Estimation of Embodied CO_2 Emissions by General Equilibrium Model

M. Kainuma[a] Y. Matsuoka[b], and T. Morita[a]

[a] Global Environment Division, National Institute
for Environmental Studies,
16-2 Onogawa, Tsukuba 305-0053, Japan
Tel: +81-298-50-2422, Fax: +81-298-50-2524
e-mail: mikiko@nies.go.jp
[b] Faculty of Engineering, Kyoto University,
Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

Abstract: This study estimates the extent to which embodied CO_2 emissions are increased or reduced when a socioeconomic structural change occurs. Embodied CO_2 emissions were estimated by input-output models (I-O models) and a general equilibrium model (GE model), and the respective results were compared. The embodied CO_2 emissions differ greatly depending on the assumptions of the total system. The embodied CO_2 emissions obtained by I-O models are much larger than those obtained by the GE model. In some cases, the total CO_2 emissions increase even if less intermediate inputs are required owing to technological improvement. It is shown that taking I-O type embodied emissions alone into consideration is insufficient for the estimation of policy effects. Careful consideration is necessary to effectively reduce emissions when production and consumption are interconnected in a complex way.

Keywords: General equilibrium model, Economics, Environment, I-O model, CO_2 emissions,

1. Introduction

It is highly important to know what loads are added to the environment when goods are produced and/or consumed. One way to express such loads is to quantify the embodied pollutant emissions. A unit of embodied pollutant emissions is the additional amount of emissions, including both direct and indirect emissions, when an additional one unit of goods is produced, or the amount of reduction when consumption of one unit of goods is saved. Input-output analysis has been used to estimate embodied pollutant emissions [Imura et al., 1995]. The input-output model was originally developed by Leontief [1966]. The model was widely applied to the analysis of energy consumption induced by the final demands of goods and services in an economy [Miller et al., 1985]. Breuil [1992] tested the plausibility of the input-output model by attempting to replicate data on French emissions of SO_2 and NO_x by combustion and processes. The input-output model has also been used in life-cycle assessment to quantify the environmental implications of alternative products and processes, tracing pollution discharges and resource use through the chain of producers and consumers [Lave et al., 1995]. Moreover, input-output modelling has been used to estimate primary energy and greenhouse gas embodiments in goods and services in Australia [Lenzen, 1998]. Hawdon et al. [1995] showed how a number of the complex interrelationships between energy, the environment, and economic welfare could be investigated with an input-output model of the UK, using pollution emission coefficients and a European sulphur deposition vector. Proops et al. [1995] investigated how economic structural change has brought about increased atmospheric concentrations of CO_2, and how economic structural change may be used to reduce CO_2 emissions over the next 20 years by input-output analysis.

The input-output method is highly effective for estimating emissions from the standpoint of production. However, it is difficult to incorporate indirect effects caused by changes in socioeconomic structures such as utility and production efficiencies. A general equilibrium model has the advantage of incorporating nonlinear effects of structural changes. Many types of general equilibrium models have been developed and applied to the estimation of CO_2 emissions and impacts of CO_2 mitigation policies. MERGE, developed by Manne et al. [1995], is an example of a general equilibrium model which provides a framework for thinking about climate change management proposals. Another example is CETA, which presents worldwide economic growth, energy consumption, energy technology choice, global warming, and global warming costs over a time horizon of more than 200 years [Peck et al., 1995]. McKibbin et al. [1998(a)] developed the G-Cubed model, a multi-country, multi-sector intertemporal general equilibrium model for studying a variety of topics such as greenhouse gas policy, trade liberalization, tax policy, and macroeconomic policy. A programming environment for economic equilibrium analysis has also been developed by Rutherford [1994, 1997]. These models have been used to analyse the impacts of climate policies [Bernstein et al., 1998; Jacoby et al., 1998; McKibbin et al., 1998(b); Kainuma et al., 1998; Manne et al., 1998].

In order to estimate embodied CO_2 emissions incorporating direct and indirect emissions through socioeconomic systems, it is necessary to clarify the extent to which indirect emissions are included. Many studies conducted to date have only considered direct changes in production. These studies used fixed-coefficient production functions and assumed there were no structural changes in consumption. Based on these assumptions, Imura et al. [1995] estimated the embodied energy intensity; that is, the total energy required directly and indirectly by the economy in supporting one unit of monetary value of final demand.

However, CO_2 emissions caused by the additional production of goods and services differ greatly according to the reason why such changes occur. For example, reductions in emissions due to changes in consumer preferences, technological changes, and policies are different even if the direct reduction of consumption is the same. Moreover, a small perturbation of the socioeconomic structure may sometimes cause large structural changes.

This study estimates the increase or reduction in CO_2 when a structural change occurs. Embodied CO_2 emissions were estimated by input-output models (I-O models) and a general equilibrium model (GE model), and the respective results were compared. The following section explains the economic and trade database used in this study, and the method of analysis is described in Section 3. Section 4 shows the simulation results, and Section 5 presents concluding remarks.

2. Economic and Trade Database

Embodied CO_2 emissions are estimated based on two sets of economic and energy statistics. One is the GTAP database, which contains bilateral trade, transport, and protection data characterizing economic linkages among regions, together with individual-country input-output databases accounting for intersectoral linkages within each region [Hertel, 1995; McDougall, 1997]. The GTAP database is widely used for analysing international issues on trade and industry. As the database expresses economic activities by monetary flow, data on energy flow are also necessary to describe CO_2 emissions. Energy statistics by IEA/OECD [1995(a), 1995(b)] are therefore used to supplement energy data, and an energy-balanced economic and trade database is prepared by combining these two sets of statistics.

2.1 International economic and trade statistics

The Global Trade Analysis Project (GTAP) was established in 1992, with the objective of lowering the cost of entry for those seeking to conduct quantitative analyses of international economic issues in an economywide framework. GTAP continuously updates its database. The database used here is GTAP 3, which was released in 1995 and consists of a 37-sector, 24-region database. Its reference year is 1992.

2.2 IEA energy statistics

IEA reports data on production, consumption, and trade concerning energy-related materials such as oil, coal, petroleum products, gas, nuclear, hydro, and combustible renewable and wastes. OECD has made considerable use of the United Nations' World Energy Supplies database. This has been supplemented by material obtained directly from the countries concerned in published or other form. There have also been wide contacts made with industry, especially with international oil and coal companies [IEA/OECD, 1995(a), 1995(b)].

2.3 Integration of GTAP and IEA databases

The GTAP data are aggregated into 26 regions and 13 sectors. The data for sectors are prepared as follows.

(1) Energy sector: OECD energy balance data are used to estimate energy flows between sectors such as coal, crude oil, petroleum products, gas, and electricity.
(2) Industrial sector: IEA statistics are basically used for five sectors; namely, primary ferrous metals, chemicals, nonferrous metals, nonmetallic mineral products, and pulp and paper. GTAP data are used for supplementing IEA data.
(3) Transport sector: Energy consumption in the transport sector is prepared using IEA data. When energy data are missing in the transport sector, GTAP data are used by calculating the share of transport in total energy use.
(4) Household sector: IEA statistics are used to estimate energy consumption in the household and agriculture sectors. When these data are listed in an aggregated form, GTAP data are used to separate them. When data are missing in the IEA statistics, GTAP data are used.
(5) Government: GTAP data are used to estimate energy consumption in the government sector.
(6) Miscellaneous sector: Energy consumption outside the above 13 sectors is allocated to the miscellaneous subsector in the industrial sector.

The energy price data of IEA are also used for both imports and exports. The consumption price in 1992 is used for the IEA statistics of the OECD countries, India, Mexico, Korea, Taiwan, and Russia. For other countries, the average data of non-OECD countries is used.

3. Embodied CO_2 emissions

Fossil fuels are used to provide energy services. Estimating the CO_2 emissions from each service is important in order to analyse the relationships between socioeconomic activities and the environment. In this study, embodied CO_2 emissions are assessed in three ways:

(1) embodied CO_2 emissions in an I-O type closed system,
(2) embodied CO_2 emissions in an I-O type open system, and
(3) embodied CO_2 emissions in the GE model.

The flow of the study is shown in Figure 1, and the relationships among the CO_2

emissions are shown in Figure 2.

A direct CO_2 emission is one that is directly emitted from the production of one unit of goods. In the production of some goods, however, intermediate inputs are necessary, and CO_2 is also emitted during the process of producing intermediate goods. Embodied CO_2 emissions include such indirect CO_2 emissions.

Embodied CO_2 emissions in the I-O type closed system comprise increases in CO_2 estimated by means of a domestic input-output table. Here, the current production system and prices are fixed. Embodied CO_2 emissions of imported and exported goods are assumed to be the same as those of domestic goods. In the I-O type open system, an international I-O table is used and embodied CO_2 emissions of imported and exported goods are estimated using the data for the region where the goods are produced. Another model is the static general equilibrium model, which we refer to as the GE model. This model takes changes in production systems and utility into consideration. For example, improved efficiency reduces the cost of the associated energy service and therefore stimulates increased demand for the energy service. Such structural changes are included in the static general equilibrium model. This study compares direct emissions, embodied CO_2 emissions obtained by I-O type models, and embodied CO_2 emissions obtained by the GE type model.

3.1 Direct CO_2 emissions

CO_2 is emitted into the atmosphere in the process of burning fossil fuels. The direct CO_2 emission $d_{j,r}$ in sector j in region r is expressed as follows:

$$d_{j,r} = \sum_f k_f \, e_{f,j,r} \tag{1}$$

where k_f represents the emission factor of fuel f, and $e_{f,j,r}$ represents the input of fossil fuel f in region r to produce one unit of goods j.

3.2 I-O type embodied CO_2 emissions

Intermediate goods and energy are directly and indirectly necessary for the production of goods. The embodied CO_2 emission includes not only direct CO_2 emissions, but also indirect emissions for producing one unit of goods. The embodied CO_2 emission $x_{j,r}$ of goods j in region r is calculated as follows:

$$x_{j,r} = d_{j,r} + \sum_i (a_{j,i,r} \, x_{i,r} + t_{j,i} x_{i,t}) \tag{2}$$

$$x_{i,t} = d_{t,w} + \sum_r a_{t,i,r} \, x_{i,r} \tag{3}$$

where $a_{j,i,r}$ is an input-output matrix, $t_{j,i}$ is the share of the international transportation sector, suffix t represents transportation sector, and suffix w represents world.

The above equations assume that the embodied CO_2 emissions of imported/exported goods are equal to those of domestic goods. When imported/exported goods are not distinguished from domestic goods, the system is called a closed system. The open system distinguishes import/export goods from domestic goods, and hence uses different emission factors. To calculate the embodied CO_2 emissions in the I-O type open system, equation (4) is used instead of equation (2).

$$x_{j,r} = d_{j,r} + \sum_i (a_{j,i,r}\, x_{i,r} + t_{j,i} x_{i,t}) + \sum_{r'} (m_{r',r,j} x_{j,r'}) \tag{4}$$

where $m_{r',r,j}$ is an input matrix representing inputs of intermediate goods from region r' for producing one unit of goods in region r.

3.3 Embodied CO_2 emissions in the GE model

A static general equilibrium model of the world economy has been developed to estimate embodied CO_2 emissions including structural changes. In this model, the following assumptions are made:

(1) Goods are produced by intermediate goods, energy goods, and primary factors (labor and capital).
(2) The goods produced in one region are consumed domestically or exported. Goods for export use are not distinguished from goods for domestic use.
(3) Crude oil is traded freely among regions and its quality is assumed to be the same.
(4) The ratio of investment/savings to production is assumed to be constant.
(5) Imported goods are assumed to be Armington goods excluding crude oil. Consumers can distinguish domestic goods from foreign ones.
(6) The elasticity of final consumption goods is zero.

Non-energy goods, energy goods (oil, coal, gas, and electricity) and primary factors (labor and capital) are necessary for the production of goods. Energy goods are combined by a constant elasticity of substitution (CES) production function with a small elasticity (0.5). Primary factors (labor and capital) are combined by a Cobb-Douglas production function. A fixed-coefficient (Leontief) production function is used to estimate the productions of domestic and export goods. Figure 3 shows the structure of the production functions used in the model.

These production functions are expressed as follows:

$$Y_{i,r} = LS(Y_{1,r}, Y_{2,r}, \cdots, Y_{f,e,r}) \tag{5}$$

$$Y_{f,e,r} = CES(ES_{f,r}, ES_{oil,r}, ES_{col,r}, ES_{gas,r} ES_{egw,r}) \tag{6}$$

$$ES_{f,r} = CD\,(K_r, L_r) \tag{7}$$

where,

$Y_{i,r}$: non-energy goods i produced in region r,

$ES_{e,r}$: energy goods e = {*oil* , *col* , *gas* , *egw*} produced in region r ,

$ES_{f,r}$: primary factor f used in region r ,

K_r :capital in region r , *and*

L_r :labor in region r .

Suffix i represents goods, and *r* represents region. LS, CES and CD represent Leontief, constant elasticity substitution, and Cobb-Douglas production functions, respectively.

When changes take place in socioeconomic factors such as population, lifestyle, and technological improvements, global CO_2 emissions change not only because of direct structural changes, but also indirect socioeconomic changes such as prices, demand and supply. The general equilibrium model simulates CO_2 emissions including such indirect effects. Changes in CO_2 emissions depend on production activities, consumption, and policies; that is, they depend on the causes of structural change. Equation (8) shows the relationships among the production system, policies, and CO_2 emissions.

$$F\,(Y_{j,r}, S, C_w) = 0 \tag{8}$$

where, $Y_{j,r}$ is the production of goods *j* in region r; S is a parameter representing scenarios concerning policies, preferences of consumers, and production structures; and C_w is world CO_2 emissions. The embodied CO_2 emission ε^w estimated based on the equation (8) is called the embodied CO_2 emission in the GE model. It is calculated based on the following equation:

$$\varepsilon^w_{j,r} = \frac{d\,C_w}{d\,Y_{j,r}} = \frac{\dfrac{\partial C_w}{\partial S}}{\dfrac{\partial Y_{j,r}}{\partial S}} \tag{9}$$

Perturbations are caused by different types of policies and preferences. For example, efficiency may be improved in the production process by technological developments, consumption may be reduced by changes in consumer preferences, and governments may impose specific taxes and regulations.

4. Simulation Results

4.1 Embodied CO_2 emissions in I-O models

Direct emissions and embodied emissions in I-O models are presented. A total of 26 regions and 13 types of goods are used to estimate CO_2 emissions based on 1992 data. Direct emissions and I-O type embodied CO_2 emissions in 7 regions (Australia, Japan, China, India, USA, EU, and Central and Eastern Europe, and the Commonwealth of

Independent States (CEE&CIS)) and 4 categories of goods (primary ferrous metals; nonferrous metals, agriculture, fisheries and livestock; and transportation equipment) are shown in Figure 4.

Several interesting observations are obtained. Emissions in OECD countries are smaller than those in non-OECD countries except in a few cases. Emissions in China are the highest in each sector except the agriculture sector. In the agriculture sector, emissions in CEE&CIS are the highest. Embodied emissions of the I-O type in CEE&CIS, EU, and Japan are large in the agriculture sector, although direct emissions are not so large. This suggests that the structures of agricultural production are complex and affected by foreign industries in these regions. Figure 5 shows the percentage change in embodied CO_2 emissions of the open system compared to the closed system. In OECD countries except Australia, embodied emissions in the open system are larger than those in the closed system. In non-OECD countries and Australia, on the other hand, embodied emissions in the open system are smaller than those in the closed system. This reflects the fact that direct emissions in these countries are relatively large.

4.2 CO_2 emissions in GE model

Changes in emissions caused by structural changes are also estimated. Such changes depend on what scenarios for reduction of emissions are considered. The following two types of perturbation are assumed.

(1) Preference change: End users (household and government) evaluate goods differently and are satisfied with smaller amounts of goods.
(2) Efficiency Change: Intermediate inputs are reduced due to technological improvement.

The first case, called GE(1), assumes that the utility of goods to end users changes due to various reasons such as education and changes in lifestyle. The utility of one unit of goods is assumed to change so that the same utility can be obtained by (1-δ) unit of goods, where δ is a small positive number.

The second case, called GE(2), assumes that the same amount of goods is produced with less intermediate goods because of technological improvement, and that the corresponding CO_2 emissions are reduced. Let us explain this situation with the system of two inputs and one output. Assume Y_0 is produced using $x_{1,0}$ and $x_{2,0}$ in the base year. Further assume that the same amount of goods is produced with $(1-\delta)\, x_{1,0}$. The equation (10) shows the CES production function after perturbation:

$$Y_t = Y_0 \left[\theta \left(\frac{x_{1,t}}{(1-\delta) \cdot x_{1,0}} \right)^{\rho} + (1-\theta) \left(\frac{x_{2,t}}{x_{2,0}} \right)^{\rho} \right]^{1/\rho} \qquad (10)$$

$$q = \frac{p_{1,0} \cdot (1 - d)\ x_{1,0}}{p_{1,0} \cdot (1 - d)\ x_{1,0} + p_{2,0}\ x_{2,0}}$$

where r is an elasticity parameter, $p_{1,0}$ is the price of goods 1, and $p_{2,0}$ is the price of good 2 in the base year. The improvement in efficiency of the production system changes not only the production of goods 1, but also other related goods in the domestic region as well as goods in foreign regions. The embodied CO_2 emissions are calculated by equation (9) focusing on production of the goods of interest.

Figure 6 shows embodied CO_2 emissions in the I-O open model and GE model in 7 regions for 4 goods. GE(1) is the result when the structure of utility is changed, and GE(2) corresponds to the case when efficiency is improved. The embodied CO_2 emissions in the I-O open type show an increase in CO_2 emissions when 1000 US$ worth of products are added. The embodied CO_2 emissions in GE(1) show the reduction in CO_2 emissions when satisfaction is attained with lower amounts of goods corresponding to the value 1000 US$, while the embodied CO_2 emissions in GE(2) show the reduction in CO_2 emissions when 1000 US$ worth of intermediate goods can be saved. In the I-O open system, plus values indicate an increase in emissions, while in the GE model, plus values indicate a reduction in emissions.

Emissions decrease in the industrial sectors in most regions, although increases are seen in some cases. For example, emissions increase when efficiency is improved in the nonferrous metals sector in China. This is because when efficiency is improved in that sector, the production of ferrous metals increases, causing an increase in China's total CO_2 emissions. This phenomenon occurs in the agriculture sector, also. Figure 7 shows the production change when the consumption of intermediate and final goods in the nonferrous metals sector is reduced by 1% in China and Japan. In China, the amount of ferrous metals produced increases by 0.16% and the consumption of other goods such as paper, oil, coal, and gas also increases. This causes an increase in the total energy consumption. In Japan, the consumption of goods such as chemical products and paper increases, but the amount is not so large and the total energy consumption decreases.

In the agriculture sector, the embodied CO_2 emissions become negative. Figure 8 shows the changes in final consumption in China and the USA when consumption decreases in the agriculture sector. When China decreases agricultural consumption by 1%, the consumption of other goods increases by about 1%. For example, the consumption of chemicals increases by 0.87%. This leads to an increase in production of other goods in China as well as in foreign countries. When the USA reduces consumption of agricultural products by 1%, the consumption of other goods also increases but by less than 0.1%. Consequently, the increase in production is not so large. The CO_2 emissions resulting from the increased production of other goods are less than those resulting from the reduced agricultural consumption. What creates this difference? Figure 9 shows the amounts of goods produced and used in final consumption when final consumption in the agriculture sector is assumed to be 100. In China, production in the agriculture sector accounts for a large part of the total production, so savings of agricultural goods influence the consumption of other goods. In contrast, the share of agricultural production in the USA is not so large compared to China, so savings in agricultural production in the USA do not have much impact on the consumption of other goods. This structural difference causes the difference in embodied CO_2 emissions.

In the transportation sector, improvement of efficiency promotes the consumption of energy, especially in CEE&CIS, China, and India. These are cases where the current cost of transportation is very high, and transportation will be supplied much more cheaply by the improvement of efficiency. The reduction of costs in the transportation sector promotes consumption in other sectors.

It can be seen that embodied CO_2 emissions calculated by the GE model are much smaller than those calculated by the I/O models. Sometimes, in fact, they become negative. When there is a saving in the consumption of a particular type of goods, the share of those goods in the total expenditure decreases and the consumption of other goods is promoted. If the embodied CO_2 emissions of the increased goods estimated by the I-O model are higher than those of the decreased goods, the change in CO_2 emissions becomes negative. When the efficiency of production processes is improved, production costs are reduced and the price of the goods is decreased. This promotes the consumption of goods. In endeavoring to reduce CO_2 emissions by reducing the consumption of goods, care should be exercised because sometimes an adverse effect occurs and emissions increase. This adverse effect is called CO_2 "leakage".

"leakage" is defined by equation (11) as the difference between emissions calculated by the I-O open model and emissions calculated by the GE model, divided by emissions calculated by the I-O open model.

$$\text{Leakage (\%)} = \frac{\text{Emissions in I-O open model - Emissions in GE model}}{\text{Emissions in I-O open model}} \text{ x } 100 \qquad (11)$$

Zero leakage means that the emissions when one unit of goods savings is achieved are the same as the emissions when the goods are produced. That is, there is no "take back" or "rebound." A value of greater than 100 means that goods savings through preferences and efficiency changes will, on the contrary, increase emissions.

Figure 10 shows CO_2 leakage. In the ferrous, nonmetallic, and nonferrous industries, leakage is relatively small. However, total emissions increase when savings or improvement of efficiency are undertaken in the agriculture sector. Leakage in the GE(2) model is generally larger than that in the GE(1) model. One reason is that the effects of technological improvement activate the economy and promote consumption.

How much do domestic and foreign regions contribute to emission reductions? The total emission reduction consists of the domestic reduction and the foreign reduction, in which the domestic share represents the reduction in the domestic region and the foreign share represents the reduction in the foreign region. These are defined by equations (12) and (13):

$$\text{Domestic share} = \frac{\text{Domestic } CO_2 \text{ reduction}}{} \qquad (12)$$

$$| \text{Domestic } CO_2 \text{ reduction} | + | \text{Foreign } CO_2 \text{ reduction} |$$

$$\text{Foreign share} = \frac{\text{Foreign } CO_2 \text{ reduction}}{| \text{Domestic } CO_2 \text{ reduction} | + | \text{Foreign } CO_2 \text{ reduction} |} \qquad (13)$$

A plus sign indicates reduction and a minus sign indicates increase. Figure 11 shows the domestic and foreign contributions to the total emission reduction in the oil, gas, nonferrous metals, and agriculture sectors. Reductions in oil and coal consumption directly reduce emissions in the domestic region, but slightly increase emissions in foreign regions. This comes from the fact that a decrease in energy prices promotes increased consumption in other regions and increases the total CO_2 emissions. However, a reduction in gas consumption decreases emissions in foreign countries as well. This is because a shift to gas from oil or coal is promoted in foreign countries, which decreases CO_2 emissions as the emission factor of gas is less than those of oil and coal. In the agriculture sector, the domestic share becomes negative, but the foreign share is positive in many regions.

5. Concluding Remarks

In this study, embodied CO_2 emissions were estimated using I-O models and the GE model. From these estimations, the following observations can be made.

(1) The embodied CO_2 emissions per unit of goods of one region estimated by I-O models are much larger than those estimated by the GE model. In some cases, the total CO_2 emissions increase even if less intermediate inputs are required owing to technological improvement.

(2) Embodied CO_2 emissions saved per sector and region depend on the way in which socioeconomic structural change occurs. A reduction achieved by a change in utility is larger than that achieved by a change in efficiency for most goods. Emissions will increase in some cases. When there is a saving in the consumption of a particular type of goods, the share of those goods in total household expenditure decreases, promoting the consumption of other goods. This increases the production of other goods. When the efficiency of a particular type of production increases, the cost of the goods concerned decreases and the consumption of those goods increases. In both cases, embodied CO_2 emissions do not decrease as expected.

(3) The embodied CO_2 emissions of non-OECD countries are larger than those of the OECD countries.

(4) The reductions in the industrial sectors are positive while those in the agriculture and transport sectors are negative in most cases. Rebound is largest in the agriculture sector, especially in China. The production share of the agriculture sector is very large in China. When there is a saving in the agriculture sector in China, resources are used

in another sector and this increases consumption in other sectors. This, in turn, increases the total CO_2 emissions, as direct emissions in the agriculture sector are small.

It is found that embodied CO_2 emissions depend on the form of socioeconomic structural change. Many previous studies have estimated embodied CO_2 emissions by I-O models, keeping the consumption structure constant. However, a change in production structure usually leads to a change in the consumption structure. If less intermediate goods are necessary to produce one unit of goods, the price of those goods decreases, promoting their consumption. It is shown that the reduction of CO_2 by reducing the consumption of one unit of goods is less than the embodied CO_2 emissions of those goods calculated by the I-O model. In some cases, the total CO_2 emissions increase even if less intermediate inputs are required or the consumption of one goods of interest is reduced. Careful consideration is necessary in using the concept and the estimated values of embodied emissions. The total system should be carefully designed to effectively reduce CO_2 emissions when production and consumption are interconnected in a complex way.

Acknowledgement

This research was funded by the Environment Research Program of the Japan Environment Agency. The authors are grateful to Eiichi Okeya for his extensive support.

References

Bernstein, P.M., Montgomery, W.D. and Rutherford, T.F., Trade impacts of climate policies: the MS-MRT model, *Yale University/NBER Workshop on International Trade and Climate Policy*, Snowmass, Colorado, Aug., 1998.

Breuil, J.M., Input-Output analysis and pollutants emissions in France, *Energy Journal*, **13**(3), 173-184, 1992.

Hawdon, D. and Pearson, P., Input-output simulations of energy, environment, economy interactions in the UK, *Energy Economics*, **17**(1), 73-86, 1995.

Hertel, T.W., *Global Trade Analysis: Modeling and Applications*, Cambridge University Press, 1995.

IEA/OECD, *Energy Statistics and Balances of Non-OECD Countries 1992*-1993, OECD, 1995(a).

IEA/OECD, *Energy Statistics of OECD Countries 1992-1993*, OECD, 1995(b).

Imura, H. and Moriguchi, Y., Economic interdependence and eco-balance: accounting for the flow of environmental loads associated with trade, in *Toward Global Planning and Sustainable Use of the Earth*, ed. S. Murai, 189-208, Elsevier, 1995.

Jacoby, H.D., Schmalensee, R., and Wing, I.S., Toward a useful architecture for climate change negotiations, *Economic Modelling of Climate Change: OECD Workshop Report*, Chapter 15, http://www.oecd.org/ dev/ news/ environment/modelling.htm, 1998.

Kainuma, M., Matsuoka, Y. and Morita, T., Analysis of Post-Kyoto scenarios: the AIM model, *Economic Modelling of Climate Change: OECD Workshop Report*, Chapter 9, http://www.oecd.org/dev/news/environment/ modelling.htm, 1998.

Lave, L.B. Cobas-Flores, E., Hendrickson, C.T. and McMichael, F.C., Using input-output analysis to estimate economy-wide discharges, Environmental Science and Technology, **29**(9), 420A-426A, 1995.

Lenzen, M., Primary energy and greenhouse gases embodied in Australian final consumption: an input-output analysis, *Energy Policy*, **26**(6), 495-506, 1998.

Leontief, W., Input-output Economics, Oxford University Press, 1966.

Manne, A.S., Mendelsohn, R. and Richels, R., MERGE: a model for evaluating regional and global effects of GHG reduction policies, *Energy Policy*, **23**(1), 17-34,1995.

Manne, A.S., International Trade - Potential Impacts of the Kyoto Protocol, presented at University of Geneva, June, 1998.

McDougall, R.A., *Global Trade Assistance, and Protection: The GTAP 3 Data Base*, Center for Global Trade Analysis, Purdue University, 1997.

McKibbin, W.J. and Wilcoxen, P.J., *The Theoretical and Empirical Structure of the G-Cubed Model*, Brookings Institution, April 1995, revised June 1998(a).

McKibbin, W.J., Shackleton, R. and Wilcoxen, P.J., *What to Expect from an International System of Tradable Permits for Carbon Emission*s, Brookings Institution, July, 1998(b).

Miller, R.E. and Blair, P.D., *Input-Output Analysis, Foundations and Extensions*, Prentice-Hall, New Jersey, 1985.

Peck, S.C. and Teisberg, T.J., International CO_2 emissions control: an analysis using CETA, *Energy Policy*, **23**(4/5), 297-308, 1995.

Proops, J.L.R., Faber, M., and Wagenhals, G., *Reducing* CO_2 *emissions, A comparative input-output study for Germany and the UK*, Springer, 1993.

Rutherford, T.F., *Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem*, GAMS Development Corp., Washington, 1994.

Rutherford, T.F., Montgomery, W.D. and Berstein, P.M., CETM: *A Dynamic General Equilibrium Model of Global Energy Markets, Carbon Dioxide Emissions and International Trade*, Discussion Papers in Economics, 97-3, University of Colorado, 43p., 1997.

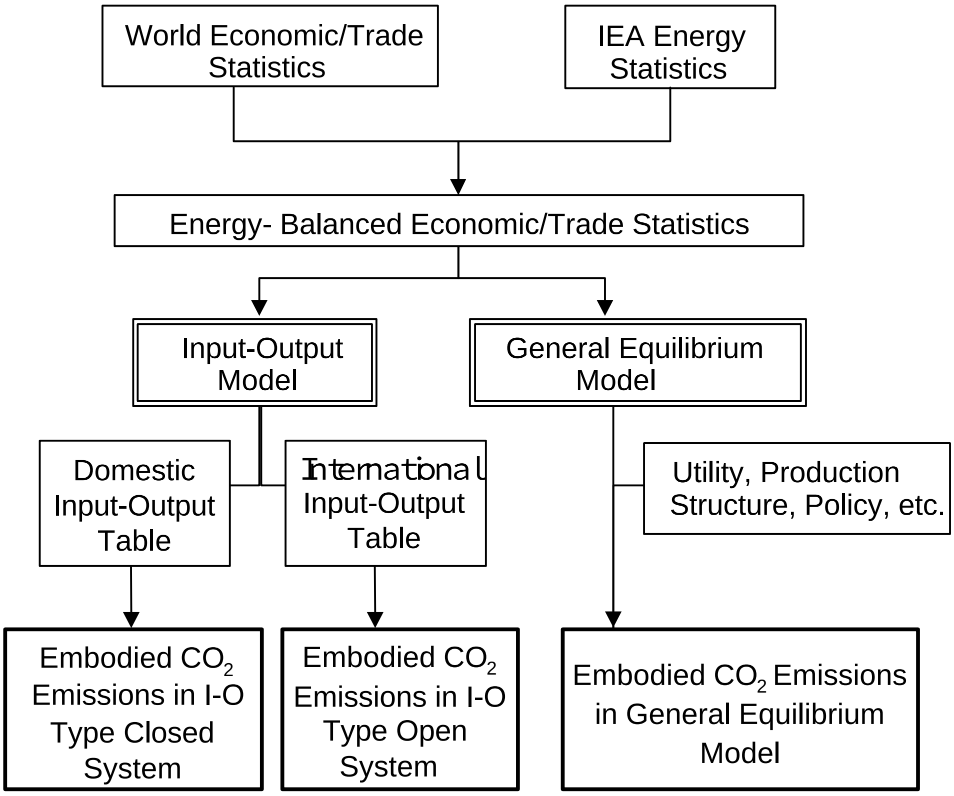


Figure 1 Flow for calculating embodied CO_2 emissions

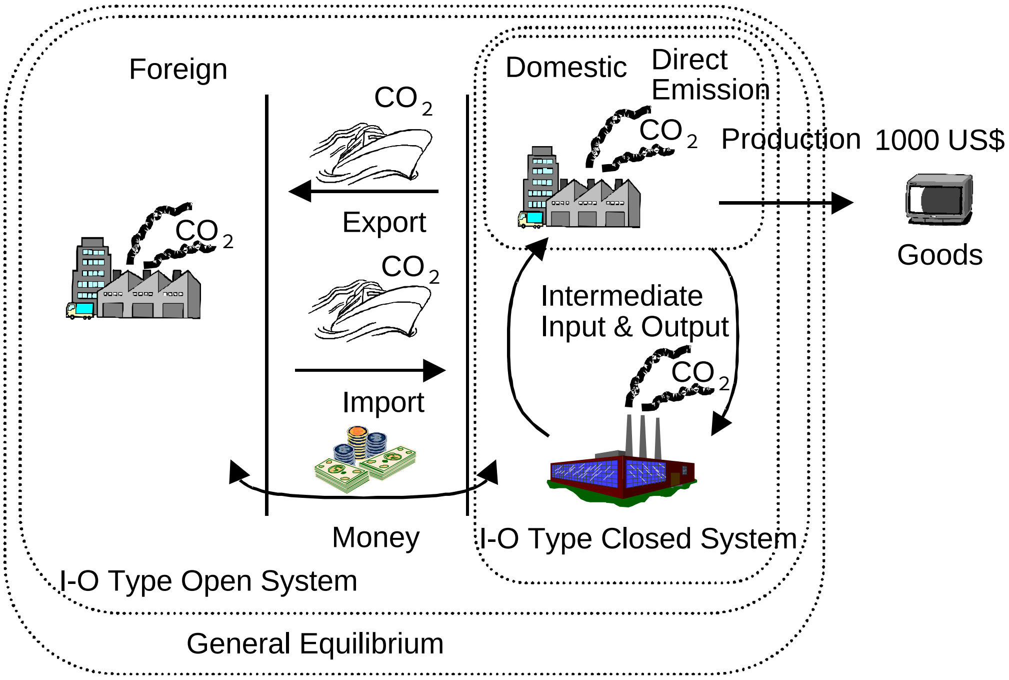


Figure 2 Relationships among embodied CO_2 emissions

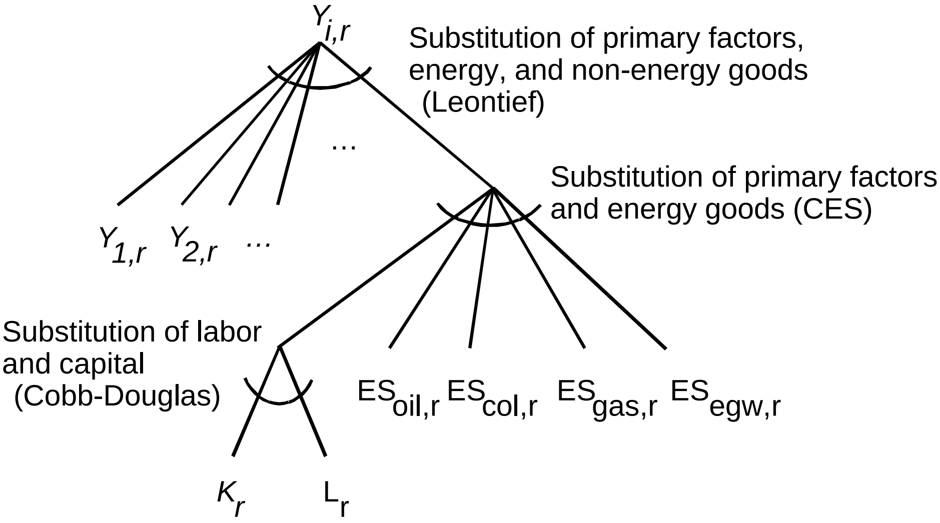


Figure 3 Production structure of GE model

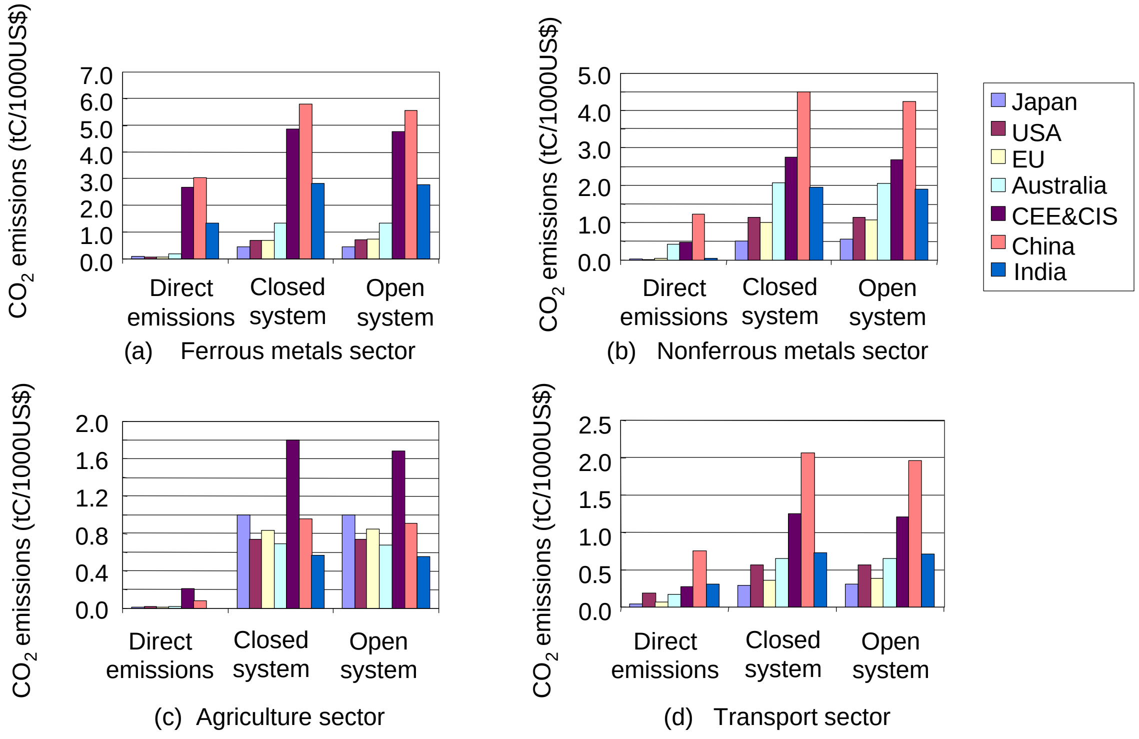


Figure 4 Direct and embodied CO_2 emissions in I-O type models

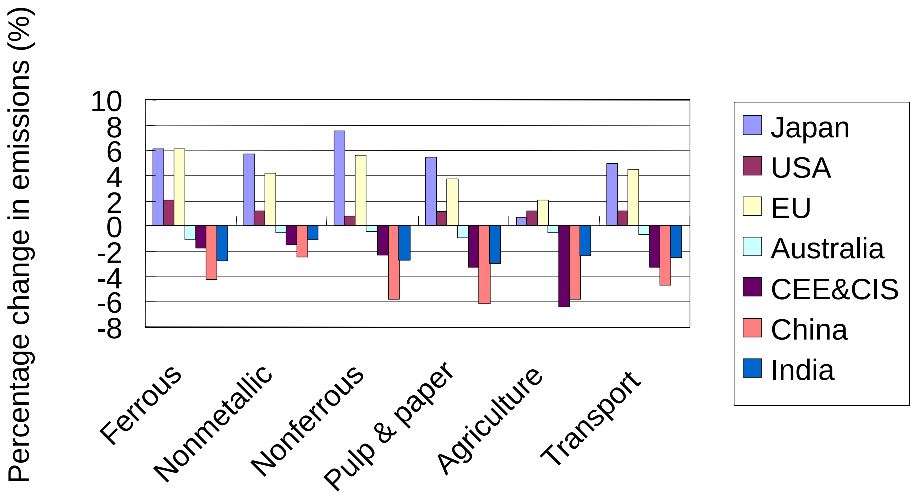
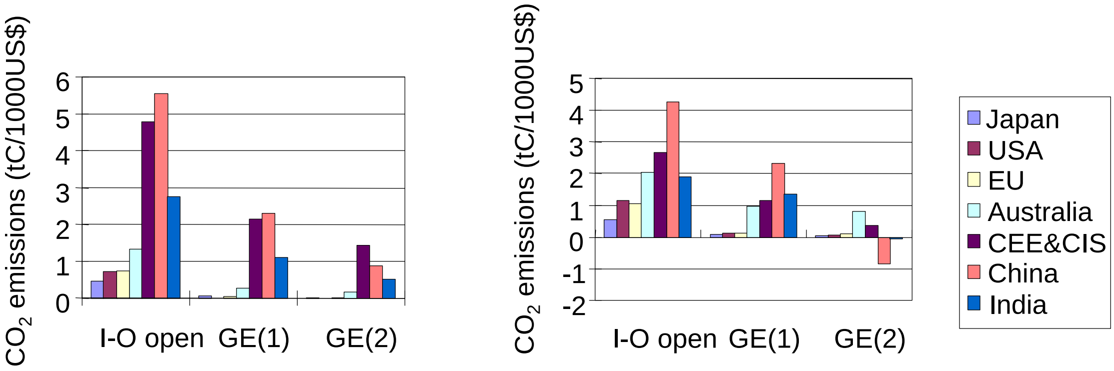
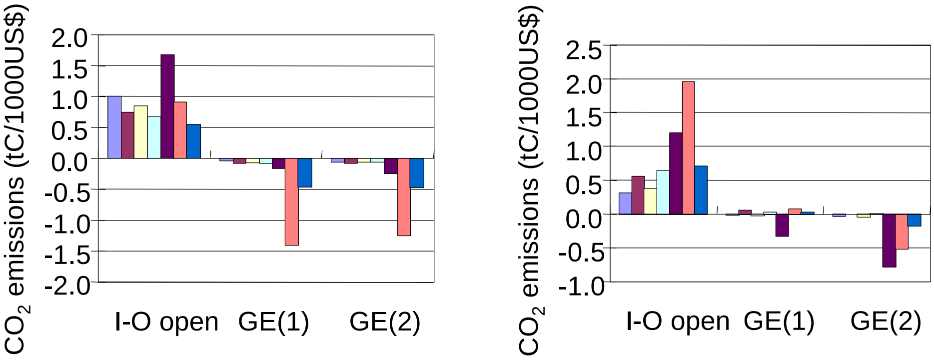


Figure 5 Percent change in embodied CO_2 emissions of open system compared to closed system ((Open - Closed) / Closed x100)



(a) Ferrous metals sector (b) Nonferrous metals sector



(c) Agriculture sector (d) Transport sector

Figure 6 Embodied CO$_2$ emissions in I-O open and GE models

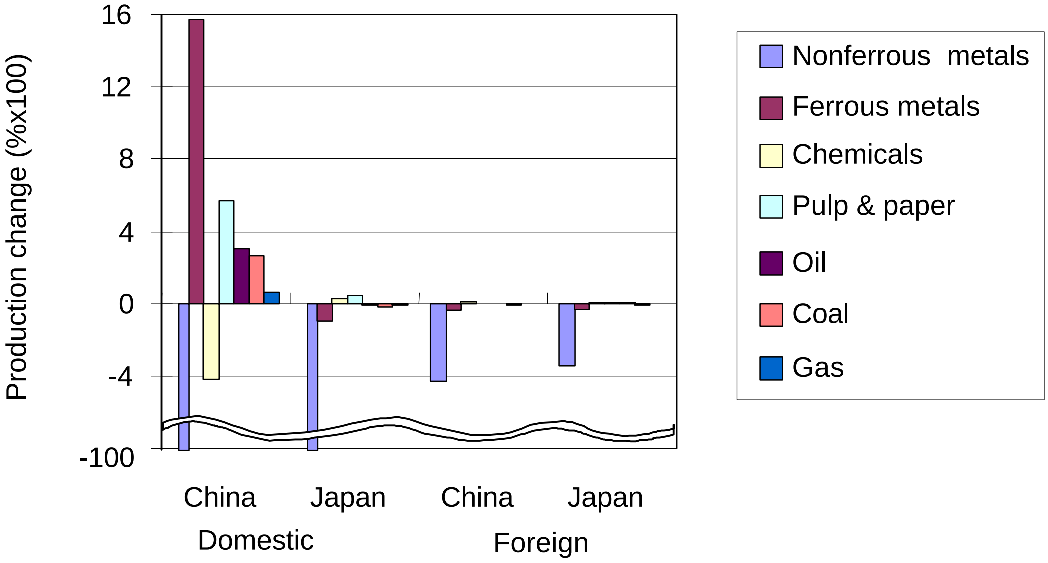


Figure 7 Production change when efficiency is improved in nonferrous metals sector

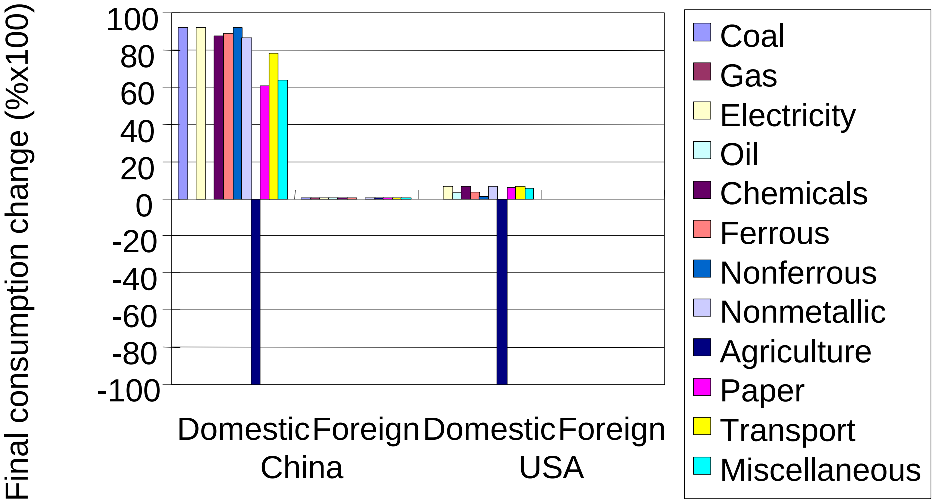


Figure 8 Change in final consumption caused by 1% decrease in agricultural final consumption

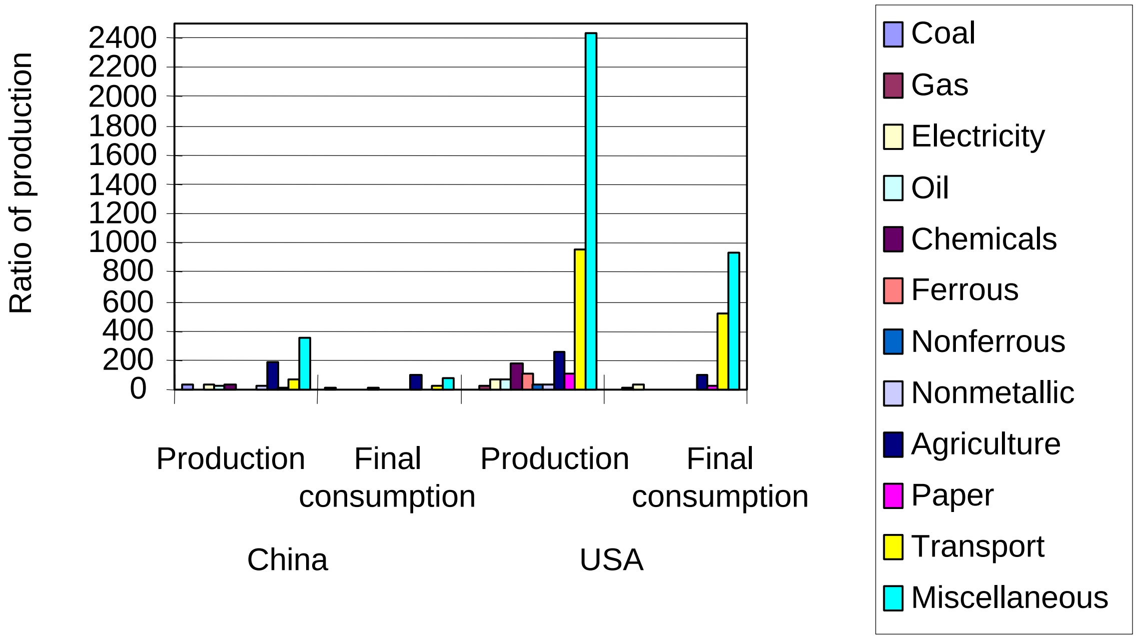
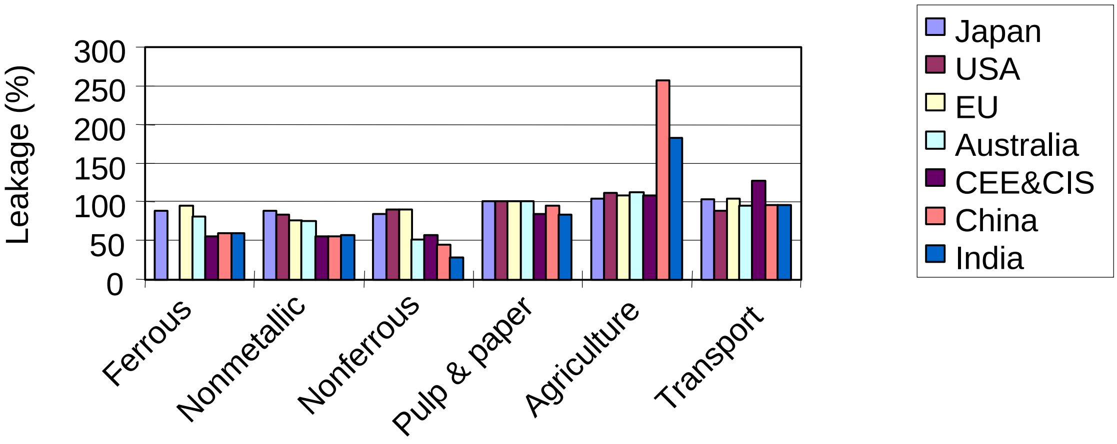
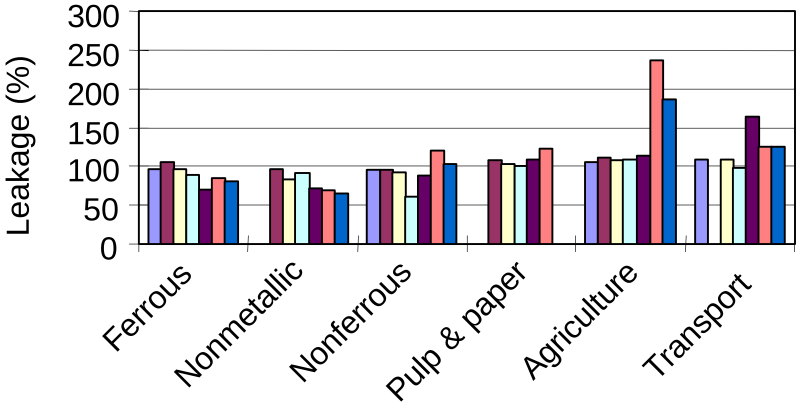


Figure 9 Ratio of production assuming final consumption in agriculture = 100

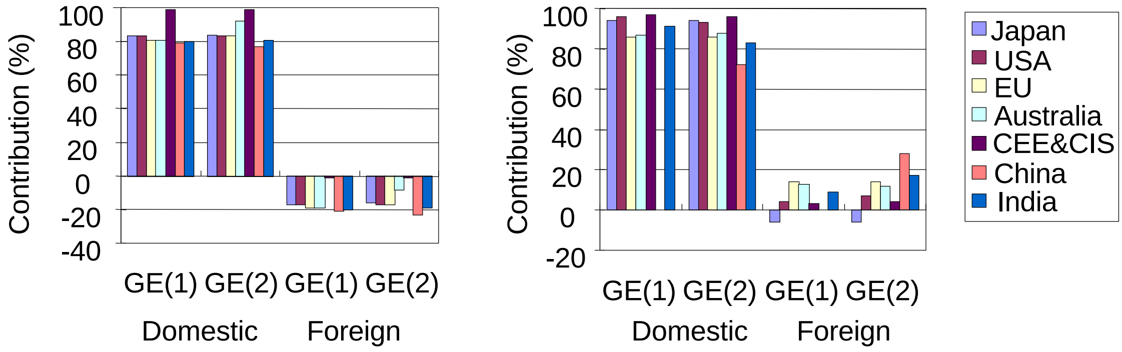


(a) Leakage calculated by GE(1)



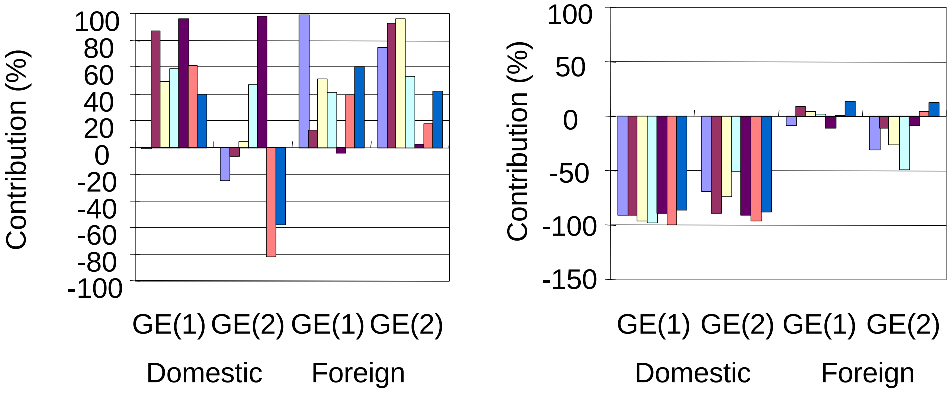
(b) Leakage calculated by GE(2)

Figure 10 CO_2 leakage in GE model



(a) Oil sector

(b) Gas sector



(c) Nonferrous metals sector

(d) Agriculture sector

Figure 11 Domestic and foreign contributions