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A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS OF BORDER ADJUSTMENTS UNDER THE CAP-AND-TRADE SYSTEM: A CASE STUDY OF THE JAPANESE ECONOMY

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Using a multi-region and multi-sector computable general equilibrium model, this paper evaluates the border adjustment policies of carbon regulations in Japan. We consider five types of border adjustments and examine their effects on the welfare, carbon leakage, and competitiveness of the Japanese energy-intensive trade-exposed (EITE) sectors.

Our analysis shows that no single border adjustment policy is superior to the other policies in terms of simultaneously solving three primary issues: Welfare degradation, carbon leakage, and a loss of competitiveness in the EITE sectors. In addition, we show that export border adjustments are effective at restoring the competitiveness of Japanese exporters and reducing leakage. Our analysis also reveals that border adjustment in Japan significantly affects carbon leakage to China and the competitiveness of the iron and steel sectors. Finally, we show that border adjustments with and without consideration of indirect emissions have similar impacts, which indicates that the information regarding direct emissions is sufficient for implementing border adjustment in Japan.

Keywords: CGE analysis; climate change; border adjustment; carbon leakage; competitiveness.

1. Introduction

Developed nations are considering the adoption of carbon-pricing policies, such as domestic emissions-trading schemes or carbon taxes, to counter climate change. At the same time, developing countries that are Non-Annex I Countries under the Kyoto Protocol are delaying the introduction of emissions restrictions. It is projected that this internationally asymmetrical adoption of emissions restrictions could bring about a situation in which developed countries restrain CO_2 emissions, while developing countries increase production and emissions in carbon-intensive industries. This problem, in which the adoption of policies to restrain carbon emissions in one region results in an increase in other regions, is referred to as carbon leakage. In addition, the international competitiveness of carbon-intensive industries in developed countries could decrease in comparison to that of industries in developing countries that do not need to bear the costs associated with restraining emissions. Recently, a lively debate occurred regarding the introduction and efficacy of border adjustments (BAs) as a solution to these issues of carbon leakage and reduced international competitiveness. Border adjustments in this context refer to trade policies intended to compensate for disadvantages resulting from CO_2 emissions regulations. In this study, we will quantitatively verify the effects of border adjustments on restraining carbon leakage and decreases in the international competitiveness of the domestic industry in Japan. In addition, we will examine the effects of border adjustments on welfare levels in the event of the introduction of carbon-pricing policies, such as a carbon tax or an emissions-trading scheme in Japan.

Measures have been proposed in recent years to counter carbon leakage and decreases in international competitiveness resulting from the adoption of emissions-trading schemes, such as the Waxman-Markey Bill, the Kerry-Boxer Bill, and the Cantwell-Collins Bill in the United States. Border adjustments have garnered particular attention. In particular, the Waxman-Markey Bill, which passed the U.S. House of Representatives in 2009, proposed refunding the majority of the costs of emissions caps if an energy-intensive trade-exposed (EITE) industry is determined to address the problem of carbon leakage. It also proposed granting the president the authority to implement border adjustments requiring the purchase of carbon credits for products imported from countries with no emissions restrictions. This plan truly resembles border adjustments that would assess a carbon tax as a tariff. A similar debate is underway in Europe as well, where a CO_2-emissions-trading scheme known as EU–ETS took effect beginning in 2005. With the shift from Phase I to the following phase, the percentage of carbon credits distributed free of charge decreased slightly (from 95% in Phase I to 90% in Phase II). In Phase III, beginning in 2012, the distribution of free credits will decrease further and the system will shift to an auctioning scheme. In doing so, in consideration of the impact on the European industry, the European Commission has already opted to establish cost-mitigating measures (European Commission, 2010). In this debate, President Sarkozy of France argued for the need to enable appropriate border adjustments against countries whose efforts are inadequate, and the leaders of individual European nations are greatly interested in border adjustments as well.[1]

In Japan, during the debate on the introduction of carbon-pricing policies,[2] the issues of carbon leakage and decreasing international competitiveness, resulting from

[1]Multilateral Trade System Department, Trade Policy Bureau, Ministry of Economy, Trade and Industry of Japan. *2010 Report on Compliance by Major Trading Partners with Trade Agreements — WTO, FTA/EPAs, BITs.* http://www.meti.go.jp/report/downloadfiles/g100402a03j.pdf.

[2]Since April 2010, the Global Environment Subcommittee of the Central Environmental Council is deliberating on the design of an emissions-trading scheme in Japan. Furthermore, in the Ministry of Finance's Study Group on the Environment and Tariff Policies, which met from March through June 2010, discussions proceeded with a focus on solutions to the problem of carbon leakage and decreased international competitiveness of the domestic industry accompanying the adoption of an emissions-trading scheme.

an increase in production costs faced by the domestic industry, have emerged as the greatest topics of concern. While border adjustments have enjoyed considerable attention as countermeasures against these issues in policy debate, the impact of enacting border adjustments in the event of the adoption of carbon-pricing policies in Japan has not been quantitatively verified. Furthermore, the term "border adjustment" encompasses a variety of types of adjustments. The first of these is an import tariff applied based on the volume of carbon emitted in the production of imported goods to ensure fairness in domestic markets. This import tariff can be based on the emissions coefficient in either the importing country (Japan) or the exporting (foreign) country. The next type of border adjustment is a measure providing rebates of the cost of carbon prices for goods exported from Japan (export subsidies) to maintain fairness in overseas markets. In this case, it is conceivable that border adjustments could be enacted in such a way as to utilize both import tariffs and export subsidies simultaneously. Furthermore, some measures could apply these import tariffs and export subsidies to the industry as a whole, while others could be implemented by limiting their application to certain industries. Analysis of the efficacy of border adjustments, which in this way cover a diverse range of measures for restricting carbon leakage and decreases in international competitiveness, can provide valuable information for the formulation of carbon-pricing policies in Japan.

Recent studies on the subject of border adjustments are summarized as follows. Fischer and Fox (2009) and Böhringer *et al.* (2010) compared various measures (border adjustments and gratis allocation of emissions permits) to tackle the leakage and competitiveness issues. However, they only investigated policies in the US, Canada and EU. Alexeeva *et al.* (2008) conducted a comparative analysis of the two countermeasures against leakage and decreases in the competitiveness of border adjustments and integrated emissions trading, employing theoretical and demonstrative methods (CGE analysis). Although their study introduced a new point of comparison with the policy of integrated emissions trading, it addressed only simple border adjustment rules. Furthermore, the subject of its simulation analysis was the European EU-ETS emissions restrictions. Using a CGE model, Winchester (2011) analyzed border adjustments with alternative firm behaviors. Kuik and Hofkes (2009) again used CGE analysis to analyze the effects of border adjustments. Although they analyze the effects of each sector in detail, like Alexeeva *et al.* (2008), the analysis concerns only EU emissions restrictions. Mattoo *et al.* (2009) used CGE analysis to analyze emissions restrictions accompanying border adjustments in developed countries. Although their study also considered Japan's border adjustments, rather than just those of Europe and North America, and analyzed a diverse range of border adjustment policies, the main subjects of the analysis were North America, Europe, and developing countries. Thus, as outlined above, the subjects of the existing studies have, for the most part, been Europe and North America, with no study having conducted a detailed analysis of Japan. Therefore, the contribution of this paper is to compare a diverse range of measures to prevent leakage and maintain competitiveness by analyzing the detailed impacts of Japan's border adjustment policies on Japan.

In this study, we employ simulation analysis using a multi-region, multi-sector computable general equilibrium (CGE) model. The model is a 14-region, 26-sector static CGE model, developed by improving on the GTAP-EG model, using the GTAP 7 database as benchmark data with 2004 as the base year. Assuming that Japan adopts a policy of reducing emissions by 25% from 1990 levels in the form of a cap-and-trade emissions-trading scheme, we analyze the impact of the adoption of border in such a case. Specifically, we address the following six policy scenarios: (1) no border adjustment, (2) border adjustments on imports based on emissions coefficients in the exporting (foreign) country, (3) border adjustments on imports based on emissions coefficients in Japan (the importing country), (4) border adjustments on both imports and exports, (5) border adjustments on imports in EITE industries only, and (6) border adjustments on exports and imports in EITE industries only. We compare these scenarios from the standpoints of welfare effects, carbon leakage, and international competitiveness in EITE industries.

The major results of our analysis are as follows. Our analysis shows that no single border adjustment policy is superior to the other policies in terms of simultaneously solving all three issues: Retaining welfare levels, mitigating carbon leakage, and suppressing the loss of competitiveness in the EITE sectors. This finding means that the type of border adjustment to be adopted depends on the issue of highest priority. In addition, we show that export border adjustment often plays a crucial role in Japan. This insight is interesting because the policy debate on border adjustment is often biased toward import border adjustment. Our analysis also reveals that border adjustment in Japan significantly affects carbon leakage to China and the competitiveness of the iron and steel sector. This finding indicates that we must give special consideration to China and the iron steel sector in designing a border adjustment policy in Japan. Finally, border adjustments with and without consideration of indirect emissions have similar impacts, indicating that information on direct emissions is sufficient to implement border adjustment in Japan.

The rest of the paper is organized as follows. Section 2 describes the CGE model and data used in our analysis, while Sec. 3 defines the emissions-trading scheme and border adjustments analyzed. In Sec. 4, we discuss the results of the analysis from the perspective of welfare levels, carbon leakage and international competitiveness under an emissions-trading scheme. Next, in Sec. 5, we conduct a sensitivity analysis, and we compare the advantages and disadvantages among different border adjustment policies in Sec. 6. Finally, we present our conclusions in Sec. 7.

2. Model and Data

2.1. *Model*

We construct a static CGE model with 14 regions and 26 sectors, as listed in Table 1. The structure of the model is similar to GTAP-EG (Rutherford and Paltsev, 2000; Paltsev, 2001; Fischer and Fox, 2007; Takeda *et al.*, 2011). The details of the model structure are provided in the Appendix. We assume perfect competition in all markets

Table 1. Regions and sectors.

Symbol	Regions	Symbol		Sectors
USA	United States	FSH	Fishery	Energy-intensive Trade Exposed Sectors (EITE)
CAN	Canada	OMN	Other mining	
JPN	Japan	PPP	Paper-pulp-print	
OOE	Other OECD	CRP	Chemical industry	
EUR	EU27	NMM	Non-metallic minerals	
FSU	Former Soviet Union	NFM	Non-ferrous metals	
OEU	Other European regions	I_S	Iron and steel industry	
CHN	China	ELY	Electricity	
KOR	Korea	P_C	Petroleum and coal products	
IND	India	COA	Coal	Fossil Fuel Sectors (FENE)
BRA	Brazil	OIL	Crude oil	
ASI	Other Asia	GAS	Gas	
MPC	Mexico + OPEC	OTP	Other transport	Transport Sectors (TRANS)
ROW	Rest of world	WTP	Water transport	
		ATP	Air transport	
		AGR	Agriculture	Non-energy Intensive Sectors (NEIT)
		FPR	Food products	
		TWL	Textiles-wearing apparel-leather	
		LUM	Wood and wood-products	
		TRN	Transport equipment	
		OME	Other machinery	
		OMF	Other manufacturing	
		CNS	Construction	Services Sectors (SVCES)
		TRD	Trade	
		CMN	Communication	
		SER	Commercial and public services	

Table 2. Regions and sectors.

Scenario	Sectors	BA for imports	BA for export
NBA	None	None	None
BIF	All sectors	Based on foreign emissions coefficient	None
BID	All sectors	Japanese emissions coefficient	None
BED	All sectors	Japanese emissions coefficient	Japanese emissions coefficient
BIDR	EITE	Japanese emissions coefficient	None
BEDR	EITE	Japanese emissions coefficient	Japanese emissions coefficient

and that production is subject to constant returns to scale technology (CES production functions). The production sectors are divided into two types: Fossil fuel and non-fossil fuel sectors, and we assume that these sectors have different production structures.

Fossil fuel production activities include the extraction of coal (COA), crude oil (OIL), and gas (GAS) and are structured as shown in Fig. 1. Fossil fuel production is treated essentially the same as in the GTAP-EG model. Fossil fuel output is produced as a constant elasticity of substitution (CES) aggregate of natural resources and non-natural resources input composite. The non-natural resources input is a Leontief composite of capital, labor and other intermediate inputs.

Non-fossil fuel production (including electricity) has the structure shown in Fig. 2. Non-fossil fuel production is also basically the same as in the GTAP-EG model. Output is produced by the Leontief aggregation of non-energy goods and an energy-primary factor composite. The energy-primary factor composite is a nested CES function of energy goods and primary factors. With respect to the petroleum and coal products sector, we assume that crude oil enters into the production function at the top-level Leontief nest because most crude oil is used as feedstock. Similarly, we divide the energy use of the chemical products sector into feedstock requirements, which are treated as non-energy intermediate inputs, and the remainder using the feedstock ratio data of Lee (2008).

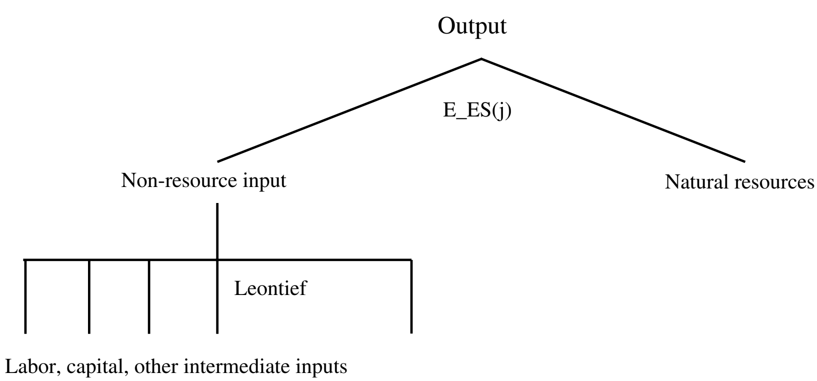

Figure 1. Production function of fossil fuel sectors.

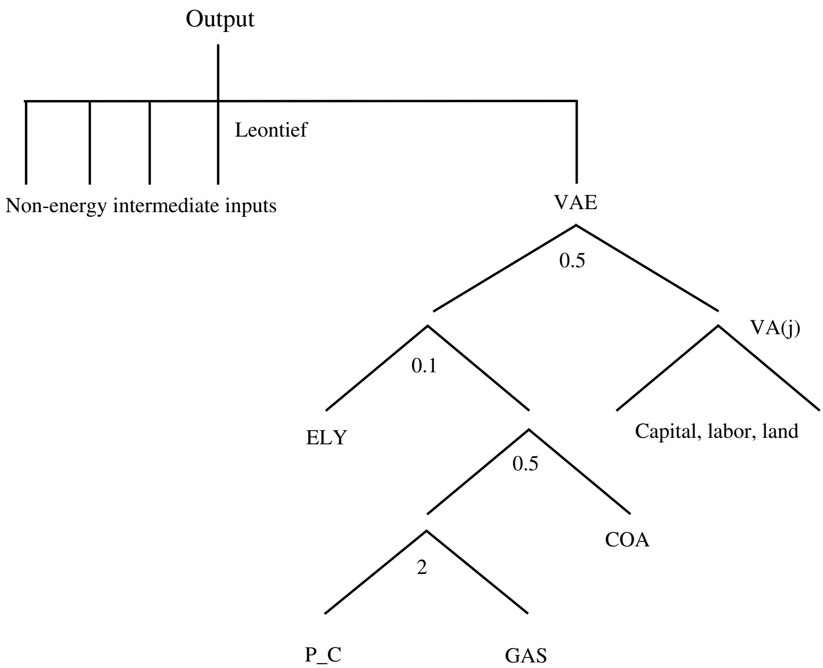

Figure 2. Production function of nonfossil fuel sectors.

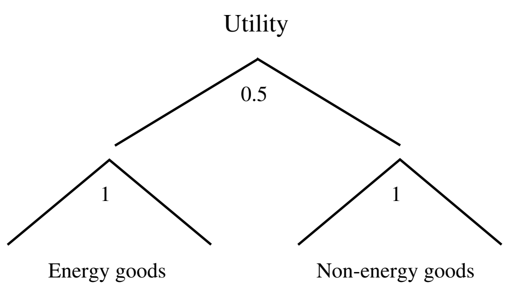

Figure 3. Utility function.

The demand side of each economy is represented by the representative household. The representative household's utility has the structure depicted in Fig. 3. The representative agent aims to maximize utility subject to the budget constraint. The household's income consists of the factor income minus tax payments. We assume that the endowments of primary factors are exogenously constant. To model international trade, we use the Armington assumption (Armington, 1969) as in many multi-region CGE models,[3] that is, we assume that goods produced in different regions are imperfect substitutes. Goods from different regions are aggregated through two stage CES function: First, imports from different regions are aggregated into a composite

[3]The Armington assumption is used, for example, in the standard GTAP model (Hertel, 1997), MIT EPPA model (Paltsev *et al.*, 2005), OECD ENV-Linkages model (Château and Burniaux, 2008).

import and then a composite import and a domestic goods are aggregated. Note that as Brown (1987) pointed out, the Armington assumption tends to strengthen terms-of-trade effects. We assume that there is no international movement of primary factors and that government expenditure and investment are held constant at the benchmark values.

2.2. *Benchmark data and parameters*

For the benchmark data, we employ the GTAP 7 database with 2004 as the base year. For CO_2 emissions data, we use the data provided by Lee (2008); however, her values for the CO_2 emissions of the Japanese iron and steel sector (I_S) are lower than the actual value. Because I_S is of great importance in the analysis of emissions regulation, we correct the data according to the data provided by 3EID (Nansai and Moriguchi, 2010). For elasticity parameters in production functions, we use the values of Fischer and Fox (2007) and GTAP data, and for Armington elasticity parameters, we use GTAP values. The elasticity of substitution between resource and non-resource inputs in the fossil fuel sectors (e_es(j) in Fig. 1) is calibrated from the benchmark supply elasticity of fossil fuels, which is assumed to be two for all fossil fuels.

The following data are necessary for developing an understanding of the characteristics of the Japanese economy. Figure 4 depicts the carbon intensity (tons of CO_2 per US$1,000 output) of each sector in Japan. As expected, iron-steel (I_S), non-metallic minerals (NMM), non-ferrous metals (NFM), chemical products (CRP), paper-pulp products (PPP), and transport sectors (OTP, ATP, WTP) have high carbon

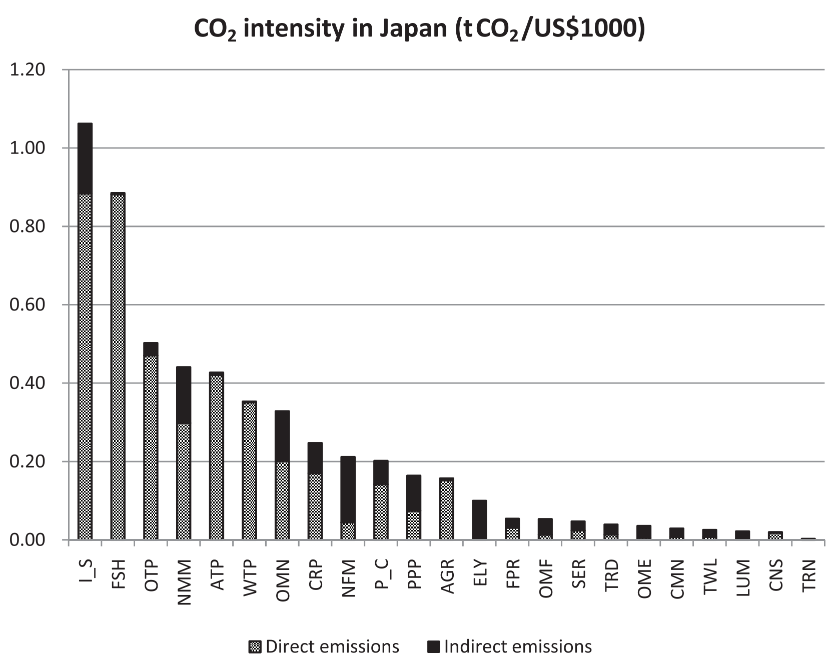

Figure 4. Carbon intensity by sectors in Japan (tCO_2/US$1000).
Source: GTAP7 data.

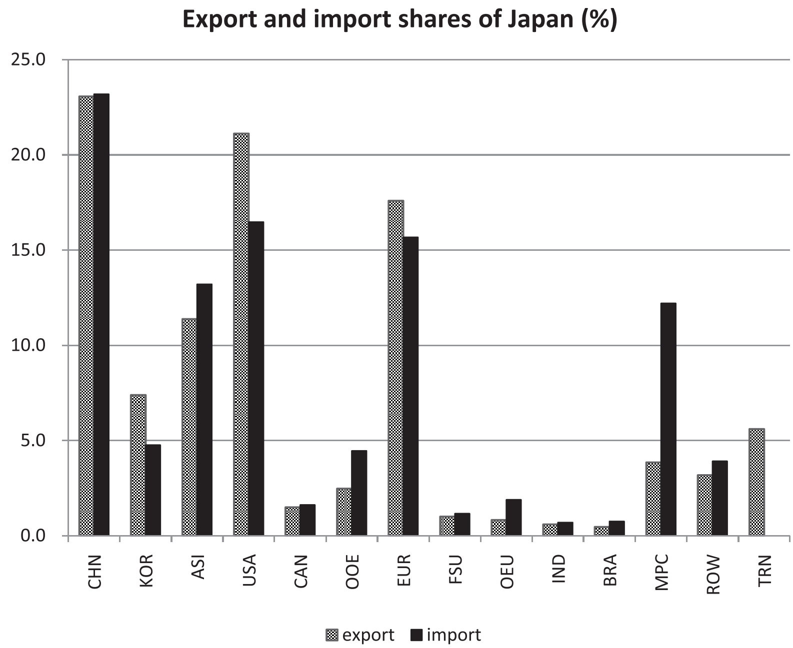

Figure 5. Export and import shares of Japan (%). TRN is the global transport sector. Calculated from GTAP7 data.

intensity. In addition, the fishery (FSH) sector is also prominent in Japan. These sectors are likely to be significantly affected by carbon regulations. According to carbon intensity, we categorize I_S, FSH, NMM, OMN, CRP, NFM and PPP as EITE sectors. Figure 5 reports the export and import shares of Japan by destination and source, showing that China (CHN), Korea (KOR), and other Asian regions (ASI), which are not obliged to reduce CO_2 emissions, are Japan's primary trade partners. This finding suggests that emissions regulation in Japan is likely to damage the competitiveness of EITE sectors in Japan compared to those in China, Korea, and other Asian countries. Finally, Fig. 6 reports carbon intensity (tons of CO_2 per US $1,000 output) of EITE sectors in Japan's major trading partners. This shows that carbon intensity in China and other Asian regions is generally much higher than in Japan while carbon intensity in EU27 is sometimes lower than in Japan. This difference in carbon intensity is reflected in the difference in carbon tariff rates when we consider carbon tariffs based on carbon coefficient in exporting side (scenario BIF in the next section).

3. Permit Trading System and Border Adjustment

3.1. *Permit trading system*

We assume that the Japanese government will introduce a cap-and-trade permit trading system. Moreover, we assume that permits are allocated to sectors through an auction.

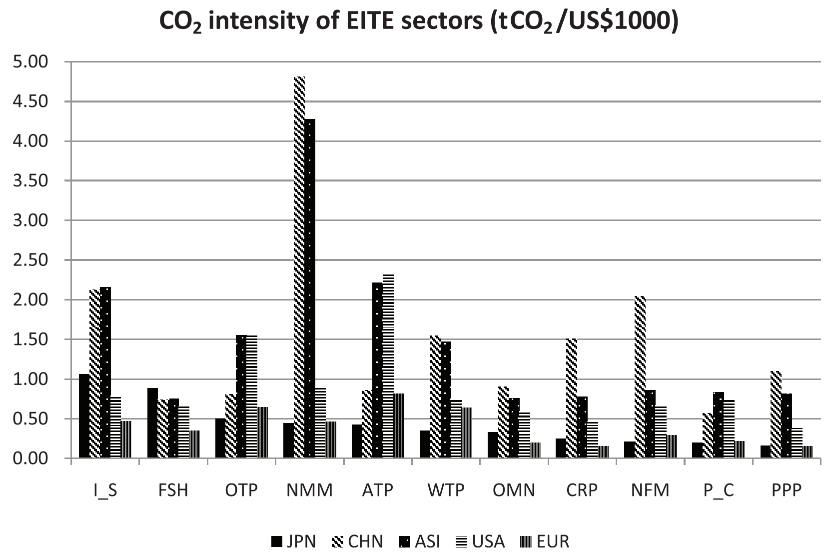

Figure 6. Carbon intensity of EITE sectors (tCO_2/US$1000).

The targeted CO_2 reduction is set at a 30% reduction from the 2004 levels of CO_2 emissions, which is almost equivalent to a 25% reduction from the 1990 levels. It is well known that a cap-and-trade permit trading system with an auction scheme has the same economic impact as an emission tax. Thus, we can interpret this policy as a carbon tax as well. We also assume that the revenue from the auction is returned to the representative household in a lump-sum fashion.

Note that we assume that only Japan implements a cap-and-trade system and that no other regions regulate carbon emissions. This assumption is made because our main aim is to analyze the Japanese economy and because the assumption of unilateral policy by Japan will clarify the pure impacts of Japanese border adjustments.

3.2. *Border adjustment policies*

We consider six policy scenarios to mitigate carbon leakage and the loss of competitiveness. Table 2 summarizes the characteristics of these scenarios. NBA is the no border adjustment scenario, whereas BIF involves a carbon tariff on imports based on the carbon content in foreign production. BIF is the carbon content tariff in the true sense of the term. However, BIF may be difficult to implement because it requires a large volume of information on energy use in foreign countries. Thus, we consider another type of carbon tariff, BID, which involves assigning a carbon tariff to all imported products based on the carbon content in Japanese domestic production.

In BIED, border adjustment is applied to both imports and exports (BID + export border adjustment). In this scenario, the carbon tariff on imports is based on carbon content in domestic production, and the additional costs of domestic production incurred by this carbon pricing policy are rebated when the products are exported from

Table 3. Results of the simulation.

	NBA	BIF	BID	BIED	BIDR	BIDER
Permit price ($/t$CO_2$)	93.8	94.0	94.3	97.7	94.4	97.5
Welfare	−0.83	−0.71	−0.79	−0.83	−0.81	−0.84
Real GDP	−0.58	−0.59	−0.58	−0.59	−0.58	−0.59
Export	−3.39	−7.37	−4.45	−3.67	−3.93	−3.48
Import	−3.14	−7.18	−4.17	−3.36	−3.68	−3.19
Export price	0.50	0.73	0.56	0.01	0.55	0.23
Import price	−0.40	−1.05	−0.55	−0.96	−0.45	−0.70
Terms of trade	0.90	1.80	1.12	0.98	1.01	0.94
Leakage rate (%)	24.5	16.8	23.4	20.9	23.8	21.3
Import of EITE	3.09	−9.52	−0.88	0.59	−0.97	0.21
Export of EITE	−15.28	−21.12	−16.74	−8.26	−16.20	−6.86
Output of EITE	−4.43	−4.19	−4.30	−3.09	−4.15	−2.74

Note: Except for permit price and carbon leakage rate, all values in this table shows the % changes from BAU.

Japan. Comparison between BID and BIDR will show the additional impacts generated by export border adjustment. Scenario BIDR limits the sectors to which the BID is applied to the EITE sector. In BIEDR, the sectors to which the BIED is applied are also limited to the EITE sector.

The carbon tariff and export rebate are determined according to the carbon content based on direct and indirect emissions. The direct emissions of CO_2 are defined as the amount of CO_2 emitted from fossil fuel use. On the other hand, the indirect emissions are the amount of CO_2 embodied in the purchased electricity (CO_2 emitted at power plants where electricity is generated by burning fossil fuels). The indirect emissions sometimes are defined to include CO_2 embodied in other intermediate inputs. However, we do not consider emissions embodied in intermediate inputs other than electricity because it is difficult (perhaps impossible) to calculate them in our CGE model, which assumes substitution among inputs, thereby variable emissions coefficients.

Denote q_{ir}^{CO2T} to be the total amount of CO_2 emitted from a given ith sector in a given region r. q_{ir}^{CO2T} is defined as the sum of the direct and indirect emissions:

$$q_{ir}^{CO2T} = q_{ir}^{CO2D} + q_{ir}^{CO2ID}$$

where q_{ir}^{CO2D} and q_{ir}^{CO2ID} are the direct and indirect CO_2 emissions at the ith sector in region r, respectively. From the definition, the direct emissions of CO_2 are given as:

$$q_{ir}^{CO2D} = \sum_{e} \phi_{eir} q_{eir}$$

where ϕ_{eir} is the emissions coefficient of fossil fuel e in sector i of region r and q_{eir} is the amount of fossil fuel used in sector i of region r. On the other hand, the indirect emissions are calculated as follows. First, define θ_{ir}^{ELY} as the share of electricity used in sector i (d_{ir}^{ELY}) over the total quantity of electricity supplied in region r ($q_{ELY,r}$):

$$\theta_{ir}^{ELY} = d_{ir}^{ELY}/q_{ELY,r}$$

Letting $q_{ELY,r}^{CO2D}$ be the direct emission of CO_2 from the electricity sector, we can calculate the indirect emission of CO_2 from sector i by multiplying $q_{ELY,r}^{CO2D}$ by θ_{ir}^{ELY}:

$$q_{ir}^{CO2ID} = \theta_{ir}^{ELY} q_{ELY,r}^{CO2D}$$

Then the carbon content of a unit of product of sector (ξ_{ir}), which is the quantity of CO_2 emissions contained in a unit of production, is given as:

$$\xi_{ir} = q_{ir}^{CO2T}/q_{ir}$$

In the carbon tariff based on the domestic emissions coefficient, the tariff rate assigned to a unit of imported product of sector i of region r is defined by:

$$\tau_{ir} = p_r^{CO2}\xi_{ir}$$

where p_r^{CO2} is the price of a permit in the region r. On the other hand, in the carbon tariff based on the foreign emissions coefficient, the tariff rate assigned to a unit of imported product of sector i from region s to r is defined by:

$$\tau_{isr} = p_r^{CO2}\xi_{is}$$

In export rebates, a subsidy of τ_{ir} is applied to export goods i from region r. Note that emissions coefficient ξ_{is} changes according to substitution between inputs.

In the sensitivity analysis, we consider the case in which the emissions coefficient is based only on the direct emissions. In this case, ξ_{ir} is calculated as follows:

$$\xi_{ir} = q_{ir}^{CO2D}/q_{ir}$$

4. Results

We first compare the effects of six separate policies on welfare, carbon leakage and the competitiveness of the Japanese EITE. We measure carbon leakage using the conventional metric of the carbon leakage rate, which is defined as the fraction of the increase in foreign emissions over the decrease in domestic emissions induced by the carbon pricing policy. We also measure the change in competitiveness of the Japanese EITE sectors by the percent change in their production. Welfare is defined as the utility levels of the representative household in Japan. The results are summarized in Table 3.

4.1. *Effects on welfare*

Let us first examine the effects on welfare. Border adjustments with only carbon tariffs, such as BIF, BID, and BIDR, yield better welfare levels than NBA. This finding is mainly due to the improvement in terms of trade. BIF, BID, and BIDR are policies in which import tariffs are increased by the imposition of a carbon tariff. Such increases in import tariffs decrease the world price of imports and increase the world price of exports, thereby improving the terms of trade in Japan and thus the welfare of the Japanese economy. Table 3 shows the percent changes in export price, import price and the terms of trade in Japan for each scenario.[4] In the NBA scenario, the terms of trade are increased 0.9% from BAU. However, the terms of trade increase more significantly in the scenario of a border adjustment that only imposes a carbon tariff. In particular, in BIF, the terms of trade increase by 1.8% from BAU.

On the other hand, results for BIDE and BIDER show that the combined policies of import and export border adjustments have similar welfare impacts to NBA. Welfare in BIDE and BIDER is inferior to that in BID and BIDR because of the higher permit price and the smaller improvement of the terms of trade. Export border adjustment restores the competitiveness of Japanese firms and stimulates the production of EITE sectors. This approach requires a higher emissions permit price (marginal abatement cost) to satisfy the emission limit and lowers the welfare level. In addition, export border adjustments have an effect similar to that of export subsidies and lower the world price of exported goods, deteriorating Japan's terms of trade and lowering the welfare level.

Border adjustment policies were originally designed to sustain the competitiveness of domestic industries and suppress carbon leakage; they were not designed to improve welfare levels. However, as the above results show, border adjustment policies that impose only a carbon tariff on imports can improve the welfare impacts of carbon regulation.

4.2. *Carbon leakage*

Next, we compare leakage rates among the policy scenarios. The fifth line in Table 3 shows the leakage rates (%). As expected, the highest leakage rate (24.45%) is observed when no border adjustment policy is conducted (i.e., NBA). The policy scenario in which a carbon tariff based on a foreign emission coefficient is adopted (i.e., BIF) is the most effective policy for suppressing the carbon leakage. In BIF, the leakage rate decreases to 16.78% from 24.45% in NBA. The emission coefficient in foreign countries is generally higher than that in Japan, and thus a carbon tariff based on a foreign coefficient has higher rates, strengthening the effect of the carbon tariff based on a foreign emissions coefficient. In addition, carbon tariffs in BIF are differentiated across regions and thus work more effectively in restraining carbon leakage.

BID and BIDR show that border adjustments on imports based on domestic emissions coefficients also reduce carbon leakage, but the decrease in the leakage rate is very small. On the other hand, with BIDE and BIDER, in which an export border adjustment is added to BID and BIDR, the leakage rate reduces by 3 points compared

[4]Export (import) price is the weighted average of prices of export (import) goods and the terms of trade is defined as the ratio of export price and import price.

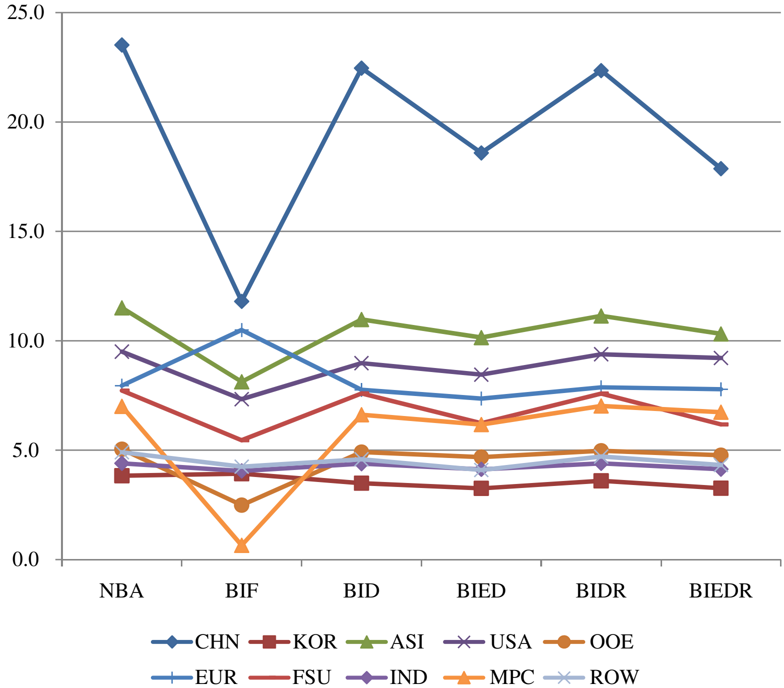

Figure 7. Carbon leakage to other regions ($MtCO_2$).

to NBA. This finding indicates that export border adjustment plays a more important role in restraining carbon leakage. Finally, a comparison of BID and BIDR shows that limiting border adjustment sectors to EITE increases carbon leakage, although only slightly. This finding means that limiting border adjustment sectors to EITE is undesirable for restraining carbon leakage. A similar argument is applied to BIDE and BIDER. Because carbon leakage occurs through both an energy channel and a trade channel, the leakage cannot be thoroughly suppressed by border adjustment policies.[5] However, our analysis shows that border adjustment has an effect in restraining carbon leakage.

Figure 7 shows the changes in the CO_2 emission in foreign countries induced by the introduction of carbon pricing policy and BAs.[6] First, by observing NBA, we find that the introduction of a carbon pricing policy in Japan increases CO_2 emissions in all the regions. However, the emission changes among countries differ substantially. In IND, KOR, OOE, and ROW, the increase of CO_2 emissions is very small; the highest increase among these countries is 5 $MtCO_2$. Furthermore, the introduction of BAs in Japan increases emissions in these countries by no more than 1 $MtCO_2$, which is a

[5]Carbon leakage through the energy channel occurs through the energy market. The demand for energy decreases in the country in which a carbon pricing policy is introduced. This decreased demand in turn decreases the price of energy in the international energy market, thereby increasing the demand for energy increases in foreign countries in which the carbon pricing policy is not introduced. This leakage occurs regardless of sector competitiveness.

[6]We omit BRA, OEU, and CAN from Fig. 7 because the changes in CO_2 emissions in these countries are almost zero.

limited impact. Conversely, in countries such as CHN, ASI, USA, EUR, and MPC, CO_2 emissions increase significantly with the introduction of a Japanese carbon pricing policy. These countries also show significant variations in the impact of border adjustments. CHN experiences the largest increases in CO_2 among these countries (23.5 $MtCO_2$), which is twice as large as the second highest emission increase, which occurs in ASI.

It is also worth mentioning that when different border adjustments are adopted, CO_2 emissions fluctuate substantially more dramatically in China than in any other region. This finding implies that border adjustments in Japan affect China much more significantly than any other region. Because China accounts for the largest carbon leakage in the world induced by the Japanese carbon pricing policy, the impact of border adjustments on worldwide carbon leakage depends on their impact on CO_2 emissions in China. This result implies that China is a key country to consider when introducing carbon pricing policy and its corresponding border adjustments.

4.3. *Competitiveness of EITE sectors*

Finally, we examine the impact of border adjustments on Japanese EITE sector competitiveness. The sixth to eighth lines in Table 3 report percentage changes in the import, export and output of EITE sectors. The table shows that NBA increases the amount of imports of EITE goods by 3.09% from BAU. This change is due to an increase in the costs of domestic production and therefore the price of the domestic products of the EITE sectors, which reduces their competitiveness in the domestic market. The introduction of border adjustments eases this increase in imports; the increase in imports is decreased from 3.09% in NBA to 0.59% and 0.21% in BIED and BIEDR, respectively.

On the other hand, in BIF, BID, and BIDR, the amount of imports decreases from the BAU level. An extreme case of this behavior is exhibited by BIF, in which the imports decrease by 9.52% from the BAU case. This finding suggests that imported products are less competitive in the Japanese domestic market when the border adjustments are applied than in the BAU case, which can be considered overprotection of Japanese domestic products in the domestic market.

The introduction of the carbon pricing policy also decreases the competitiveness of Japanese domestic products exported to foreign regions. The impact of the carbon pricing policy on exports is much greater than that on imports. For example, in NBA, exports from the EITE sector decrease by 15.28% from the BAU case. We now must determine the extent to which border adjustment policies can improve this number. If carbon tariffs were only imposed on imported products (BIF, BID, and BIDR), then the exports from the EITE sector would be smaller than in NBA. Thus, the competitiveness of exported goods deteriorates as a result of border adjustment only for imported goods.

On the other hand, if rebates are given to exported Japanese products (BIED and BIEDR), the decrease in exports eases significantly, from a 15.28% decrease in NBA to a 8.26% and 6.86% decrease in BEIDE and BIEDR, respectively. Therefore, to mitigate the negative impact of carbon pricing policy on exports, rebates on exports must be included in border adjustment policies because a border adjustment policy with only carbon tariffs will not improve the negative effects.

With NBA, output decreases due to the increase in imports and decrease in exports. As we mentioned earlier, a border adjustment policy with only carbon tariffs (BIF, BID, BIDR) causes exports to decrease even more. Thus, such border adjustment policies improve the output level from the NBA case only slightly. On the other hand, the combined border adjustments (BIED and BIEDR), which significantly alleviate the decrease in exports, improve the output of EITE sectors. This finding suggests that to retain the output levels, it is important to include both carbon tariffs and export rebates in the border adjustment policy.

Regarding individual EITE sectors, we find that the results for most of the EITE sectors are the same as the aggregate results for all EITE sectors (Table 4). The I_S (iron and steel sector) is worth examining separately because it is most strongly

Table 4. Impacts of border adjustments on competiveness of Japanese EITE sectors (% change from BAU).

	Sector	NBA	BIF	BID	BIED	BIDR	BIDER
Import	FSH	6.00	2.16	0.89	1.20	0.75	0.96
	OMN	−6.09	−5.67	−6.20	−4.53	−6.06	−4.21
	PPP	0.34	−8.93	−1.76	−0.66	−1.94	−1.26
	CRP	2.35	−7.68	−1.19	0.40	−1.41	−0.14
	NMM	6.93	−30.32	0.87	1.91	0.69	1.33
	I_S	33.24	−1.27	13.36	15.95	13.84	15.39
	NFM	0.90	−17.08	−1.48	−0.46	−1.51	−0.74
	EITE	3.09	−9.52	−0.88	0.59	−0.97	0.21
Export	FSH	−16.08	−18.82	−17.77	−7.52	−17.57	−7.09
	OMN	−3.58	−4.70	−3.97	−2.22	−3.90	−1.98
	PPP	−2.40	−5.36	− 3.10	−0.07	−2.70	1.19
	CRP	−9.04	−15.17	−10.51	−4.19	−9.80	−2.59
	NMM	−12.80	−15.50	−13.53	−4.22	−13.23	−3.15
	I_S	−43.00	−45.78	−44.14	−26.51	−43.96	−25.64
	NFM	−8.55	−23.09	−11.70	−5.12	−11.30	−3.74
	EITE	−15.28	−21.12	−16.74	−8.26	−16.20	−6.86
Output	FSH	−4.04	−3.60	−3.60	−3.65	−3.60	−3.62
	OMN	−2.16	−1.01	−1.88	−1.57	−1.84	−1.47
	PPP	−0.94	−0.64	−0.88	−0.85	−0.86	−0.79
	CRP	−3.70	−4.09	−3.65	−2.40	−3.41	−1.84
	NMM	−2.43	−0.73	−2.22	−1.48	−2.16	−1.31
	I_S	−11.12	−10.95	−10.70	−7.77	−10.58	−7.47
	NFM	−3.44	−1.05	−3.58	−3.05	−3.37	−2.59
	EITE	−4.43	−4.19	−4.30	−3.09	−4.15	−2.74

affected by the carbon pricing and border adjustment policies. In the NBA case, the amount of imports increases by 33%, the amount of exports decreases by 43%, and the output decreases by 15%. Because the effects of the introduction of the carbon pricing policy are very large, the effects of the border adjustment policies are significant as well. In BIED, the increase in imports is reduced by half, and the decreases in exports and outputs are reduced to half and two-thirds of the previous values, respectively. These results suggest that border adjustment policy is crucial in determining the impacts on individual sectors.

5. Sensitivity Analysis

In this section, we conduct sensitivity analyses by changing assumptions in the benchmark analysis. First, we change the assumed emissions coefficients used to calculate the carbon tariff and export rebate. In the analysis of the previous sections, we include not only direct emissions (emissions from fossil fuel use) but also indirect emissions (emissions embodied in electricity) when calculating the emissions coefficients for individual sectors. This approach was chosen because the cap-and-trade system increases the cost of industries directly by the increase in fossil fuels price and also indirectly by the increase in the price of electricity. Thus, we must consider indirect emissions to level the playing field. However, the calculation of indirect emissions from each sector often involves technical and administrative difficulties. Therefore, we consider the case in which the emissions coefficient is calculated based on only the direct emissions. In this case, the levels of the carbon tariff and export rebate are generally lowered because the emissions coefficients become smaller. This case is denoted by S_DEMI.

Second, we change the values of Armington elasticity (elasticity of substitution between domestic and imported goods and elasticity of substitution between imports from different regions). Section 4 shows that terms-of-trade effects play an important role in determining welfare effects. Since the size of terms-of-trade effects depend on the values of Armington elasticity, we try to change them. We halve and double the values of the Armington elasticity parameters (represented by S_SARM and S_LARM respectively).

Table 5 reports the result of sensitivity analysis. First, let us examine Scenario S_DEMI. Compared to the benchmark case (Table 3), welfare loss from emissions regulation becomes slightly larger. This change is mainly due to the decrease in the improvement of the terms of trade. The leakage rate is slightly larger than in the benchmark case. This result is expected because the levels of the carbon tariff and export rebate decrease. Finally, the increase in the import and the decrease in the export and output of the EITE sectors generally become larger. These results show that the exclusion of indirect emissions is generally undesirable in terms of welfare, carbon leakage, and competitiveness. However, the size of the impacts is almost the same as the benchmark case with a few exceptions. It follows that we do not need to pay much attention to the indirect emissions in implementing border tax adjustment in Japan.

Table 5. Results of sensitivity analysis.

		NBA	BIF	BID	BIED	BIDR	BIDER
S_DEMI	Permit price (US$/t$CO_2$)	93.8	93.8	94.2	97.0	94.3	96.8
	Welfare	−0.83	−0.76	−0.80	−0.84	−0.82	−0.84
	Real GDP	−0.58	−0.58	−0.58	−0.59	−0.58	−0.59
	Export	−3.39	−5.56	−4.13	−3.65	−3.79	−3.47
	Import	−3.14	−5.28	−3.85	−3.36	−3.53	−3.19
	Export price	0.50	0.64	0.54	0.19	0.53	0.30
	Import price	−0.40	−0.76	−0.51	−0.77	−0.44	−0.62
	Terms of trade	0.90	1.42	1.06	0.96	0.98	0.93
	Leakage rate (%)	24.5	18.6	23.6	21.5	23.9	22.1
	Import of EITE	3.09	−3.70	0.18	1.12	0.13	0.95
	Export of EITE	−15.28	−18.85	−16.33	−9.90	15.93	−9.12
	Output of EITE	−4.43	−4.44	−4.34	−3.41	−4.22	−3.18
S_SARM	Permit price (US$/t$CO_2$)	98.5	98.0	98.6	100.8	98.8	100.8
	Welfare	−0.62	−0.41	−0.56	−0.63	−0.60	−0.64
	Real GDP	−0.58	−0.59	−0.58	−0.59	−0.58	−0.59
	Export	−3.99	−6.72	−4.67	−4.12	−4.32	3.98
	Import	−2.79	−4.98	−3.31	−2.90	−3.05	−2.80
	Export price	0.60	0.87	0.66	0.02	0.65	0.25
	Import price	−1.23	−2.09	−1.43	−1.81	−1.30	−1.53
	Terms of trade	1.85	3.02	2.12	1.87	1.98	1.82
	Leakage rate (%)	20.9	16.0	20.3	19.1	20.6	19.3
	Import of EITE	1.38	−5.83	−0.67	0.11	−0.74	−0.09
	Export of EITE	−10.25	−14.03	−11.13	−6.29	10.78	−5.55
	Output of EITE	−3.40	−3.47	−3.39	−2.66	−3.28	−2.47
S_LARM	Permit price (US$/t$CO_2$)	87.8	89.7	89.2	93.8	89.2	93.4
	Welfare	−0.91	−0.86	−0.87	−0.90	−0.89	−0.91
	Real GDP	−0.56	−0.57	−0.56	−0.58	−0.56	−0.57
	Export	−3.05	−9.39	−4.89	−3.65	−4.04	−3.35
	Import	−3.24	−10.35	−5.23	−3.78	−4.32	−3.48
	Export price	0.35	0.54	0.41	−0.03	0.40	0.18
	Import price	−0.08	−0.65	−0.22	−0.61	−0.14	−0.36
	Terms of trade	0.43	1.20	0.62	0.58	0.54	0.54
	Leakage rate (%)	30.2	18.5	28.2	23.9	28.8	24.8
	Import of EITE	7.06	−14.16	−0.77	1.82	−0.88	1.07
	Export of EITE	−23.64	−32.65	−26.20	−12.09	−25.30	−9.44
	Output of EITE	−6.34	−5.62	−5.95	−4.04	−5.71	−3.37

Note: Except for permit price and carbon leakage rate, all values in this table shows the % changes from BAU.

Next let us examine S_SARM and S_LARM. Results show that changes in Armington elasticity alter quantitative impacts significantly. In particular, the large values of Armington elasticity imply the large welfare deterioration, the large leakage rate and the large decrease in output of EITE. However, the qualitative results concerning the relative sizes of impacts among different border adjustment policies are generally the same as the benchmark case. It follows that the analysis of the previous sections has a certain level of robustness.

6. Comparison of Border Adjustment Policies

We have thus far examined various border adjustment policies. In this section, we summarize the results and compare border adjustments. The main results are summarized as follows. First, in terms of ensuring the welfare of the Japanese economy, border adjustment policies, such as BIF, BID and BIDR, which impose carbon tariffs on imported goods, are relatively effective. Second, in terms of suppressing carbon leakage, import border adjustment policy based on the carbon content in the foreign production (BIF) or border adjustments for both imports and exports (BIED and BIEDR) are effective. Our analysis also shows that import border adjustment based on the domestic carbon content (BID and BIDR) barely reduces the level of carbon leakage, which means that if we try to reduce carbon leakage, it is necessary to adopt border adjustment not only for imports but also for exports or to use import border adjustment based on the foreign carbon content.

Third, to mitigate the loss of competitiveness of the EITE sectors, border adjustment policies for both imports and exports (BIED and BIEDR) are the most effective, and border adjustment only on imports (BIF, BID and BIDR) only slightly mitigates the loss of competitiveness, which is another interesting insight. In the discussion of border adjustment policy, border adjustment on imports (carbon tariff) has attracted most of the attention. However, our analysis shows that, at least for Japan, border adjustment only on imports cannot resolve the competitiveness issue; the border adjustment on exports is rather important. This finding is mainly due to the large export of EITE sectors in Japan.

NBA is clearly inferior to policies with border adjustments because it generates a large welfare loss and leakage and suppresses the output of EITE sectors significantly. BID and BIDR are slightly superior to NBA, BIDE and BIDER in welfare impacts but can barely mitigate the carbon leakage and competitiveness problems. Considering that border adjustment policy is originally designed to suppress the carbon leakage and to mitigate the loss of competitiveness, we can conclude that BID and BIDR are not desirable policies.

On the other hand, BIF (import border adjustment based on the foreign carbon content) is superior to other policies in terms of both welfare and carbon leakage. However, this policy has several drawbacks. First, it imposes a heavy burden on EITE sectors by reducing their export and output significantly. Second, it reduces the quantity of imported goods from foreign EITE sectors to amounts that are much lower than the BAU levels, which may be considered overprotection of the Japanese EITE sectors. In addition, BIF implies differentiated tariff rates, which may be considered a discriminatory trade policy. Ever since border adjustment policies have been considered for mitigating carbon leakage and the loss of competitiveness, the compliance with WTO rules has been debated due to the possibility of the use of the adopted policy as a hidden trade barrier. Third, as already mentioned in Sec. 3.2, carbon tariffs based on the foreign carbon coefficient are difficult to implement because they require a lot of information on energy use in foreign countries. Although the Japanese government can obtain detailed information on Japan, it is difficult to acquire similar information from foreign countries. These drawbacks decrease the validity of BIF.

BIED and BIEDR are inferior to BIF, BID and BIDR in terms of welfare, but they are effective for both the carbon leakage and competitiveness issues. Thus, we can conclude that border adjustments on both imports and exports are desirable to tackle carbon leakage and competitiveness problems. Finally, the fact that BID and BIDR generally have similar impacts in terms of welfare, carbon leakage, and competitiveness indicates that limiting border adjustment sectors to EITE has a small impact. A similar argument is applied to BIDE and BIDER. In the debate of carbon regulation, the selection of regulated sectors often becomes the issue. However, our analysis shows that limiting border adjustment sectors to EITE is of little importance.

7. Concluding Remarks

In this paper, we have evaluated the impact of border adjustment policies on the Japanese economy when the carbon-pricing policy is levied only on Japan. We employed a multi-region and multi-sector static CGE model using GTAP 7 data, in which the world was divided into 14 regions, each containing 26 sectors. We assumed that the Japanese government targets a reduction in CO_2 emissions by 25% of the 1990 levels using either a carbon tax policy or a cap-and-trade permit trading system with an auction scheme. We considered a no border adjustment scenario (NBA) with five border adjustment policies and examined the impact of the border adjustment policies on the welfare of the Japanese economy, carbon leakage, and the competitiveness of the Japanese EITE sectors.

Our analysis shows that no single border adjustment policy is superior to the other policies in terms of simultaneously solving all three issues: Retaining welfare levels, mitigating carbon leakage, and suppressing the loss of competitiveness in the EITE sectors. This finding means that the type of border adjustment to be adopted depends on the issue of priority. In addition, we show that export border adjustment often plays a crucial role in Japan. This insight is interesting because the policy debate on border adjustment is often biased toward an import border adjustment. Our analysis also reveals that border adjustment in Japan significantly affects carbon leakage to China and the competitiveness of the iron and steel sector. This finding indicates that we need to give special consideration to China and the iron and steel sector when designing a border adjustment policy in Japan. Finally, we show that border adjustments with and without consideration of indirect emissions have similar impacts, which indicates that the information regarding direct emissions is sufficient to implement border adjustment in Japan. This insight is useful for policy makers because it makes border adjustment easier to introduce.

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Appendix

A.1. *Model Structure*

A.1.1. *Notes*

- All taxes except labor and lump sum taxes are omitted for notational simplicity.
- All functions are written in calibrated share form.
- All reference prices are omitted for notational simplicity.

A.1.2. *Notations*

Table A1. Energy goods.

Symbol	Description
OIL	Crude oil
GAS	Gas
COA	Coal
P_C	Petroleum and coal products
ELY	Electricity

Table A2. Sets.

Symbol	Description
i, j	Sectors and goods
r, s	Regions
EG	All energy goods: OIL, GAS, COA, P_C and ELY
FF	Primary fossil fuels: OIL, GAS, COA
EN	Emissions source: OIL, GAS, COA and P_C
LQ	Liquid fuels: GAS and P_C
MF	Mobile factors: Labor and capital
SF	Sluggish factors: Land and natural resources
FL	Factors except labor: Capital, land and natural resources
ET	Regions participating in international emissions trading
CGD	Index of investment goods
NRS	Index of natural resources

Table A3. Activity variables.

Symbol	Description
Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
T^{SF}_{fr}	Allocation of sluggish factors in region $r(f \in SF)$
A^{F}_{jir}	Armington aggregate for good j used for sector i in region r
A^{P}_{ir}	Armington aggregate for good j used for private consumption in region r
A^{G}_{ir}	Armington aggregate for good j used for government expenditure in region r
M_{ir}	Aggregate imports of good i in region r
U_r	Household utility in r
CC_r	Aggregate household non-energy consumption in region r
EC_r	Aggregate household energy consumption in region r
Y^{T}_{i}	Global transport services
G_r	Government expenditure in region r

Table A4. Price variables.

Symbol	Description
p^{Y}_{ir}	Output price of goods i produced in region r
p^{VA}_{ir}	Price index of VA for sector i in region $(i \notin FF)$
p^{E}_{ir}	Price of aggregate energy for sector i in region $r(i \notin FF)$
p^{EF}_{jir}	Price of energy intermediate goods j for sector i in region $r(j \in EN,\ i \notin FF)$
p^{M}_{ir}	Import price aggregate for good i imported to region r
p^{MM}_{irs}	CIF price of goods i imported from r to region s
p^{AF}_{ijr}	Price of Armington good i used for sector j in region r
p^{AP}_{ir}	Price of Armington good i used for private consumption in region r
p^{AG}_{ir}	Price of Armington good i used for government expenditure in region r
p^{EC}_{r}	Price of aggregate household energy consumption in region r
p^{CC}_{r}	Price of aggregate household non-energy consumption in region r
p^{U}_{r}	Price of household utility in region r
p^{EP}_{ir}	Price of energy consumption goods i in region r
p^{F}_{fr}	Price of primary factor f in region r
p^{SF}_{fir}	Price of sluggish factor f for sector i in region r
p^{LE}_{r}	Price of leisure in region r
p^{G}_{r}	Price index of government expenditure in region r
p^{T}_{i}	Price of global transport service i
p^{CO2}_{r}	Price of emissions permit for region r
p^{CO2W}	Price of emissions permit in international permit market

Table A5. Cost shares.

Symbol	Description
θ_{jir}	Share of intermediate good j for sector i in region $r(i \notin FF)$
θ_{ir}^{VAE}	Share of VAE aggregate for sector i in region $r(i \notin FF)$
θ_{ir}^{E}	Share of energy in the VAE aggregate for sector i in region $r(i \notin FF)$
θ_{fir}^{F}	Share of primary factor f in VA composite for sector i in region $r(i \notin FF)$
θ_{ir}^{R}	Share of natural resources for sector i in region $r(i \in FF)$
θ_{fir}^{FF}	Share of primary factor f for sector i and region $r(i \in FF)$
θ_{jir}^{NR}	Share of non-resource intermediate inputs j for sector i and region $r(i \in FF)$
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector i in region $r(i \notin FF)$
θ_{ir}^{ELY}	Share of electricity in overall energy demand by sector i in region r
θ_{jir}^{LQD}	Share of liquid fossil fuel j in liquid energy demand by sector i in region $r(i \notin FF)$, $(j \in LQD)$
θ_{fir}^{SF}	Share of sector i in supply of sluggish factor f in region r
θ_{ijr}^{AF}	Share of domestic variety in Armington good i used for sector j of region r
θ_{ir}^{AP}	Share of domestic variety in Armington good i for private consumption in region r
θ_{ir}^{AG}	Share of domestic variety in Armington good i for government expenditure in region r
θ_{isr}^{M}	Share of imports of good i from region s to region r
θ_{r}^{C}	Share of composite energy input in household consumption in region r
θ_{ir}^{CC}	Share of non-energy good i in non-energy household consumption demand in region r
θ_{ir}^{EC}	Share of energy good i in energy household consumption demand in region r
θ_{ir}^{T}	Share of supply from region r in global transport sector i
θ_{ir}^{G}	Share of Armington good i in government expenditure in region r
θ_{ir}^{EC}	Share of energy good i in energy household consumption demand in region r

Table A6. Income and policy variables.

Symbol	Description
H_r	Household income in region r
H_r^G	Government income in region r
t_r^L	Labor tax rate in region r
T_r^L	Lump-sum tax in region r
V_r^R	Value of permit revenue in region r
T_r^L	Lump-sum tax in region r
$\bar{G}_r$	Exogenous level of government expenditure in region r
$\bar{Y}_{CGD,r}$	Exogenous level of investment in region r

Table A7. Endowments and emissions coefficients.

Symbol	Description
$\overline{E}_{fr}$	Aggregate endowment of primary factor f for region r
$\overline{B}_r$	Balance of payment deficit or surplus in region $r(\sum_r \overline{B}_r = 0)$
$\overline{CO2}_r$	Carbon emission limit for region r
a_{ijr}^{CO2F}	Carbon emissions coefficient for fossil fuel i used for sector j in region $r(i \in FF)$
a_{ir}^{CO2P}	Carbon emissions coefficient for fossil fuel i used for private consumption in region $r(i \in FF)$
τ_{jirs}	Amount of global transport service j required for the shipment of goods i from r to s

Table A8. Elasticities.

Symbol	Description	
η_f	Elasticity of transformation for sluggish factor allocation	$\eta_{NRS} = 0.001$ $\eta_{LND} = 1$
σ_i^{VA}	Substitution between primary factors in VA composite of production in sector i	GTAP values
σ_{VAE}	Substitution between energy and VA in production	0.5
σ_i^R	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}	$\mu_{COA} = 2$ $\mu_{OIL} = 2$ $\mu_{GAS} = 2$
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.1
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_{LQD}	Substitution between gas and oil in the liquid fossil fuel composite in production	2
σ_i^A	Substitution between the import aggregate and the domestic input	GTAP values
σ_i^M	Substitution between imports from different regions	GTAP values
σ_C	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.5

Table A9. Variables for border adjustments.

Symbol	Description
τ_{irs}^M	Border adjustment import tariff on import of goods i from r to s
τ_{ir}^X	Border adjustment export rebate rates on export of goods i from r
ξ_{ir}	Emissions coefficient (CO2 per unit of output) including indirect emissions of sector i in region r

A.1.3. *Model*

A.1.3.1 Zero profit conditions

Production of goods except fossil fuels ($i \notin FF$)

$$\Pi^Y_{ir} = p^Y_{ir} - \sum_{j \notin EG} \theta_{jir} p^A_{jr} - \theta^{VAE}_{ir} [\theta^E_{ir} p^{E^{1-\sigma_{VAE}}}_{ir} + (1-\theta^E_{ir}) p^{VA^{1-\sigma_{VAE}}}_{ir}]^{\frac{1}{1-\sigma_{VAE}}} = 0 \qquad \{Y_{ir}\}$$

Price index of primary factors ($i \notin FF$)

$$p^{VA}_{ir} = \left[\sum_{f \in MF} \theta^F_{fir} p^{F^{1-\sigma^{VA}_i}}_{fr} + \sum_{f \in SF} \theta^F_{fir} p^{SF^{1-\sigma^{VA}_i}}_{fir}\right]^{\frac{1}{1-\sigma^{VA}_i}} \qquad \{p^{VA}_{ir}\}$$

Production of fossil fuels ($i \in FF$)

$$\Pi^Y_{ir} = p^Y_{ir} - \left[\theta^R_{ir} p^{SF^{1-\sigma^R_i}}_{NRS,ir} + (1-\theta^R_{ir}) \times \left(\sum_{f \in MF} \theta^{FF}_{fir} p^F_{fr} + \sum_{j \notin EN} \theta^{NR}_{jir} p^{AF}_{jir} + \sum_{j \in EN} \theta^{NR}_{jir} p^{EF}_{jir}\right)^{1-\sigma^R_i}\right]^{\frac{1}{1-\sigma^R_i}} = 0 \qquad \{Y_{ir}\}$$

Sector-specific energy aggregate: ($i \notin FF$)

$$\Pi^E_{ir} = p^E_{ir} - \left\{\theta^{ELE}_{ir} (p^{AF}_{ELY,ir})^{1-\sigma_{ELE}} + (1-\theta^{ELY}_{ir}) \left[\theta^{COA}_{ir} p^{EF^{1-\sigma_{COA}}}_{COA,ir} + (1-\theta^{COA}_{ir}) \left(\sum_{jLQD} \theta_{jir}^{LQD p_{jir}^{EF^{1-\sigma_{LQD}}}}\right)^{\frac{1-\sigma_{COA}}{1-\sigma_{LQD}}}\right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}}\right\}^{\frac{1}{1-\sigma_{ELE}}} = 0 \qquad \{E_{ir}\}$$

Price of energy intermediate goods ($i \in EN$)

$$p^{EF}_{ijr} = p^{AF}_{ijr} + p^{CO2}_r a^{CO2F}_{ijr} \qquad \{p^{EF}_{ijr}\}$$

Allocation of sluggish factor ($f \in SF$)

$$\Pi^{SF}_{fr} = \left(\sum_i \theta^{SF}_{fir} p^{SF^{1+\eta_f}}_{fir}\right)^{\frac{1}{1+\eta_f}} - p^F_{fr} = 0 \qquad \{T^{SF}_{fr}\}$$

Armington aggregate for intermediate inputs

$$\Pi^{AF}_{ijr} = p^{AF}_{ijr} - (\theta^{AF}_{ijr} p^{Y^{1-\sigma^A_i}}_{ir} + (1-\theta^{AF}_{ijr}) p^{M^{1-\sigma^A_i}}_{ir})^{\frac{1}{1-\sigma^A_i}} = 0 \qquad \{A^F_{ijr}\}$$

Armington aggregate for private consumption

$$\Pi_{ir}^{AP} = p_{ir}^{AP} - (\theta_{ir}^{AP} p_{ir}^{Y^{1-\sigma_i^A}} + (1-\theta_{ir}^{AP}) p_{ir}^{M^{1-\sigma_i^A}})^{\frac{1}{1-\sigma_i^A}} = 0 \qquad \{A_{ir}^P\}$$

Armington aggregate for government expenditure

$$\Pi_{ir}^{AG} = p_{ir}^{AG} - (\theta_{ir}^{AG} p_{ir}^{Y^{1-\sigma_i^A}} + (- \theta_{ir}^{AG}) p_{ir}^{M^{1-\sigma_i^A}})^{\frac{1}{1-\sigma_i^A}} = 0 \qquad \{A_{ir}^G\}$$

Aggregate imports across import regions

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left(\sum_s \theta_{isr}^{M} p_{isr}^{MM^{1-\sigma_i^M}}\right)^{\frac{1}{1-\sigma_i^M}} = 0 \qquad \{M_{ir}\}$$

CIF price of imports

$$p_{isr}^{MM} = p_{is}^{Y} + \sum_j p_j^T \tau_{jisr} + \tau_{isr}^{M} - \tau_{is}^{X} \qquad \{P_{isr}^{MM}\}$$

Household utility

$$\Pi_r^U = p_r^U - (\theta_r^{C p_r^{EC^{1-\sigma_C}}} + (1-\theta_r^C) p_r^{CC^{1-\sigma_C}})^{\frac{1}{1-\sigma_C}} = 0 \qquad \{U_r\}$$

Household non-energy demand

$$\Pi_r^{CC} = p_r^{CC} - \prod_{i \notin EG} p_{ir}^{AP^{\theta_{ir}^{CC}}} = 0 \qquad \{CC_r\}$$

Household energy demand

$$\Pi_r^{EC} = p_r^{EC} - (p_{ELY,r}^{AP})^{\theta_{ELY,r}^{EC}} \prod_{i \in EN} (p_{ir}^{EP})^{\theta_{ir}^{EC}} = 0 \qquad \{E_{Cr}\})$$

Price of consumption goods ($i \in EN$)

$$p_{ir}^{EP} = p_{ir}^{AP} + p_r^{CO2} a_{ir}^{CO2P} \qquad \{p_{ir}^{EP}\}$$

Global transport sector

$$\Pi_i^T = p_i^T - \prod_r (p_{ir}^Y)^{\theta_{ir}^T} = 0 \qquad \{Y_i^T\}$$

Government expenditure

$$\Pi_r^G = p_r^G - \sum_i \theta_{ir}^G p_{ir}^{AG} = 0 \qquad \{G_r\}$$

A.1.3.2 Market Clearance Conditions

Mobile factors ($f \in MF$)

$$\overline{E}_{fr} = -\sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{fr}^F} \qquad \{p_{fr}^F\}$$

Sluggish factors ($f \in SF$)

$$\bar{E}_{fr} = T_{fr}^{SF} \qquad \{p_{fr}^{F}\}$$

Sector specific sluggish factors ($f \in SF$)

$$T_{fr}^{SF} \frac{\partial \Pi_{fr}^{SF}}{\partial p_{fir}^{SF}} = -Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{fir}^{SF}} \qquad \{p_{fir}^{SF}\}$$

Output

$$Y_{ir} = -\sum_{j} A_{ijr}^{F} \frac{\partial \Pi_{jr}^{AF}}{\partial p_{ir}^{Y}} - A_{ir}^{P} \frac{\partial \Pi_{ir}^{AP}}{\partial p_{ir}^{Y}} - A_{ir}^{G} \frac{\partial \Pi_{ir}^{AG}}{\partial p_{ir}^{Y}} - \sum_{s} M_{is} \frac{\partial \Pi_{is}^{M}}{\partial p_{ir}^{Y}} - Y_{i}^{T} \frac{\partial \Pi_{i}^{T}}{\partial p_{ir}^{Y}} \qquad \{p_{ir}^{Y}\}$$

Sector specific energy aggregate

$$E_{ir} = -Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{E}} \qquad \{p_{ir}^{E}\}$$

Import aggregate

$$M_{ir} = -\sum_{j} A_{ijr}^{F} \frac{\partial \Pi_{ir}^{A}}{\partial p_{ir}^{M}} - A_{ir}^{P} \frac{\partial \Pi_{ir}^{AP}}{\partial p_{ir}^{M}} - A_{ir}^{G} \frac{\partial \Pi_{ir}^{AG}}{\partial p_{ir}^{M}} \qquad \{p_{ir}^{M}\}$$

Armington aggregate for intermediate inputs

$$A_{ijr}^{F} = -Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ijr}^{AF}} \qquad \{p_{ijr}^{AF}\}$$

Armington aggregate for government expenditure

$$A_{ir}^{G} = -G_{r} \frac{\partial \Pi_{r}^{G}}{\partial p_{ir}^{AG}} \qquad \{p_{ir}^{AG}\}$$

Armington aggregate for private consumption

$$A_{ir}^{P} = -CC_{r} \frac{\partial \Pi_{r}^{CC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}, i \notin EG$$

$$A_{ir}^{P} = -EC_{r} \frac{\partial \Pi_{r}^{EC}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}, i \in EG$$

Household utility

$$U_{r} = p_{r}^{U} H_{r} \qquad \{p_{r}^{U}\}$$

Aggregate household energy consumption

$$EC_{r} = -U_{r} \frac{\partial \Pi_{r}^{U}}{\partial p_{r}^{EC}} \qquad \{p_{r}^{EC}\}$$

Aggregate household non-energy consumption

$$CC_r = -U_r \frac{\partial \Pi_r^U}{\partial p_r^{CC}} \qquad \{p_r^{CC}\}$$

Government expenditure

$$G_r = p_r^G H_r^G \qquad \{p_r^G\}$$

Global transport service

$$Y_i^T = \sum_{j,r,s} \tau_{ijrs} M_{jrs} \qquad \{p_i^T\}$$

Price of emissions permit

$$\overline{CO2}_r = -\sum_i E_{ir} \frac{\partial \Pi_{ir}^E}{\partial p_r^{CO2}} - EC_r \frac{\partial \Pi_r^{EC}}{\partial p_r^{CO2}} \qquad \{p_r^{CO2}\}$$

A.1.3.3 Income

Income of the representative household

$$H_r = \sum_f p_{fr}^F \bar{E}_{fr} + p_{CGD,r} \overline{Y}_{CGD,r} + p_{USA}^C \overline{B}_r - p_r^C T_r^L \qquad \{H_r\}$$

Government income

$$H_r^G = p_r^C T_r^L + V_r^R + \text{BA tariff revenue} - \text{ BA export rebate (subsidy)} \qquad \{H_r^G\}$$

Lump-sum transfer (tax) to household

$$G_r = \bar{G}_r \qquad \{T_r^L\}$$

Permit revenue

$$V_r^R = p_r^{CO2} \overline{CO2}_r \qquad \{V_r^R\}$$

A.1.3.4 Equations for border adjustment

BA import tariff rates (BID, BIED, BIDR, BIEDR)

$$\tau_{isr}^M = p_r^{CO2} \xi_{ir} \qquad \{\tau_{isr}^M\}$$

BA import tariff rates (BIF)

$$\tau_{isr}^M = p_r^{CO2} \xi_{is} \qquad \{\tau_{isr}^M\}$$

BA export rebate (subsidy) rates (BIED and BIEDR)

$$\tau_{ir}^X = p_r^{CO2} \xi_{ir} \qquad \{\tau_{ir}^X\}$$

The sum of direct and indirect emissions

$$q_{ir}^{CO2T} = q_{ir}^{CO2D} + q_{ir}^{CO2ID} \qquad \{q_{ir}^{CO2T}\}$$

The direct emissions

$$q_{ir}^{CO2D} = -E_{ir} \frac{\partial \Pi_{ir}^{E}}{\partial p_{r}^{CO2}} \qquad \{q_{ir}^{CO2D}\}$$

The demand share of electricity

$$\theta_{ir}^{ELY} = -A_{ELY,jr}^{F} \frac{\partial \Pi_{jr}^{AF}}{\partial p_{ELY,r}^{Y}} \Big/ Y_{ELY,r} \qquad \{\theta_{ir}^{ELY}\}$$

The indirect emissions

$$q_{ir}^{CO2ID} = \theta_{ir}^{ELY} q_{ELY,r}^{CO2D} \qquad \{q_{ir}^{CO2ID}\}$$

Emissions coefficient based on both direct and indirect emissions

$$\xi_{ir} = q_{ir}^{CO2T} / q_{ir} \qquad \{\xi_{ir}\}$$

Emissions coefficient based on only direct emissions

$$\xi_{ir} = q_{ir}^{CO2D} / q_{ir} \qquad \{\xi_{ir}\}$$

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