13	1.11	1.09
MEX	6.8	13.6	20.3	0.15	0.15	0.15
CHN	4.7	9.4	14.1	1.42	1.40	1.37
IND	0.8	1.5	2.3	0.43	0.44	0.44
ASI	1.2	2.4	3.7	0.73	0.74	0.74
MIE	3.8	7.5	11.2	0.48	0.48	0.47
CSA	4.8	9.6	14.4	0.38	0.38	0.37
ROW	0.5	1.0	1.5	0.42	0.43	0.43
Annex I				3.91	3.81	3.72
Non-Annex I				4.02	4.00	3.98
World				7.92	7.81	7.70

B is the base case, x 2 and x 3 are the cases where estimated value of b is doubled and tripled respectively.

Table 9: Sensitivity of various parameters and assumptions. Carbon emissions (BtC).

				BAU				END			
				1997	2010	2015	2020	1997	2010	2015	2020
(A)	The base case.		AI	3.68	4.40	4.76	5.17	3.68	3.58	3.74	3.91
			NA	2.32	3.32	3.90	4.65	2.32	3.56	3.78	4.02
			World	6.00	7.73	8.66	9.82	6.00	7.14	7.51	7.92
(B)	Supply elasticity of fossil fuel.	x 0.5	AI	3.68	4.14	4.37	4.65	3.68	3.51	3.63	3.76
			NA	2.32	3.17	3.68	4.39	2.32	3.38	3.55	3.77
			World	6.00	7.31	8.06	9.05	6.00	6.90	7.18	7.52
		x 2	AI	3.68	4.60	5.04	5.54	3.68	3.61	3.80	4.00
			NA	2.32	3.47	4.11	4.92	2.32	3.69	3.95	4.24
			World	6.00	8.07	9.15	10.47	6.00	7.31	7.75	8.23
(C)	Trade elasticity.	x 0.5	AI	3.68	4.40	4.71	5.05	3.68	3.57	3.73	3.91
			NA	2.32	3.17	3.56	3.99	2.32	3.36	3.55	3.73
			World	6.00	7.57	8.27	9.05	6.00	6.93	7.28	7.64
		x 2	AI	3.68	4.51	4.97	5.51	3.68	3.59	3.76	3.95
			NA	2.32	3.76	4.83	6.30	2.32	3.91	4.28	4.71
			World	6.00	8.27	9.81	11.81	6.00	7.50	8.04	8.66
(D)	Elasticity of substitution related to energy goods.	x 0.5	AI	3.68	4.39	4.73	5.12	3.68	3.57	3.72	3.89
			NA	2.32	3.41	4.05	4.87	2.32	3.60	3.84	4.12
			World	6.00	7.80	8.79	9.99	6.00	7.17	7.57	8.02
		x 2	AI	3.68	4.41	4.76	5.19	3.68	3.58	3.75	3.92
			NA	2.32	3.26	3.77	4.44	2.32	3.53	3.73	3.95
			World	6.00	7.66	8.53	9.63	6.00	7.10	7.47	7.87
(E)	US does not join Annex I.		AI	2.20	2.60	2.81	3.07	2.20	2.29	2.40	2.51
			NA	3.80	5.13	5.84	6.74	3.80	5.26	5.54	5.86
			World	6.00	7.73	8.66	9.82	6.00	7.55	7.94	8.37

BAU is BAU scenario and END is endogenous tax scenario.
AI is carbon emissions from Annex I regions, NA is carbon emissions from Non-Annex I regions.
x 0.5 indicates the case where value of parameters is multiplied by 0.5 and x 2 indicates the case where value of parameters is multiplied by 2.

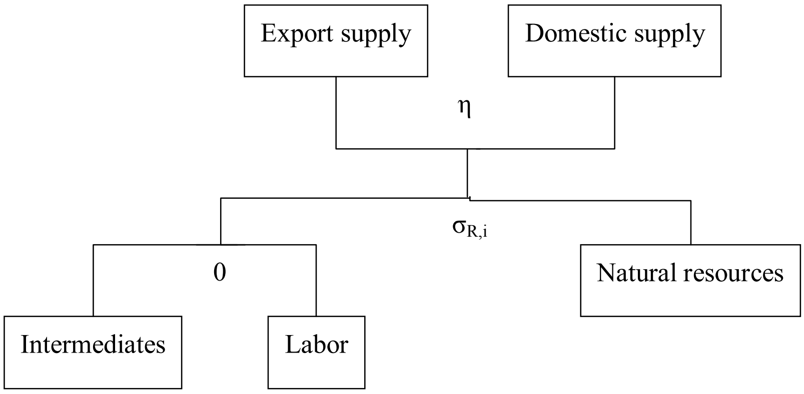

Figure 1: The nesting structure of fossil fuel sector.

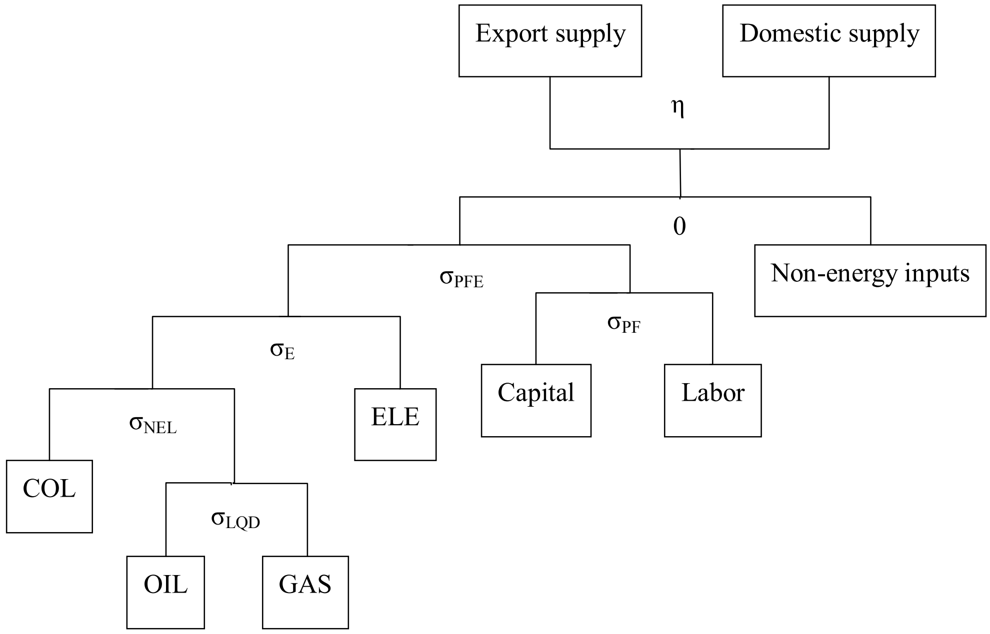

Figure 2: The nesting structure of non-fossil fuel sector.

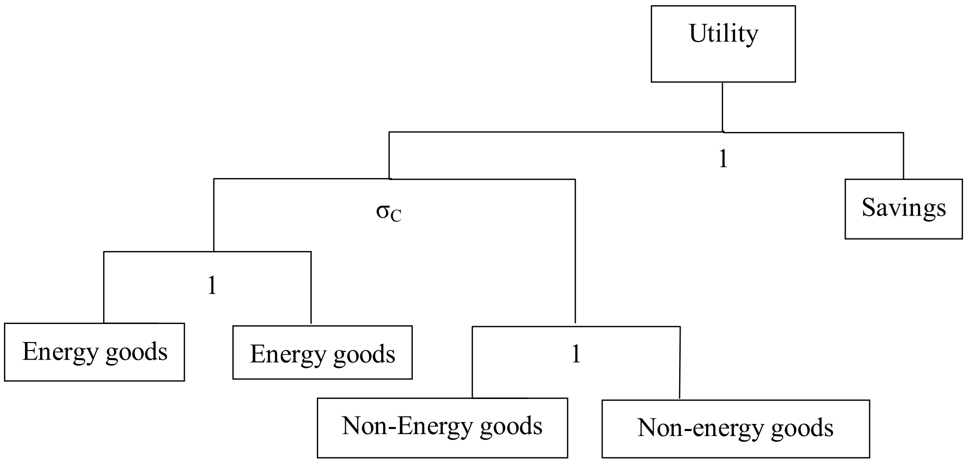

Figure 3: Utility function.