Structural changes in embodied CO_2 trade due to US withdrawal from Paris Agreement: Fusion of CGE and IO analysis

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1. Introduction

The Paris Agreement to limit global warming was adopted on December 12, 2015 and came into force on November 4, 2016. This agreement is based on the comprehensive national climate action plans submitted by 188 countries before and during the Paris Conference. These national plans are called NDCs, Nationally Determined Contributions. The Paris Agreement is the first historical agreement that mandates action on climate change without regard to developed and developing countries.

However, on November 11, 2019, the Trump administration has formally notified the United Nations that it will withdraw the US from the Paris Agreement. As the US is the world's second-biggest emitter of greenhouse gases, behind only China, its withdrawal will reduce the effectiveness of the Paris Agreement and may induce carbon leakage.

In this study, we analyze the economic and environmental impacts of carbon pricing policies implemented based on NDCs of major countries both with and without the US.

The research method is the following two stage method. In the first stage, we investigate the economic and carbon impacts of the Paris Agreement with and without the US using the GDyn-E model and the GTAP 10 Data Base.

In the second stage, we apply Input-Output (I-O) analysis to the ex-ante and ex-post simulation interregional I-O tables. I-O analysis reveal the interdependence of the CO_2 load (embodied CO_2 trade). Furthermore, it allows us to decompose the change in CO_2 emissions into such contributions as the emission coefficient change, the technology change, and the final-demand change.

We found that with the US departure from the Paris Agreement, the world's CO_2 emissions increase by about 2.4 billion tons compared to the case without the US departure. This is due to an increase in CO_2 emitted in the US. However, our I-O analysis revealed that about 8.3% of the increase in CO_2 is due to the increase in consumption-based CO_2 emissions in countries other than the US. In another word, if a large country like the US leaves the agreement, it will undermine the effectiveness of carbon reduction policies by increasing CO_2 imports of other countries.

2. CGE Analysis

2.1. Gdyn-E Model and Data Base

We use the Gdyn-E model which is a recursive dynamic model developed by Golub (2013). The Gdyn-E model combines the Gdyn model with the GTAP-E model[1]. This model allows us to analyze the impacts of intertemporal global carbon policies. We apply the Gdyn-E model to estimate the impacts of carbon pricing policies implemented based on NDCs of major countries both with and without the US.

Here, we explain substitution structure in production function in the Gdyn-E model to understand the simulation results.

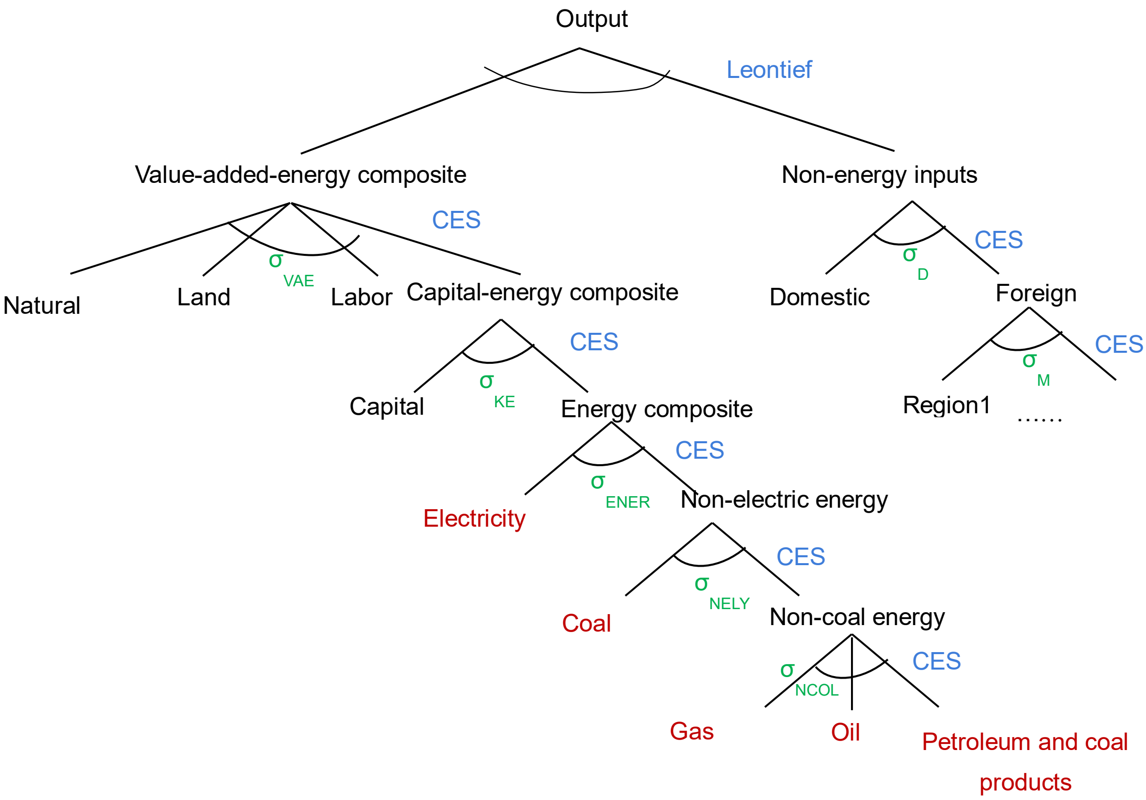

Figure 1 Energy substitution structure in the GDyn-E model

Source: Authors' modification based on Figures 16 and 17 in Burniaux and Truong (2002)

[1] See Hertel ed. (1997) for the standard GTAP model. See Burniaux and Truong (2002) and McDougal and Golub(2007) for the GTAP-E model. See Ianchovichins and Walmsley (2012) for the GDyn model. See Golub (2013) for the GDyn-E model.

Table 1 Substitution elasticity

	σ_{KE}	σ_{ENER}	σ_{NELY}	σ_{NCOL}
Coal	0	0	0	0
Oil	0	0	0	0
Gas	0	0	0	0
Petroleum and coal products	0	0	0	0
electricity	0.5	0	0.5	1
Other industries	0.5	1	0.5	1

Notes

σ_{KE} :The substitution elasticity within the capital-energy composite

σ_{ENER}:The substitution elasticity within the energy composite

σ_{NELY} :The substitution elasticity within the non-electric energy composite

σ_{NCOL} :The substitution elasticity within the non-coal energy composite

Source: GTAP 10 Data Base

Figure 1 shows that this function has a Leontief structure with zero elasticity of substitution at the top level and a constant elasticity at substitution (CES) structure at the lower level. The energy composite is combined with capital and incorporated into the value-added nest. The substitution elasticity within the value-added-energy composite(σVAE) differs between industries and countries. The other values of substitution elasticity are shown in Table 1.

We use the GTAP 10 Data Base, which corresponds to the global economy of 2014 with 141 countries/regions and 65 industries. We aggregate the data into following 23 regions and 28 sectors:

23regions: Oceania, China, Japan, Korea, Taiwan, Indonesia, Malaysia, Singapore, Thailand, Vietnam, Rest of ASEAN, India, Rest of Asia, Canada, US, Mexico, Latin America, EU, Rest of Europe, Russia, Turkestan, the Middle East and North Africa(MENA), Sub-Saharan Africa (SSA)

28sectors: Agriculture, Livestock, Forestry, Fishing, Coal mining, Crude oil, Gas & distribution, Petroleum & coal products, Electricity, Other mining, Processed food, Textiles & clothing, Paper & publishing, Chemical products, Nonmetallic minerals, Iron, Automobile & parts, Transportation equipment, Electronics equipment, Machine equipment, Other manufactures, Water, Construction, Trade, Water transport services, Air transport services, Other transport services, Other services

2.2. Baseline and Scenarios

Our simulation starts from the global economy in 2014 that is described by the GTAP 10 Data Base. We form our baseline using the GTAP 10 Data Base and Chappuis and Walmsley (2011). The estimated growth rates in GDP, population, skilled and unskilled labor are incorporated into the baseline scenario.

We implement the following two scenarios: The Paris Agreement scenario (Sim1), in which major countries including the US achieve their NDCs; and the US withdrawal scenario (Sim2), in which major countries excluding the US achieve their NDCs. We deal only with countries which have unconditional carbon restrictions.

To set target CO_2 growth rates, we estimate the target CO_2 levels based on NDCs using CO_2 data from IEA (2015) and the baseline. Then, we calculate the target CO_2 growth rates by year required to the target level. Target CO_2 growth rates are given in Table 2 and 3.

Table 2 NDCs and corresponding targets for CO_2 growth rate

	NDCs (unconditional target)	Target CO_2 growth rates (%)
Oceania	Australia: 26%–28% reduction by 2030 compared with 2005; New Zealand: 30% reduction by 2030 compared with 2005	–4.14
China	Peaking of CO_2 emissions around 2030	Table 4
Japan	26% reduction by 2030 compared with 2013	–1.51
Korea	37% reduction by 2030 compared with BAU	–2.50
Taiwan	20% reduction by 2030 compared with 2005	–2.88
Indonesia	29% reduction by 2030 compared with BAU	2.06
Malaysia	35% reduction of emissions intensity (CO_2/GDP) by 2030 compared with 2005	1.59
Singapore	36% reduction of emissions intensity (CO_2/GDP) by 2030 compared with 2005	–1.99
Thailand	20% reduction by 2030 compared with BAU	2.08
Vietnam	8% reduction by 2030 compared with BAU	3.12
Canada	30% reduction by 2030 compared with 2005	–4.83
US	26%–28% reduction by 2025 compared with 2005	–4.39
Mexico	25% reduction by 2030 compared with BAU	0.04
EU	40% reduction by 2030 compared with 1990	–3.41
Russia	25%–30% reduction by 2030 compared with 1990	–1.29

Source: Target CO_2 growth rates are Authors' calculations based on the NDCs, IEA(2015), and the baseline.

Table 3 China's target CO_2 growth rate

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	7.29	7.15	6.96	6.79	6.63	6.58	6.41	6.23	6.05	5.88	5.82
C-NDC	6.62	5.96	5.30	4.64	3.97	3.31	2.65	1.99	1.32	0.66	0

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

2.3. *Analysis of macro impacts*

In this section, we discuss the macro impacts on main countries of the two scenarios. Table 4 shows the impacts of the Paris Agreement scenario (Sim1), and the US withdrawal scenario (Sim2) on macro economy and CO_2 emissions in 2030.

Table 4 Macro impacts (differences from the baseline, 2030)

	Sim1					Sim2				
	GDP %	EV* Billion $	tot %	Real carbon price of CO_2 $/ton	CO_2 %	GDP%	EV Billion $	tot %	Real carbon price of CO_2 $/ton	CO_2 %
Oce	-1.6	-32.9	0.4	189.5	-44.4	-1.8	-41.4	-0.7	183.8	-44.4
Chn	-0.1	-201.0	0.1	29.1	-28.8	-0.3	-212.2	0.0	28.4	-28.8
Jpn	-1.0	-35.4	2.3	164.6	-26.8	-1.3	-39.9	2.1	159.4	-26.8
Kor	-2.6	-17.0	2.2	179.8	-37.0	-2.8	-18.1	2.1	175.0	-37.0
Twn	-5.1	-25.5	1.8	288.3	-54.7	-5.3	-25.5	1.6	282.8	-54.7
Idn	-1.4	-15.3	-1.5	82.5	-29.0	-1.6	-18.8	-1.8	80.2	-29.0
Mys	-2.4	-4.7	-0.0	85.3	-28.4	-2.5	-4.9	-0.1	82.6	-28.4
Sgp	-9.2	21.3	7.5	616.9	-49.9	-9.3	20.1	7.2	600.7	-49.9
Tha	0.8	8.6	0.6	30.7	-20.0	0.5	6.0	0.4	28.6	-20.0
Vnm	-0.4	-3.9	-1.2	11.9	-8.0	-0.4	-3.5	-1.1	11.1	-8.0
O_ASEAN	0.8	2.3	-0.8		5.8	0.5	-0.0	-1.1		4.6
Ind	2.1	84.8	2.0		5.0	1.8	75.9	1.8		4.4
O_Asia	1.2	28.2	1.4		4.2	1.0	22.6	1.0		4.1
Can	-2.9	-63.1	-2.7	217.3	-48.6	-2.9	-54.0	-1.5	205.9	-48.6
US	-1.2	-247.9	0.1	145.1	-46.8	0.6	6.0	0.2		2.5
Mex	-0.6	-10.7	-1.1	82.6	-22.0	-0.5	-2.9	-0.3	78.4	-22.0
Latin	2.2	111.8	1.2		7.2	1.8	87.3	0.6	0.0	5.5
EU	-2.2	-240.3	1.7	305.5	-41.1	-2.4	-272.0	1.4	295.6	-41.1
O_Euro	1.3	-24.4	-1.6		12.1	1.0	-24.8	-1.6		11.2
Rus	-8.2	-172.9	-6.9	146.8	-40.9	-8.3	-165.2	-6.0	145.1	-40.9
Turkestan	0.8	-10.7	-5.5		7.1	0.6	-9.5	-4.8		5.6
MENA	0.9	-127.3	-5.0		4.9	0.6	-117.3	-4.3		4.4
SSA	1.2	1.5	-2.8		5.6	1.0	-1.8	-2.5		4.6

Sources: Authors' simulation with GDyn and the GTAP 10 Data Base.
Note: *EV is the total difference from the baseline of equivalent variation from 2020 to 2030.

The GDP of carbon-constrained countries except Thailand is below the baseline. It is remarkably low for Singapore, Russia and Taiwan. The GDP of all regions that have no carbon-constrain is above the baseline. Comparing Sim1 and Sim2, GDP in countries other than the US, Canada, Mexico, and Vietnam decreases.

Equivalent variations (EV) of most carbon-constrained countries are below the baseline but higher in Singapore and Thailand. The EV for Turkestan and the Middle East and North Africa deteriorate despite their absence of carbon constraints.

Terms of trade (tot) improves in Singapore, but deteriorations in Russia, Turkestan and MENA are remarkable.

Comparing real carbon prices, it is lower in Sim2 than in Sim1.As will be seen later, this is because production in carbon-restricted countries decrease due to the US withdrawal. In addition, the energy price of Sim2 is higher than that of Sim1. Therefore, restricted countries can achieve reductions with lower carbon prices.

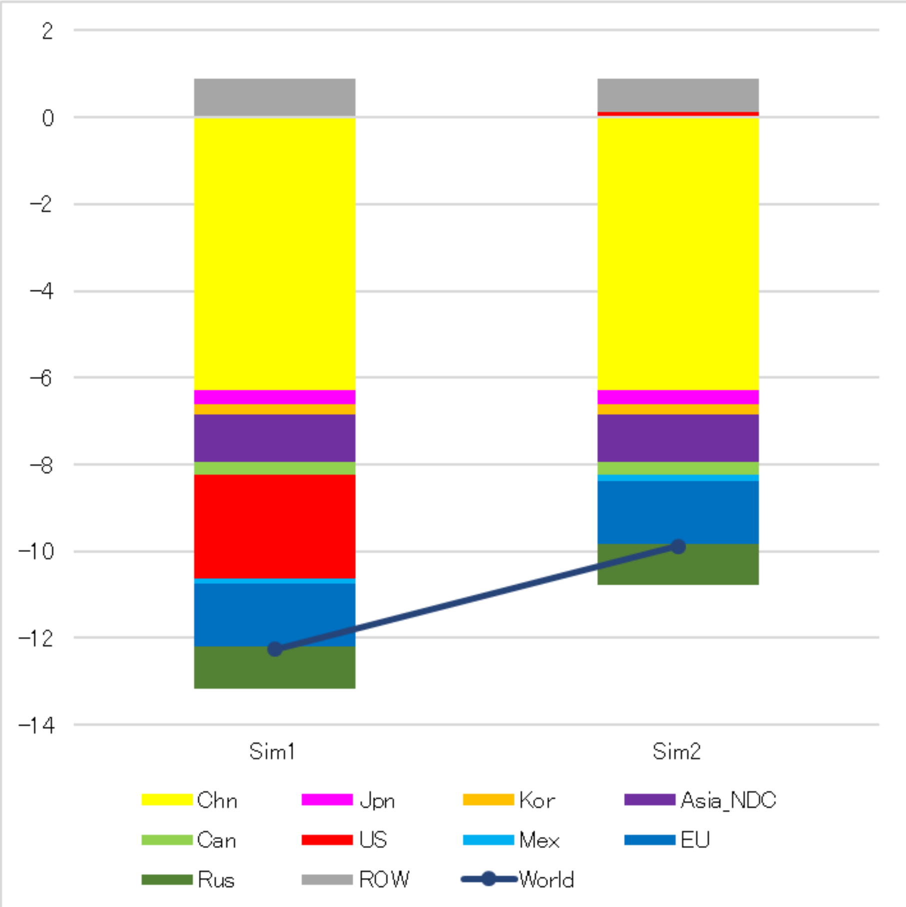

Figure 2 Impacts of CO_2 emissions in 2030 (differences from the baseline, Billion ton)
Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Figure 2 shows impacts on CO_2 emissions in 2030. Main difference between Sim1 and Sim2 seems to be change in CO_2 emissions in the US. The difference of world's CO_2 emissions from the baseline is -12,261 million tons for Sim1 and -9,876 million tons for Sim2. In other words, the CO_2 emissions of Sim2 is 2,385 million tons higher than that of Sim1.

CO_2 emissions in the US increase by 2,506 million tons due to its withdrawal compared to Sim1. Therefore, the cause of an increase in CO_2 emissions in the world in Sim2 is due to an increase in CO_2 emissions in the US. CO_2 emissions in unconstrained countries decrease slightly.

2.4. *Analysis of sectorial impacts*

We now investigate the results of scenario analysis by industry, focusing on China, Japan, the US and the EU.

In China, the US withdrawal will lead to a greater decline in production in the service sector. In addition, the production volume of petroleum coal products and ceramics, which had exceeded the baseline in Sim1, fell below in Sim2. Overall, China's production will decrease, but total CO_2 remains almost unchanged.

In Japan and the EU, the decline in service production due to the departure of the US is relatively noticeable. The total of those CO_2 is almost unchanged.

In Sim2, the output of many industries exceeds the baseline in the US. Especially the output of the service and the transportation sector is large. The increase in CO_2 is largely due to services, transportation, chemicals and petroleum coal products.

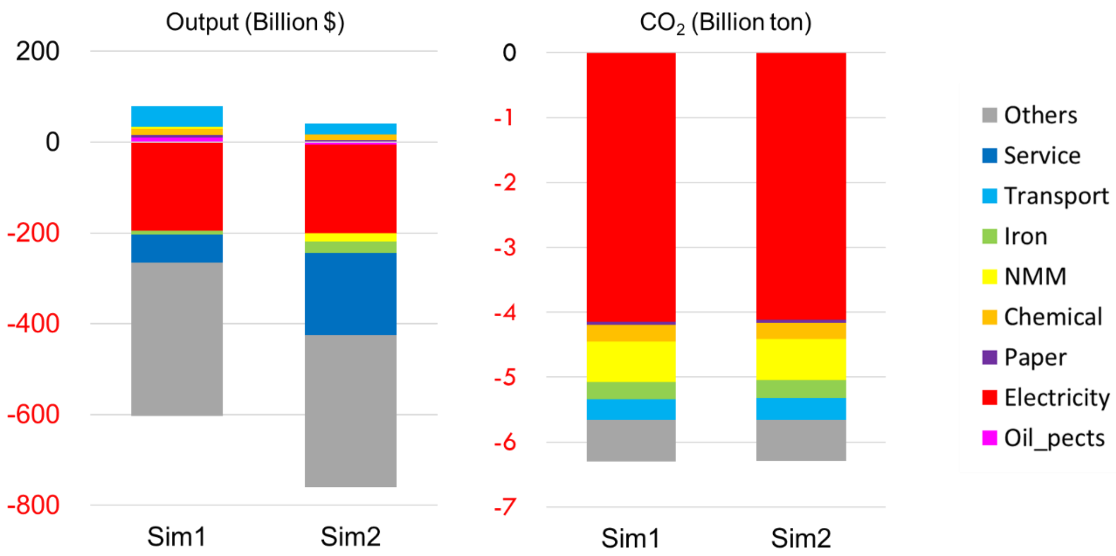

Figure 3 China's output and CO_2 in 2030 (differences from the baseline)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

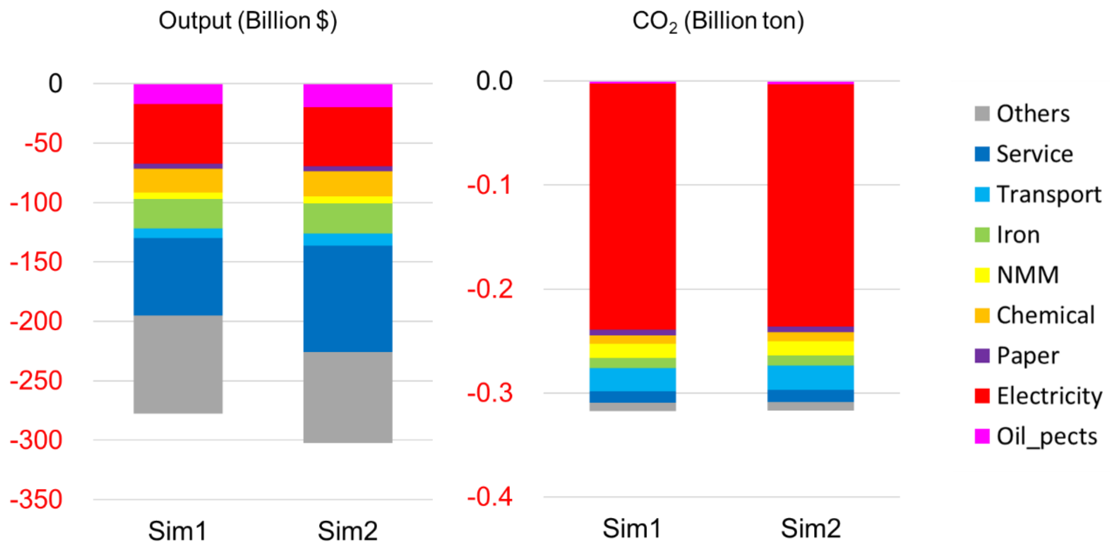

Figure 4 Japan's output and CO_2 in 2030 (differences from the baseline)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

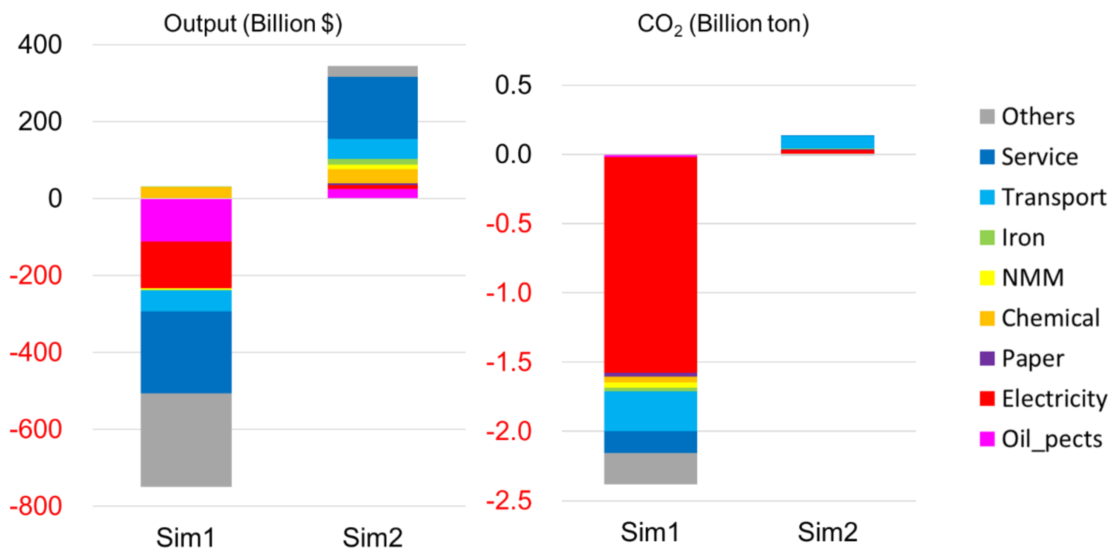

Figure 5 US's output and CO_2 in 2030 (differences from the baseline)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

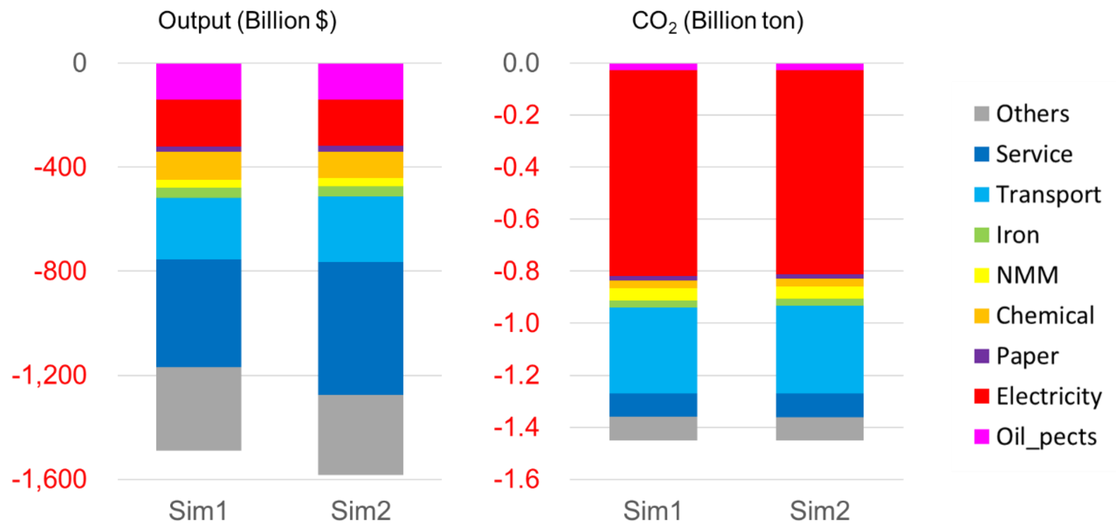

Figure 6 EU's output and CO_2 in 2030 (differences from the baseline)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

3. Interregional I-O Analysis

3.1. Interregional I-O table

For I-O analysis, we need the ex-ante and ex-post simulation interregional I-O tables. Since the GTAP Data Base used here does not contain enough data on cross-border trade between industries, we follow the proportional procedure in Bems et al. (2010, 2011) and in Johnson and Noguera (2012). We assume that the share of imported goods *i* from country *s* in total imported goods *i* is the same across both industries and final demand. Although these assumptions are rather strong, this method is helpful when when investigating the structural change in CO_2 emissions due to carbon policy in the first analytical approach.

Table 5 represents the interregional I-O table for two regions, two sectors, and a global transportation sector. The row in the global transportation sector indicates international transportation service distribution through sales to sectors and final demand. International transportation services accompanied with imported intermediate input are treated as an intermediate input from the global transportation sector. The global transportation sector purchases transportation services from regional sectors as an intermediate input. In Table 1, only sector 2 supplies transportation services. As the GTAP model assumes, the global transportation sector does not use factors.

Table 5 Interregional I-O Table for Two Regions and Two Sectors

		Intermediate input demand					Final demand		
		r=1		*r*=2		*r*=G	*r*=1	*r*=2	
		j=1	*j*=2	*j*=1	*j*=2				Total
s=1	*i*=1	Z_{11}^{11}	Z_{12}^{11}	Z_{11}^{12}	Z_{12}^{12}	0	F_1^{11}	F_1^{12}	X_1^1
	i=2	Z_{21}^{11}	Z_{22}^{11}	Z_{21}^{12}	Z_{22}^{12}	Z_2^{1G}	F_2^{11}	F_2^{12}	X_2^1
s=2	*i*=1	Z_{11}^{21}	Z_{12}^{21}	Z_{11}^{22}	Z_{12}^{22}	0	F_1^{21}	F_1^{22}	X_1^2
	i=2	Z_{21}^{21}	Z_{22}^{21}	Z_{21}^{22}	Z_{22}^{22}	Z_2^{2G}	F_2^{21}	F_2^{22}	X_2^2
s=G		Z_1^{G1}	Z_2^{G1}	Z_1^{G2}	Z_2^{G2}	0	F^{G1}	F^{G2}	X^G
Value added		V_1^1	V_2^1	V_1^2	V_2^2	0			
Total		X_1^1	X_2^1	X_1^2	X_2^2	X^G			

Notes: The superscript G represents the global transportation sector. Z_{ij}^{sr}, F_i^{sr}, X_i^s, and V_i^s are purchases of intermediate products from sector *i* in region *s* to sector *j* in region *r*, purchases of final products from sector *i* in region *s* to region *r*, amount of output of sector *i* in region *s*, and value added of sector *i* in region *s*, respectively.

We construct four real interregional I-O tables using the baseline and policy simulation GTAP Data Base.

- the baseline 2020 I-O table evaluated at 2020 prices
- the baseline 2030 I-O table evaluated at 2020 prices
- the post-policy 2030 I-O table under the Sim1 scenario evaluated at 2020 prices
- the post-policy 2030 I-O table under the Sim2 scenario evaluated at 2020 prices

3.2. Interregional I-O model

This section briefly describes a model for interregional I-O analysis. Assume that the economy consists of *N*-industries and *R*-regions. Under a constant input coefficient, the equilibrium conditions for the goods market are as follows:

$$x_i^s = \sum_{r=1}^{R}\sum_{j=1}^{N} a_{ij}^{sr} x_j^r + \sum_{r=1}^{R} f_i^{sr}, i = 1 \cdots N, s = 1 \cdots R, \quad [1]$$

where x_i^s denotes the gross output of industry *i* in region *s*, a_{ij}^{sr} denotes the direct input coefficient, indicating the amount of intermediate good *i* produced in region *s* required to produce a unit of good *j* in country *r,* and f_i^{sr} denotes final demand for good *i* produced in region *s* from country *r*.

$$\mathbf{x}^s = \begin{pmatrix} x_1^s \\ \vdots \\ x_N^s \end{pmatrix}, \mathbf{A}^{sr} = \begin{pmatrix} a_{11}^{sr} & \cdots & a_{1N}^{sr} \\ \vdots & \ddots & \vdots \\ a_{N1}^{sr} & \cdots & a_{NN}^{sr} \end{pmatrix}, \mathbf{f}^s = \begin{pmatrix} f_1^{s1} + f_1^{s2} + \cdots + f_1^{sR} \\ \vdots \\ f_N^{s1} + f_N^{s2} + \cdots + f_N^{sR} \end{pmatrix}.$$

With these notations, Equation [1] can be represented in matrix form as:

$$\begin{pmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^R \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1R} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{R1} & \cdots & \mathbf{A}^{RR} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \vdots \\ \mathbf{x}^R \end{pmatrix} + \begin{pmatrix} \mathbf{f}^1 \\ \vdots \\ \mathbf{f}^R \end{pmatrix}. \quad [2]$$

If we know the values of the input coefficients and final demand, we can solve Equation [2] for equilibrium gross output. The gross output vector **x** can be expressed as a product of the Leontief inverse matrix **L** and a final demand vector **f** as follows:

$$\mathbf{x} = \mathbf{L}\mathbf{f}, \quad [3]$$

where

$$\mathbf{x} = \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \vdots \\ \mathbf{x}^R \end{pmatrix}, \quad \mathbf{f} = \begin{pmatrix} \mathbf{f}^1 \\ \mathbf{f}^2 \\ \vdots \\ \mathbf{f}^R \end{pmatrix}$$

$$\mathbf{L} = \begin{pmatrix} \mathbf{I} - \mathbf{A}^{11} & -\mathbf{A}^{12} & \cdots & -\mathbf{A}^{1R} \\ -\mathbf{A}^{21} & \mathbf{I} - \mathbf{A}^{22} & \cdots & -\mathbf{A}^{2R} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}^{R1} & -\mathbf{A}^{R2} & \cdots & \mathbf{I} - \mathbf{A}^{RR} \end{pmatrix}^{-1} = \begin{pmatrix} \mathbf{L}^{11} & \mathbf{L}^{12} & \cdots & \mathbf{L}^{1R} \\ \mathbf{L}^{21} & \mathbf{L}^{22} & \cdots & \mathbf{L}^{2R} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{L}^{R1} & \mathbf{L}^{R2} & \cdots & \mathbf{L}^{RR} \end{pmatrix}.$$

Next, $\mathbf{L}^{sr}$ is an $N \times N$ matrix consisting of coefficients that indicate the amount of total output in each industry of region *s* directly and indirectly required to satisfy one unit of final demand for each industry in region *r*.

Let $\mathbf{e}^S$ be the $1 \times N$ direct CO_2 output ratio vector:

$$\mathbf{e}^s = \left(e_1^s, e_2^s, \cdots e_N^s\right), \quad [4]$$

where e_j^s is the CO_2 output ratio (CO_2 emission/gross output) of industry *j* in region *s*. We define the $R \times NR$ CO_2 output ratio matrix $\hat{\mathbf{e}}$ as

$$\hat{\mathbf{e}} = \begin{pmatrix} \mathbf{e}^1 & 0 & \cdots & 0 \\ 0 & \mathbf{e}^2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{e}^R \end{pmatrix}. \quad [5]$$

Pre multiplying the Leontief inverse matrix **L** by the CO_2 output ratio matrix $\hat{\mathbf{e}}$ generates the following the $R \times NR$ matrix that illustrates how CO_2 emissions are geographically generated to satisfy one unit of final demand for each industry in each region.

$$\hat{\mathbf{e}}\mathbf{L} = \begin{pmatrix} \mathbf{e}^1\mathbf{L}^{11} & \cdots & \mathbf{e}^1\mathbf{L}^{1R} \\ \vdots & \ddots & \vdots \\ \mathbf{e}^R\mathbf{L}^{R1} & \cdots & \mathbf{e}^R\mathbf{L}^{RR} \end{pmatrix}. \quad [6]$$

Each element of $\mathbf{e}^s\mathbf{L}^{sr}$ presents the amount of CO_2 embodied in one unit of each final good produced in region r with origin in region s. In other words, each column of $\hat{\mathbf{e}}\mathbf{L}$ shows the geographical division of CO_2 directly and indirectly embodied in one unit of each final good.

We use Equation [6] to calculate the structure of embodied CO_2 emissions in international trade. Multiplying $\hat{\mathbf{e}}\mathbf{L}$ by final demand vector $\mathbf{f}$ gives CO_2 emissions accompanied by equilibrium gross output induced by the final demand:

$$\hat{\mathbf{e}}\mathbf{L}\mathbf{f} = \begin{pmatrix} \mathbf{e}^1\mathbf{L}^{11}\mathbf{f}^1 + \cdots + \mathbf{e}^1\mathbf{L}^{1R}\mathbf{f}^R \\ \vdots \\ \mathbf{e}^R\mathbf{L}^{R1}\mathbf{f}^1 + \cdots + \mathbf{e}^R\mathbf{L}^{RR}\mathbf{f}^R \end{pmatrix}. \quad [7]$$

The vector $\hat{\mathbf{e}}\mathbf{L}\mathbf{f}$ consists of R elements that indicate the CO_2 emissions released in specific regions within CO_2 emissions induced from the total final demand. Using Equation [7], CO_2 induced from the final demand from a specified region can be decomposed according to the region where it was released.

Equation [7] can be used for structural decomposition analysis. Compare an economy at two different points in time. Let an apostrophe note a later point in time. The left hand side of Equation [7] is as follows:

$$\boldsymbol{\varepsilon} = \hat{\mathbf{e}}\mathbf{L}\mathbf{f} \quad \text{and} \quad \boldsymbol{\varepsilon}' = \hat{\mathbf{e}}\mathbf{L}'\mathbf{f}', \quad [8]$$

Where $\boldsymbol{\varepsilon}$ is the vector of production-based CO_2 emission by region.

The change in CO_2 emission over time is

$$\Delta\boldsymbol{\varepsilon} = \hat{\mathbf{e}}'\mathbf{L}'\mathbf{f}' - \hat{\mathbf{e}}\mathbf{L}\mathbf{f}\,. \quad [9]$$

According to Miller and Blair (2009, p.606), we can decompose the change in CO_2 emission as follows:

$$\Delta\boldsymbol{\varepsilon} = (1/2)(\Delta\hat{\mathbf{e}})(\mathbf{L}\mathbf{f} + \mathbf{L}'\mathbf{f}') + (1/2)(\hat{\mathbf{e}}(\Delta\mathbf{L})\mathbf{f}' + \hat{\mathbf{e}}'(\Delta\mathbf{L})\mathbf{f}) + (1/2)(\hat{\mathbf{e}}\mathbf{L} + \hat{\mathbf{e}}'\mathbf{L}')(\Delta\mathbf{f}). \quad [10]$$

The first term on the right hand side is the CO_2 output ratio change contribution, second term is the technology change contribution, and third term is the final demand change contribution.

We applied Equation [10] to ex-ante and ex-post international I-O table and decomposed the changes in CO_2 emission for each scenario.

3.3. Structural change in CO_2 emissions embodied in international trade

In this section, we discuss the structural change in CO_2 emissions in international trade caused by carbon policy by applying an interregional I-O analysis to the estimated ex-ante and ex-post simulation I-O tables.

According to Equation [7], we decomposed CO_2 emissions induced by the final demand from each region according to the region where the emissions were released.

Table 6 represents the CO_2 emissions embodied in trade calculated using the baseline 2030 I-O table evaluated at 2020 prices. Each column shows the source regions of CO_2 induced from the region indicated by each column header. The total emissions induced by a certain region represent the consumption-based CO_2 emissions of that region. Subtracting domestic emissions (the diagonal element) from the consumption-based CO_2 of the region indicated by the header yields its CO_2 imports.

Each row shows the export destination of CO_2 generated in the region indicated by each row header. Total emissions released in a certain region are referred to as the production-based CO_2 emissions in that region. Subtracting part of the domestic absorption (the diagonal element) from the production-based CO_2 emissions of the region indicated by the header yields its CO_2 export[2].

Tables 7 and 8 show embodied CO_2 trade of Sim1 and Sim2 in 2030, respectively. Comparing Tables 7 and 8, the production-based CO_2 emissions are almost the same except for the US and ROW. However, the consumption-based CO_2 emissions in carbon restricted countries seem to be larger in Sim2 than in Sim1. From this, the US departure does not affect production-based CO_2 emissions of the constrained countries, but increases consumption-based ones. The increase in the EU, Canada and Mexico is relatively large.

The world's CO_2 emissions in Sim2 increase by about 2.4 billion tons compared to Sim1. The US consumption-based CO_2 increase is about 2.2 billion tons, and that of countries other than the US is 199 million tons. Therefore, about 8.3% of the increase in CO_2 caused by the US withdrawal is due to the increase in consumption-based CO_2 emissions in countries other than the US.

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[2]The CO_2 emission here does not contain emission released from the combustion of fossil fuel at household and government.

Table 6 CO_2 emissions embodied in International trade (baseline, 2030, millions of tons)

	Chn	Jpn	Kor	A_NDC	Can	US	Mex	EU	Rus	ROW	P_based
Chn	17,183	283	108	637	101	738	128	915	174	1,653	21,919
Jpn	71	873	7	38	3	29	4	34	6	53	1,119
Kor	75	13	328	31	3	28	5	37	7	67	595
A_NDC	280	69	24	2,189	16	116	13	170	18	277	3,172
Can	25	7	3	11	303	144	7	33	3	54	590
US	119	31	17	62	66	4,086	62	168	15	226	4,852
Mex	13	3	1	6	9	93	352	17	1	40	536
EU	143	36	15	81	22	133	13	2,508	47	410	3,408
Rus	59	17	9	30	4	39	4	143	1,794	184	2,284
ROW	556	125	60	279	50	387	40	856	114	12,394	14,861
C_based	18,525	1,455	573	3,365	577	5,793	628	4,881	2,180	15,358	53,334

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Note: A_NDC is Asian countries with carbon constrains (Oceania, Taiwan, Indonesia, Malaysia, Singapore, Thailand, Vietnam)

Table 7 CO_2 emissions embodied in International trade (Sim1, 2030, millions of tons)

	Chn	Jpn	Kor	A_NDC	Can	US	Mex	EU	Rus	ROW	P_based
Chn	12,188	206	77	452	67	521	92	666	104	1,252	15,623
Jpn	51	622	5	27	2	21	3	26	4	41	801
Kor	46	8	194	20	2	17	3	25	4	45	365
A_NDC	174	46	15	1,404	11	80	9	121	11	196	2,066
Can	13	4	1	6	143	75	4	17	1	31	296
US	69	19	10	37	35	2,010	35	104	8	145	2,472
Mex	10	2	1	4	6	65	274	13	1	30	405
EU	87	23	10	49	12	79	8	1,424	24	244	1,959
Rus	42	12	6	18	3	27	2	90	1,013	119	1,332
ROW	597	116	58	296	55	454	44	946	110	13,080	15,755
C_based	13,276	1,058	376	2,312	336	3,349	473	3,432	1,279	15,182	41,073

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Table 8 CO_2 emissions embodied in International trade (Sim2, 2030, millions of tons)

	Chn	Jpn	Kor	A_NDC	Can	US	Mex	EU	Rus	ROW	P_based
Chn	12,160	205	77	451	69	556	95	662	105	1,247	15,625
Jpn	51	622	5	27	2	22	3	26	4	41	802
Kor	46	8	194	20	2	18	3	25	4	45	365
A_NDC	174	46	15	1,407	11	81	9	119	11	195	2,068
Can	13	3	1	5	144	76	4	17	1	30	295
US	121	33	18	64	67	4,178	61	182	14	241	4,977
Mex	9	2	1	4	6	67	276	12	1	28	405
EU	86	22	9	49	12	79	8	1,424	25	243	1,958
Rus	41	12	6	18	3	27	2	89	1,016	117	1,331
ROW	589	114	57	292	55	430	45	932	110	13,006	15,632
C_based	13,290	1,068	383	2,335	371	5,534	506	3,487	1,290	15,193	43,458

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Table 9 Trade balance in CO_2 emissions (2030, millions of tons)

	Baseline2030			Sim1 2030			Sim2 2030		
	Export	Import	Balance	Export	Import	Balance	Export	Import	Balance
Chn	4,736	1,342	3,394	3,436	1,088	2,347	3,466	1,130	2,335
Jpn	246	583	-337	179	435	-256	180	446	-266
Kor	267	245	22	171	183	-12	171	189	-18
A_NDC	983	1,176	-192	662	908	-246	661	928	-267
Can	286	274	12	153	193	-40	150	227	-76
US	766	1,707	-941	462	1,339	-877	799	1,356	-557
Mex	183	275	-92	131	199	-68	129	231	-101
EU	900	2,373	-1,473	535	2,007	-1,473	534	2,064	-1,529
Rus	489	385	104	319	267	52	315	274	41
ROW	2,467	2,964	-497	2,675	2,103	573	2,626	2,187	438

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Table 9 shows the CO_2 trade balance in 2030 for each scenario. CO_2 exports as well as CO_2 imports in carbon-restricted countries are below the baseline. While the surpluses in China and Russia become smaller, the deficit in Japan, US and Mexico decrease. In South Korea and Canada, the surplus become in the red. A_NDC's CO_2 trade deficit become large. In ROW, the deficit becomes in the black. Comparing Sim1 and Sim2, CO_2 exports increase in the US and CO_2 imports increase in other countries.

3.4. ***Structural decomposition of changes in CO_2 emissions***

Table 10 and Figure 6 show structural decomposition of changes in baseline CO_2 emissions from 2020 to 2030. The main cause of the increase in CO_2 emissions is the final demand change contribution, which greatly exceeds the minus technology change contribution. CO_2 output ratio change contribution is inconspicuous in the whole world, but it is relatively large in China.

Tables 11 and 12, and Figures 8 and 9 show the structural decomposition of the deviation from the baseline caused by the carbon reduction policy. The main cause of the decrease in CO_2 emissions is CO_2 output ratio change contribution. This is due to the substitution of coal for production factors, gas and petroleum coal products. The technology change contribution is also relatively large, which is caused by the substitution of domestic products for imported products.

Table 10 Structural decomposition of CO_2 emissions from 2020 to 2030, baseline (million tons)

	CO_2/output	Technology	final demand	Total
Chn	-563	-91	11,649	10,995
Jpn	19	-493	641	167
Kor	9	-690	778	97
A_NDC	16	-1,041	2,163	1,138
Can	-14	-330	397	53
US	-88	-1,397	2,015	530
Mex	-19	1	152	134
EU	31	-3,425	3,915	521
Rus	51	-175	884	760
ROW	-105	-1,235	7,565	6,224
World	-662	-8,876	30,157	20,619

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

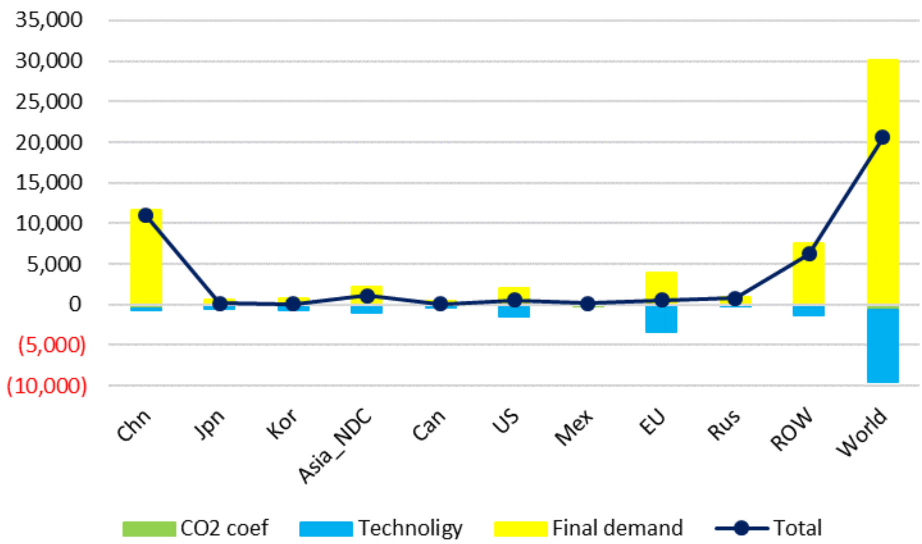

Figure 7 Structural decomposition of CO_2 emissions from 2020 to 2030, baseline (million tons)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Table 11 Structural decomposition of CO_2 emissions from the baseline under Sim1 (2030, million tons)

	CO_2/output	Technology	final demand	Total
Chn	-4,715	-1,227	-354	-6,296
Jpn	-202	-71	-44	-317
Kor	-128	-73	-29	-230
A_NDC	-645	-304	-158	-1,106
Can	-225	-39	-30	-293
US	-1,797	-288	-295	-2,380
Mex	-92	-30	-9	-131
EU	-986	-273	-190	-1,449
Rus	-367	-284	-301	-952
ROW	147	375	371	894
World	-9,010	-2,213	-1,039	-12,261

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

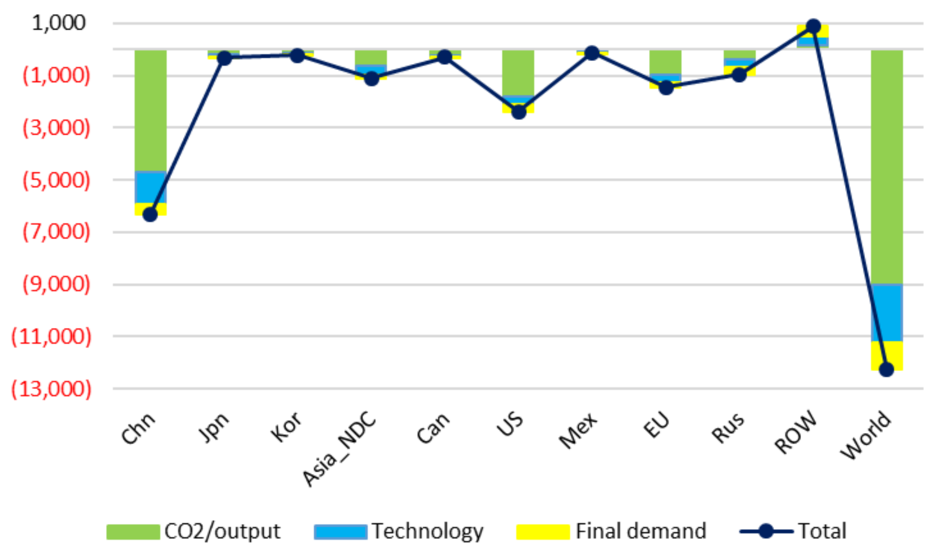

Figure 8 Structural decomposition of CO_2 emissions from the baseline under Sim1 (2030, million tons)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

Table 12 Structural decomposition of CO_2 emissions from the baseline under Sim2 (2030, million tons)

	CO_2/output	Leontief	final demand	Total
Chn	-4,678	-1,200	-416	-6,294
Jpn	-201	-69	-47	-317
Kor	-127	-73	-30	-230
A_NDC	-638	-301	-165	-1,104
Can	-220	-48	-27	-295
US	3	66	56	125
Mex	-90	-34	-6	-131
EU	-978	-274	-198	-1,450
Rus	-364	-288	-301	-952
ROW	135	332	305	771
World	-7,157	-1,890	-829	-9,876

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

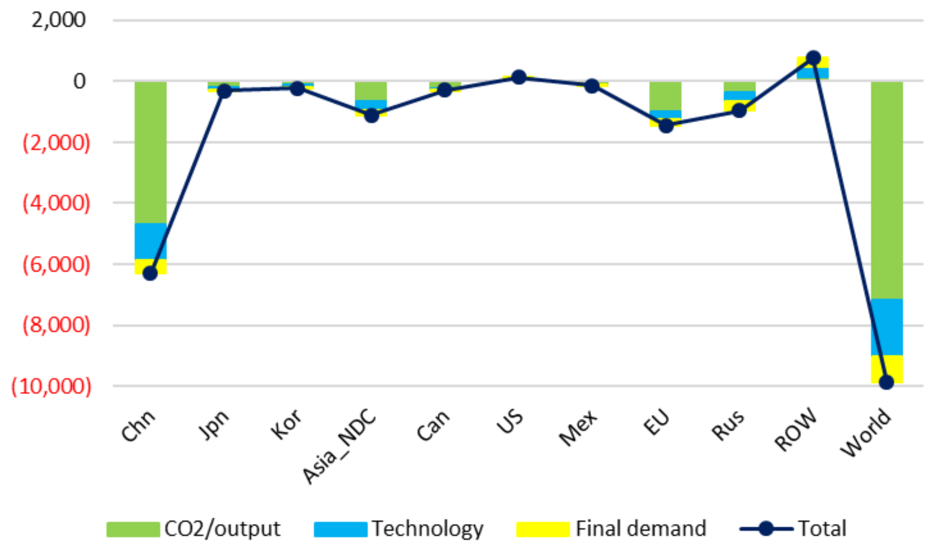

Figure 9 Structural decomposition of CO_2 emissions from the baseline under Sim2 (2030, million tons)

Source: Authors' simulations with the GDyn model and the GTAP 10 Data Base.

CO_2 emissions in the US under Sim2 are approximately 2.5 billion tons higher than under Sim1. CO_2 output ratio, technology and final demand change contribution account for 72%, 14%, and 14% of them respectively. China's final demand change contribution under Sim2 are about 62 million tons smaller than that under Sim1. However, it is offset due to deterioration of CO_2 output ratio and technology. The CO_2 emission of ROW under Sim2 is about 123 million tons less than that under Sim1. In this case, the contributions of all three factors are smaller under Sim2.

4. Conclusion

In this study, we analyzed the economic and environmental impacts of carbon pricing policies implemented based on NDCs of major countries both with and without the US.

With the US departure from the Paris Agreement, the world's CO_2 emissions increase by about 2.4 billion tons compared to the case without the US departure. This is due to an increase in CO_2 emissions in the US itself. The US withdrawal reduces production in other countries, which leads to lower carbon prices.

Our I-O analysis reveals that CO_2 emissions of production standards in carbon-constrained countries do not change with the departure of the US, but that of consumption standards increase. It means that if a large country like the US leaves the agreement, it will undermine the effectiveness of carbon reduction policies. It is important that carbon constraints cover the entire world. In another word, when there are countries without carbon reduction obligations, or when carbon reduction targets vary from country to country, evaluating CO_2 emissions based on consumption standards as well as production standards.

From the structural decomposition analysis, we found that improvement of CO_2 output ratio contributes most to carbon reduction. The relatively small reduction in carbon due to a decrease in final demand may depend on the assumption of full employment and flexible movement of production factors between industries. In other words, by improving the CO_2 output ratio, it is possible to reduce carbon while reducing the burden on the economy.

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