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Environmental and economic analyses of the carbon tax based on the imputed price using applied general equilibrium model: taxation on the upper industrial sectors

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Abstract Considering the latest arguments on global warming, CO_2 emissions reduction by not only developed countries but also by developing countries is becoming a pivotal issue. Although the worldwide uniform-rate carbon tax (UCT) is thought to be a cost-effective method to reduce CO_2 emissions, it places heavy economic burdens on developing countries. Because such a policy is likely to be opposed by developing countries and is against "common but differentiated responsibilities" of the UNFCCC, it is unlikely to be successfully implemented. This article discusses the effects of the worldwide differentiated-rate carbon tax from the policy viewpoint regarding environmental (CO_2) and economic (gross domestic product) aspects. The tax, based on the imputed price of carbon (ICT), was compared with UCT by simulation analysis using the applied general equilibrium model. The world economy was classified into 15 industries and 14 regions in the model. Each tax was imposed on the upper industrial sectors. As ICT reduced CO_2 emissions slightly less than UCT, it was found to generate positive GDP effects on developing countries, unlike UCT. With regard to the importance of worldwide introduction of CO_2 abating policies and avoidance of excessive economic burdens on developing countries, ICT has higher economic equity and policy effectiveness than UCT.

Key words Carbon tax · Imputed price · Economic equity · Upper industrial sectors · Applied general equilibrium model

1 Introduction

When the Kyoto Protocol (KP) came into effect on February 16, 2005, the Annex B countries that ratified the KP accepted the obligation to reduce their greenhouse gas (GHG) emissions by certain amounts. However, GHG emissions from most of these countries are still increasing even after the base year of the KP.[1]

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[1] In the case of Japan, about 1.34 billion t-CO_2 of GHG was emitted in 2003 and it is 8.3% above the base (about 1.24 billion t-CO_2), according to Ministry of the Environment (2005).

Therefore, because it will be difficult for them to achieve the targets of the KP[2] during the first commitment period (2008–2012) if they do not plan additional measures, some early actions will be required. In addition, considering the post-KP scenario, reduction of GHG emissions by not only developed countries but also by developing countries will become the pivotal issue.

Under the circumstances, because CO_2 is the most influential GHG on global warming, carbon taxes are drawing attention as a method to cost effectively reduce CO_2 emissions by market mechanisms. To date, some studies have analyzed the effects of carbon taxes.[3] Also, it is considered that the introduction of provisions or policies against CO_2 emissions by all countries is more effective than implementation by a group of countries due to carbon leakage.[4] However, because a worldwide uniform carbon tax imposes excessive economic burdens on developing countries, they will oppose it. Furthermore, such an approach goes against the viewpoint of "common but differentiated responsibilities" (Article 3) of UNFCCC.[5] Even if a carbon tax is not introduced worldwide, according to Hoel (2001), there is the possibility of lightening carbon leakage by differentiating the tax rate among industrial sectors.

In this article, the effects of "the differentiated-rate carbon tax among countries," which does not heavily burden developing countries, are analyzed, focusing on the effectiveness of the worldwide carbon tax mentioned in past studies. To be more precise, the carbon tax based on the imputed price of carbon (ICT) proposed by Uzawa (2003) was introduced as the differentiated-rate carbon tax. Then, environmental and economic influences [changes in CO_2 emissions and gross domestic product (GDP), respectively] brought about by ICT were compared with those brought about by a worldwide uniform-rate carbon tax (UCT). This simulation analysis was achieved using the multisectoral/multiregional applied general equilibrium model (MMAGE). Both taxes were imposed on the upper industrial sectors depending on the emission coefficients of each energy resource produced by each sector. The upper sectors are those producing coal, oil, and natural gas, and these correspond to COA, OIL, and GAS of Table 1 below, respectively. The tax revenue was treated as revenue for regional households[6] in this study.

2 Methodology

2.1 Multisectoral/multiregional applied general equilibrium model (MMAGE)

Usually, national, regional, or world economies are divided into several sectors and regions in MMAGE. Then the model analyzes the influences on resources

[2] In the case of Japan, because the target is 6% below the base, about 14% must be reduced substantially.
[3] Hibino et al. (2004), Kainuma et al. (1999), Masui et al. (2004) are examples.
[4] For example, Ban et al. (1998), Barrett (1998), Golombek (1994), and Stavins (1998) describe causes of carbon leakage.
[5] The details are in United Nations (1992).
[6] Regional households include private households and governments.

and income distribution, economic welfare, industrial and economic structures, etc. caused by behavioral changes of economic entities along with economic policy changes within the framework of Walras' Law. Recently, it has also been utilized to analyze the influences of environmental policies. The GTAP model was used in the MMAGE in this study. The GTAP model was developed by Thomas W. Hertel of Purdue University in 1992 in order to analyze international trade. It is a static model, and internal and international sectoral trades and interactions among regional households and industrial sectors are described.[7] The present database, GTAP Version 6, which is based on the world economy of 2001,[8] uses a classification of 57 sectors and 87 regions. However, if a 57×87 model was used, it would take considerable time to simulate and the fundamental outcomes of the study can be lost when analyzing the results. Therefore, the sectors were aggregated into 15 and the regions to 14 as a compromise between the computation time and the adequacy of the analyses. Tables 1 and 2 show the aggregated sectoral and regional structures. Because this study intended to analyze carbon taxes, energy-related sectors were left unchanged and the others were aggregated depending on their characteristics. Also, few main countries were aggregated and the others were aggregated depending on geography.

In Table 2, countries from designations AUS to HAR were regarded as developed countries, and the others were regarded as developing countries.

Table 1. Aggregated sectoral structure

Code	Member sectors
COA	Coal
OIL	Crude oil
GAS	Natural gas
P_C	Petroleum, cokes, etc.
ELY	Electricity
GDT	Gas
CRP	Chemicals, rubbers, etc.
AGR	Agriculture, dairy husbandry, fisheries, etc.
FRS	Forestry
OMN	Mining
PRC	Food processing, textiles, pulp, papers, etc.
MNF	Ceramics, metals, machineries, etc
CNS	Construction
TRP	Transportation
SVC	Other services

[7] The details of GTAP are in Center for Global Trade Analysis (2005) and descriptions of the model are in Hertel (1996).
[8] In order to adjust to the GTAP database, data in 2001 were used as much as possible in this study.

Table 2. Aggregated regional structure

Code	Member regions
AUS	Australia
N_Z	New Zealand
JPN	Japan
USA	United States
CAN	Canada
E_U	15 EU countries
WEU	Rest of Western Europe (e.g. Switzerland)
HAR	Russia, Eastern Europe (e.g. Bulgaria)
CHN	China
OAS	Rest of Asia (e.g. Korea)
OAM	Rest of America (e.g. Mexico)
OEU	Rest of Europe (e.g. Turkey)
M_E	Middle East (e.g. UAE)
ROW	Rest of the world

2.2 *Setup of carbon tax rates*

2.2.1 *Case of ICT*

ICT, equivalent to the imputed price of carbon, was calculated from the Uzawa formula, Eq. 1:[9,10]

$$\mathrm{IT}_r = \frac{1}{(\delta-\rho)+\mu}\frac{-\phi'(D)}{\phi(D)}NY_r \quad \text{for all } r \tag{1}$$

where r is the region (see Table 2), IT_r is the ICT in region r (\$/t-C), N is the world population, Y_r is the per capita net national income (NNI) in region r (\$), D is the atmospheric CO_2 stock (t-C), δ is the discount rate, ρ is the population growth rate, μ is the absorption rate of CO_2 by the marine surface layer ($0.02 \le \mu \le 0.04$), and $\phi(D)$ is the environmental influencing function.

Then, Eq. 2 was used as $\phi(D)$ in Eq. 1[11,12]

$$\phi(D) = (V-D)^{\beta} \tag{2}$$

[9] Equation 1 is from Uzawa (2003).

[10] The Uzawa formula is introduced from the dynamic optimization problem maximizing the utility integral subject to per capita net national income of each region (a utility index), production and final consumption, CO_2 emissions from economic activities, scarce resources, changes on the atmospheric CO_2 stock, the amount of the atmospheric CO_2 stock, and population. The details are in Uzawa (1991, 2003).

[11] Equation 2 is from Uzawa (2003).

[12] In the situation that the relationships among CO_2 emissions, CO_2 stock, and global warming are complex, the Uzawa formula was altered to capture the relationships of CO_2 transference and global warming simplistically. Therefore, the concept of CO_2 stock is adopted in Eqs. 1 and 2. Because the final purpose of this study was to analyze the effects of the carbon tax imposed based on per capita NNI, it is considered that there are few problems even though the relationships of CO_2 and global warming were simplified.

Table 3. Values of parameters in Eq. 3

Parameter	Value
δ^a	0.05
μ^a	0.04
β^a	0.1
ρ^b	0.0125
D (t-C)[c]	792 billion (equivalent to 369.6 ppm)
V (t-C)[a]	1.20 trillion (equivalent to 560 ppm)[d]
N [c]	6.148 billion

[a] From Uzawa (2003)

[b] Calculated from Food and Agriculture Organization (2005)

[c] Estimated from Ad Hoc Committee of the International Strategy about Climate Change, Global Environment Division of Central Environmental Council (2005)

[d] According to Hare and Meinshausen (2004), EU insists global warming should be limited below 2°C above the preindustrial level to avoid tremendous global damage and CO_2 stabilization level should be at most around 550 ppm to realize it. Therefore, employing 560 ppm for V is appropriate

$\phi(D)$ can be defined when $0 \le D \le V$, where V is the critical level of atmospheric CO_2 stock (t-C),[13] and β is the environmental influencing parameter ($0 < \beta < 1$).

Then Eq. 3 was obtained from Eqs. 1 and 2.

$$\mathrm{IT}_r = \frac{1}{(\delta-\rho)+\mu}\frac{\beta}{(V-D)}NY_r \quad \text{for all } r \tag{3}$$

As seen from Eqs. 1 and 3, because the imputed price of carbon is set proportionally to per capita NNI, ICT become much higher for developed countries than developing countries.[14] Table 3 shows the values of the parameters used in Eq. 3. Table 4 shows NNI, population, per capita NNI, and ICT of each region.

However, if ICT in Table 4 was imposed directly on the upper sectors, the highest rates for developed countries would be about 350%–1000%.[15] With such high rates being far from reality, the upper limit of the rate associated with ICT was set at 271.74%,[16,17] which is a rate based on taxation on COA in the USA.

[13] Critical level means that if CO_2 stock exceeds it, tremendous global influences will appear.

[14] Looking at the optimization problem explained in footnote 10 and Eqs. 1 and 3, it is obvious that ICT, the carbon tax from the Uzawa formula, brings the economic equity that the carbon tax is imposed on all regions depending on per capita NNI, a type of utility index.

[15] The details of the method to calculate percentage rates of the carbon taxes are described in Sect. 2.3.

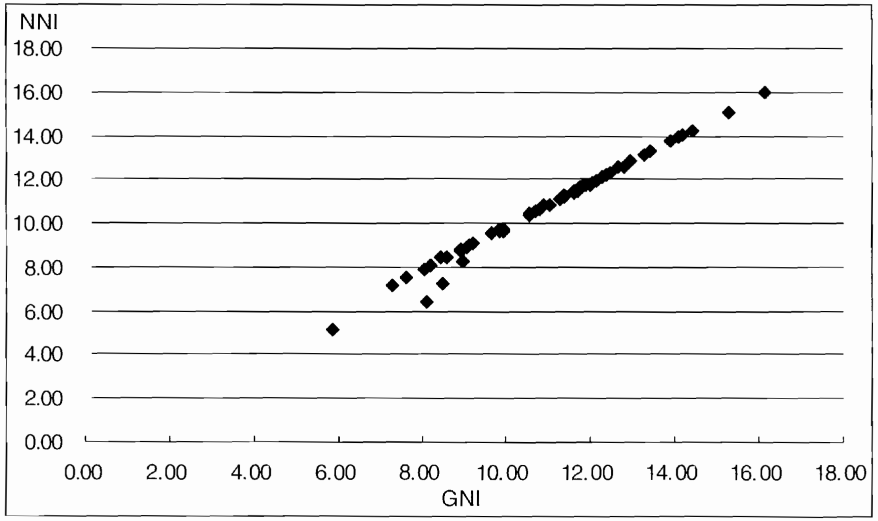
[16] It is a tax on unleaded gasoline in UK which was one of the highest energy-related taxes as International Energy Agency (2005) indicates.

[17] 271.74 % is an indicator of the carbon tax rates. In order to make the rates realistic from the policy viewpoint and to maintain the high rates to some extent to achieve meaningful CO_2 reduction effects, the world's highest energy-related tax at the present time was used.

Table 4. Net national income (NNI), population, per capita NNI (Y_r), and imputed price of carbon (ICT) of each region (IT_r)

Region	NNI (million$)[a]	Population (thousand)[b]	Y_r ($)	IT_r ($/t-C)
AUS	299 805	19 352	15 492.20	301.22
N_Z	41 701	3 815	10 930.80	212.53
JPN	3 375 317	127 271	26 520.71	515.66
USA	8 892 100	288 025	30 872.67	600.28
CAN	586 146	31 025	18 892.70	367.34
E_U	6 811 926	378 441	17 999.97	349.98
WEU	369 677	11 985	30 845.00	599.74
HAR	705 338	386 768	1 823.67	35.46
CHN	1 109 184	1 285 426	862.89	16.78
OAS	1 607 279	1 995 105	805.61	15.66
OAM	1 731 662	527 915	3 280.19	63.78
OEU	160 968	93 645	1 718.92	33.42
M_E	511 823	173 651	2 947.42	57.31
ROW	453 780	821 473	552.40	10.74

[a] Calculated from United Nations (2003a, b). However, because the data for NNI for some regions was lacking, they were estimated from the regression equation of logarithm of NNI and gross national income (GNI, million$) in United Nations (2005b). The regression equation was $\log \text{NNI} = 1.039 \times \log \text{GNI} - 0.630$, and the correlation coefficient was 0.993. The scatter diagram below shows the correlation of gross national income (*GNI*) and net national income (*NNI*) (logarithm of million$)
[b] From Food and Agriculture Organization (2005) and United Nations (2005a)



Concerning the tax rates of other regions, they were set to keep the proportionality relations among regional ICT.

2.2.2 *Case of UCT*

The world total "equivalent variant" was equalized as a result of implementation of both cases. ICT was calculated as in Sect. 2.1.1, so that UCT was arranged to achieve that. Consequently, UCT corresponding to ICT was \$102.69/t-C. Comparing the two, because ICT exceeds UCT in only three regions, JPN, USA, and WEU, it is considered that high UCT was set.

2.3 *Implementation of carbon tax in models*

In order to implement ICT and UCT mentioned in Sect. 2.2 in the model, the rates of each carbon tax against each upper sector of each region were calculated from Eqs. 4–6.

$$\text{EP}_i = \frac{\text{EM}_i}{\text{FP}_i} \quad \text{for all } i \tag{4}$$

$$T_{ir} = 271.74 \frac{\text{IT}_r}{\text{IT}_{\text{USA}}} \frac{\text{EP}_i}{\text{EP}_{\text{COA}}} \quad \text{for all } r \text{ and } i \quad (\text{for ICT}) \tag{5}$$

$$T_i = \text{EP}_i \text{UT} \quad \text{for all } i \quad (\text{for UCT}) \tag{6}$$

where i is the upper sector, EP_i is the CO_2 emissions per price from energy produced by sector i (t-C/\$), EP_{COA} is the CO_2 emissions per price from COA (t-C/\$), EM_i is the CO_2 emissions per unit from energy produced by sector i (t-C/unit), FP_i is the price per unit of energy produced by sector i (\$/unit), T_{ir} is the rate of carbon tax in sector i of region r (%), T_i is the rate of carbon tax in sector i (%), IT_{USA} is the ICT in USA (\$/t-C), and UT is the UCT (\$/t-C).

Table 5 shows CO_2 emissions per unit and prices per unit of energy used in Eq. 4. Table 6 shows the rates of the carbon taxes calculated based on ICT and UCT.

Table 5. CO_2 emissions per unit and prices per unit of coal, oil, and natural gas

	EM_i[a]	FP_i[b]
Coal (COA)	0.000654 (t-C/kg)	0.0393 ($/kg)
Oil (OIL)	0.000713 (t-C/l)	0.149 ($/l)
Natural gas (GAS)	0.000734 (t-C/kg)	0.229 ($/kg)

[a] Calculated from Department of Global Environment, Ministry of the Environment (2003)
[b] Calculated from Energy Data and Modeling Center, The Institute of Energy Economics, Japan (2004)

Table 6. Rate of carbon taxes based on ICT and uniform-rate carbon tax (UCT)

	Revised carbon tax ($/t-C)	COA (%)	OIL (%)	GAS (%)
$T_{i\,AUS}$	82.02	136.36	39.13	26.27
$T_{i\,N\_Z}$	57.87	96.21	27.61	18.54
$T_{i\,JPN}$	140.42	233.43	66.98	44.97
$T_{i\,USA}$	163.46	271.74	77.97	52.35
$T_{i\,CAN}$	100.03	166.29	47.72	32.04
$T_{i\,E\_U}$	95.30	158.44	45.4	30.52
$T_{i\,WEU}$	163.31	271.50	77.90	52.30
$T_{i\,HAR}$	9.66	16.05	4.61	3.09
$T_{i\,CHN}$	4.57	7.60	2.18	1.46
$T_{i\,OAS}$	4.27	7.09	2.03	1.37
$T_{i\,OAM}$	17.37	28.87	8.28	5.56
$T_{i\,OEU}$	9.10	15.13	4.34	2.91
$T_{i\,M\_E}$	15.61	25.94	7.44	5.00
$T_{i\,ROW}$	2.92	4.86	1.40	0.94
T_i	102.69	170.72	48.99	32.89

When implementing each tax into the model, border tax adjustment was applied considering international competitiveness of industries.[18]

2.4 *Calculation of CO_2 emissions*

CO_2 emissions only from energy consumption (fuel combustion)[19] were calculated and the changes through the simulations were analyzed. However, the data of CO_2 emissions before and after the simulations, and those of energy consumption after the simulations were not obtained directly from the simulations. Therefore, they were estimated from Eqs. 7–11. Equation 9 is based on Houghton et al. (1997), the IPCC guideline.

$$P_{jkr} = \frac{\mathrm{CV}^0_{jkr}}{Q^0_{jkr}} \quad \text{for all } j, k, \text{and } r \qquad (7)$$

$$Q^1_{jkr} = \frac{\mathrm{CV}^1_{jkr}}{P_{jkr}} \quad \text{for all } j, k, \text{and } r \qquad (8)$$

$$E_{jkr} = Q_{jkr}\left(1-\sigma_{jkr}\right)\omega_j \varepsilon_j \eta_j \quad \text{for all } j, k, \text{and } r \qquad (9)$$

[18] According to Seventh Ad Hoc Committee of the Global Warming Taxation System, Consortium of Comprehensive Policy Division and Global Environment Division of Central Environmental Council (2001) and Adachi (2004), arguments whether border tax adjustment is justified remain.

[19] COA, OIL, GAS, P_C, ELY, and GDT are involved.

Table 7. Regionally common parameters in Eq. 9

Sector	ω_j (TJ/Mtoe)	ε_j ($t\text{-}CO_2$/TJ)[a]	η_j[b]
COA	41 868	90.60	0.980
OIL	41 868	68.40	0.990
GAS	41 868	49.40	0.995
P_C	41 868	67.10	0.990
GDT	41 868	59.80	0.995

[a] From Department of Global Environment, Ministry of the Environment (2003)

[b] From Houghton et al. (1997)

$$E_r = \sum_j \sum_k E_{jkr} \quad \text{for all } r \qquad (10)$$

$$E = \sum_r E_r \qquad (11)$$

where j represents the energy resource (see footnote 19), k is the industrial sector (see Table 1) and regional household, P_{jkr} is the base price of energy j in sector k of region r in real terms [$/million tons oil equivalent (Mtoe)], CV^0_{jkr} is the real value of energy j consumed in sector k of region r before simulations ($), CV^1_{jkr} is the real value of energy j consumed in sector k of region r after simulations ($), Q^0_{jkr} is the amount of energy j consumed in sector k of region r before simulations (Mtoe), Q^1_{jkr} is the amount of energy j consumed in sector k of region r after simulations (Mtoe), Q_{jkr} represents Q^0_{jkr} and Q^1_{jkr}(Mtoe), E_{jkr} is the CO_2 emission from energy j in sector k of region r ($t\text{-}CO_2$), E_r is the total CO_2 emissions from region r ($t\text{-}CO_2$), E is worldwide CO_2 emissions ($t\text{-}CO_2$), σ_{jkr} is the feedstock ratio of energy j in sector k of region r, ω_j is the calorific value of energy j (TJ/Mtoe), ε_j is the emission coefficient of energy j ($t\text{-}CO_2$/TJ), and η_j is the carbon oxidation ratio of energy j.

CO_2 emissions from electricity sources that emit CO_2 indirectly were not calculated to avoid double counting.

Table 7 shows values of the regionally common parameters used in Eq. 9 and Table 8 shows those of regionally different parameters.[20]

3 Results and discussion

Figures 1 and 2 show the changes in CO_2 emissions and GDP, respectively, as a result of the simulations.

As Fig. 1 indicates, a 2.74% reduction in CO_2 emissions was brought about by ICT and a 3.64% reduction was brought about by UCT throughout the world. That is, UCT contributes 0.9 percent points more to reductions in CO_2 emissions

[20] The rationality to use Eq. 9 and the related parameters in this article is discussed in the Appendix.

Table 8. Regionally different parameters in Eq. 9

Region	$\sigma_{COA\ P\ C\ r}$	$\sigma_{OIL\ P\ C\ r}$	$\sigma_{GAS\ GDT\ r}$	$\sigma_{GAS\ CRP\ r}$	$\sigma_{P\_C\ CRP\ r}$
AUS	1.000	1.000	1.000	0.261	0.872
N_Z	1.000	1.000	1.000	1.000	0.000
JPN	1.000	1.000	1.000	0.000	0.941
USA	1.000	1.000	1.000	0.000	0.953
CAN	1.000	1.000	1.000	0.442	0.989
E_U	1.000	1.000	1.000	0.400	0.878
WEU	1.000	1.000	1.000	0.000	0.902
HAR	1.000	1.000	1.000	0.325	0.257
CHN	1.000	1.000	1.000	0.556	0.749
OAS	1.000	1.000	1.000	0.447	0.621
OAM	1.000	1.000	1.000	0.181	0.591
OEU	1.000	1.000	1.000	0.777	0.642
M_E	1.000	1.000	1.000	1.000	1.000
ROW	1.000	1.000	1.000	0.871	0.174

Source: Lee (2002). Note that other values of parameter σ_{jkr} are 0.000

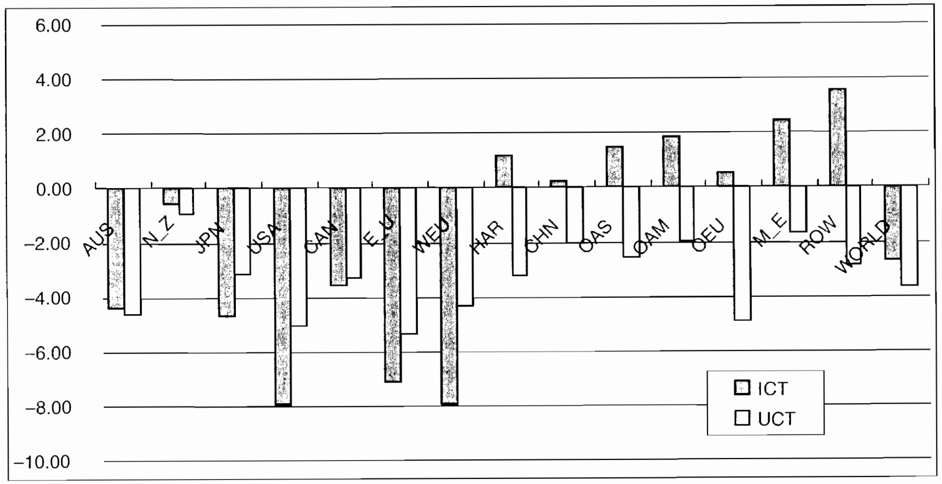


Fig. 1. Percentage changes in CO_2 emissions of each region

than ICT. This is because the tax rates higher than the average, namely UCT, were imposed on some developed countries and those lower than the average were imposed on all developing countries under ICT. This meant the differences of marginal CO_2 emissions reductions among those groups were rather big. As a result, looking overall, CO_2 emissions were reduced inefficiently with ICT. On the other hand, because the tax rate was identical worldwide under UCT, marginal CO_2 emissions reductions were equalized throughout the world. Therefore, CO_2 emissions were reduced rather efficiently and more reduction was realized. Although carbon leakage occurred in developing countries under ICT, it is due to the low-rate carbon tax on them.

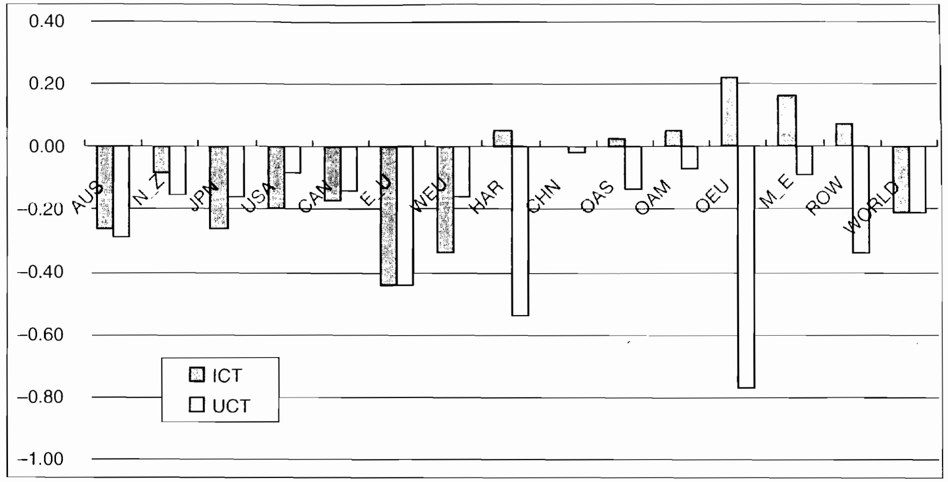


Fig. 2. Percentage changes in gross domestic product (GDP) of each region

Comparing the changes in GDP in Fig. 2, those by ICT and UCT in the world were equivalent, about −0.21%. However, looking at the changes regionally, they indicate different tendencies. Under ICT, although negative influences on GDP were observed in developed countries,[21] positive influences were observed in developing countries. Meanwhile, under UCT, negative influences were seen in all regions and some developing countries such as CHN, OEU, and ROW were damaged more than developed countries.

Regarding the results above, UCT is certainly more appropriate than ICT as a carbon tax from the environmental perspective. However, considering the economic aspects as well, the suitability of UCT diminishes. That is to say, a trade-off between economic equity and CO_2 reduction efficiency occurs between ICT and UCT. Because UCT tends to impose excessive economic burdens on developing countries, it opposes Article 3 of UNFCCC. Moreover, there is a risk that developing countries would deny the introduction of such a worldwide carbon tax policy. If a carbon tax policy is accepted without them, more CO_2 emissions reduction in developed countries will be canceled out due to carbon leakage in developing countries than would occur under ICT.[22] In contrast, because developing countries do not bear economic burdens under ICT, a tax based on "per capita NNI," there is economic equity among developed and developing countries considering their states of development. Therefore, there is a higher feasibility that the carbon tax policy can be introduced worldwide and some CO_2 emissions reductions can be achieved, although inferior to UCT. As some carbon

[21] The total change in developed countries is −0.29% and that in developing countries is +0.05%.
[22] See footnote 4.

leakage was seen under ICT as described, the influences of these would not be large considering the amount of CO_2 emissions in developing countries. Even under UCT, there will be chances to mitigate the economic burdens on developing countries by aid policies such as money transfers from developed countries as in Hoel (2001). However, with additional cost and time required for consultation and negotiations (compromise will be difficult to reach), it is hard to say that the efficiency of CO_2 emissions reductions achieved by the original UCT can be retained.

Consequently, taking account of the difficulty of introducing UCT, it can be considered that ICT, which is more feasible policy than UCT, has more policy effectiveness even though the environmental effect is slightly inferior to UCT.

4 Conclusions

In this study, environmental and economic influences of the carbon tax based on the imputed price of carbon and the worldwide uniform-rate carbon tax were evaluated from the policy viewpoint using a multisectoral/multiregional applied general equilibrium model. As a result of the analyses, a trade-off between economic equity and CO_2 reduction efficiency was observed between ICT and UCT. Although ICT achieved 0.9 percent points lower CO_2 emissions reduction than UCT, it is a more effective policy when considering the effects on GDP in developing countries. It is considered that there are some sorts of "differential-rate carbon taxes" other than ICT, which is based on capacity to pay, such as those based on population, sovereignty, past CO_2 emissions, and exemption of developing countries. However, the tax rates on developing countries will not be always lower than developed countries under the criteria of population and sovereignty, while determination of the appropriate tax rates will be complex when considering past CO_2 emissions. Furthermore, a system that exempts developing countries will be severely compromised by the huge amounts of CO_2 emitted by these nations. Taking these concerns into consideration, ICT, with a simple and clear process to determine tax rates and no economic burdens on developing countries, is the better carbon tax system. However, because the problem of carbon leakage accompanies ICT, the pursuit of solutions, such as increasing tax rates on developing countries to some extent with minimum economic damage, remains a topic future investigation.

This study investigated the scenario in which a carbon tax was introduced as a CO_2 emissions reduction policy with the tax revenue being utilized for regional households. Therefore, in future investigation, impact analyses of ICT and UCT for cases in which tax revenue is used for subsidies for provisions to global warming or for reduction in existing taxes, such as social security'premiums and income taxes, should be implemented. Also, the impact of the simultaneous introduction of other CO_2 emissions reduction policies, such as emissions trading, should also be studied. In addition, it is important to evaluate the dynamic effects of both carbon taxes, considering that the present study has targeted static analyses.

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Appendix

In order to show the rationality of applying Eq. 9 and the related parameters (Tables 7 and 8) in this article, CO_2 emissions (from energy consumption) calculated from Eq. 9 are compared with the historical data here. Table 9 shows the result.

Although there are some significant deviations between calculated values and historical data such as in CAN, E_U, and WEU, the differences are quite small overall. Therefore, it is considered that Eq. 9 approximates historical data.

Table 9. Calculated values and historical data of CO_2 emissions

Region	Calculated values (x, billion t-CO_2)	Historical data (y, billion t-CO_2)[a]	Deviation (%)[b]
AUS	0.370	0.363	1.81
N_Z	0.0358	0.0341	4.79
JPN	1.068	1.143	6.61
USA	5.693	5.741	0.84
CAN	0.539	0.467	15.55
E_U	3.418	3.031	12.75
WEU	0.104	0.0938	10.46
HAR	2.783	2.850	2.34
CHN	2.904	2.675	8.59
OAS	2.671	2.835	5.81
OAM	1.272	1.257	1.17
OEU	0.263	0.285	7.77
M_E	1.087	1.055	3.10
ROW	0.764	0.780	2.77
Total	22.971	22.611	1.59

[a] From Carbon Dioxide Information Analysis Center (2006)
[b] Deviations between calculated values and historical data [absolute values of $(x - y)/y \times 100$]