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A Computable General Equilibrium Analysis of EU CBAM for the Japanese Economy*

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Abstract

The EU plans to introduce Carbon Border Adjustment Mechanism (CBAM) to curb carbon leakage and protect energy-intensive and trade-exposed (EITE) industry. This move by the EU to introduce CBAMs has raised concerns in Japan that it will harm Japanese industry and the economy. To address these concerns, this study tries to provide an ex-ante and quantitative analysis of the economic and environmental effects of the introduction of the EU CBAM. To capture the effects of the EU CBAM, this study employs a global multi-region, multi-sector computable general equilibrium model with 18 sectors and 17 regions. The main insights obtained from the analysis are as follows. First, we find that the introduction of EU CBAM significantly reduces carbon leakage from the EU. Second, the effects of the introduction of CBAM on GDP and welfare of each country varied from country to country, but the effects were generally very small. While there is a positive impact on GDP and welfare in Japan, again, the magnitude of the impact is very small. There will also be a negative impact on Japan's EITE industry, but again, the magnitude of this impact is very small and not of great concern.

Keywords: climate change, carbon border adjustment mechanism, computable general equilibrium analysis

JEL classification: Q54

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1. Introduction

Since the Paris Agreement entered into force in 2016, there has been a growing movement among countries worldwide to actively address climate change. Many developed countries, including Japan, have set a net-zero emissions goal for 2050, and many developing countries have also set net-zero targets, although for later. Among these countries, the member states of the EU are enthusiastic about climate change mitigation and have set a very ambitious target of -55% below 1990 levels for 2030. The momentum for climate change policies is growing worldwide. However, while some regions, such as the EU, have high targets, others, especially developing countries, are relatively reluctant to take action on climate change. This wide variation in the intensity of climate change policy among regions is a factor causing so-called "carbon leakage" and a loss of international competitiveness of firms.

To address these problems, the EU, which has been active in addressing climate change, is planning to introduce a carbon border adjustment mechanism (CBAM). The CBAM is a mix of trade policies aimed at compensating for the disadvantages of greenhouse gas (GHG) emission reduction. The CBAM has long attracted attention as a means of preventing carbon leakage and of maintaining the international competitiveness of firms in regions with GHG regulations. For example, the Waxman-Markey Bill, which passed the US House of Representatives in 2009, proposed refunding the majority of the costs of emission caps if an energy-intensive trade-exposed (EITE) sector was identified 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 emission restrictions. This plan resembles the CBAM.

Although a similar debate has been underway in the EU, the EU has thus far failed to make the CBAM a realistic policy. However, in aiming for an ambitious 55% reduction from 1990 levels for 2030, the problems of carbon leakage and the loss of international competitiveness could no longer be ignored, and the EU began to design the CBAM. First, the EU Commission proposed a CBAM system in 2021. Subsequently, in June 2022, a proposal with amendments was submitted to the EU Parliament, which includes the following (European Parliament, 2022): 1) the CBAM will begin in 2027 and be phased in gradually; 2) the target sectors (goods) will be steel, fertilizer, chemicals, polymers, aluminum, cement, and electricity; 3) both indirect and direct emissions will be included when measuring carbon content; 4) actual emission data from exporters will be used to measure carbon content; 5) no adjustment will be made to exports; and 6) countries that pay an explicit carbon price will be exempted from the CBAM.

The EU's plan for the CBAM has aroused various debates. One of these debates concerns the legal issue of compatibility with the WTO. Under the EU's proposal, different tariff rates would be applied to the same goods from different exporting countries, but these different rates may violate WTO rules, which, in principle, prohibit discriminatory treatment. Of course, there are also concerns about the economic impacts. The EU's introduction of the CBAM as a carbon leakage and international competitiveness measure is a legitimate move in itself, as it has the effect of increasing the effectiveness of climate change policies. However, there is also the possibility that it will have a significant impact on international trade and production structures. There is also concern that the CBAM may be used as a disguised trade barrier. In Japan, there are concerns that the EU CBAM will harm Japanese industry and the Japanese economy. This study aims to conduct an ex ante and quantitative analysis of the economic and environmental impacts of the introduction of the EU CBAM to determine whether these concerns are genuinely justified.

There are already numerous studies on the CBAM. Since there have been few examples of CBAM implementation, most studies are ex ante simulation analyses. In particular, many analyses have been conducted using computable general equilibrium (CGE) models. For example, Böhringer et al. (2012) summarized many CBAM analyses using CGE models. Regarding Japan, Takeda et al. (2012) compared various types of CBAMs in Japan. More recently, Böhringer et al. (2017) compared the CBAM and output-based rebating in terms of welfare. Similarly, 2021) examined the effect of carbon tariffs in terms of efficiency. Balistreri et al. (2019) analyzed the effects of the carbon tariff with consideration of the strategic behavior of each country. Although these studies on the CBAM have been conducted from various perspectives, they did not analyze the effects of the CBAM planned by the EU.

The studies analyzing the CBAM currently planned by the EU include Mörsdorf (2022) and the UNCTAD (2021), both of which use the GTAP-E model (Burniaux and Truong, 2002).[1] The former compares the effects of different types of CBAM and output-based rebating based on EU proposals. The latter analyzes the impact of EU CBAM implementation on carbon leakage, individual sectors, and national incomes in a situation where the EU carbon price is set to US$44 or US$88. Similar to the studies above, this paper uses a CGE model to analyze the effects of the EU's planned CBAM. Specifically, we analyze the impact of the EU CBAM on carbon leakage, industries, the GDP of each region, and welfare. The main differences between our study and previous studies are as follows: 1) we use a model other than the GTAP-E model, 2) we provide a detailed analysis of the effects on Japan, and 3) we analyze various types of CBAM in the sensitivity analysis.

The paper is organized as follows. First, Section 2 describes the CGE model and data used in the simulations. Section 3 describes the emission regulations and how the CBAM is implemented. Section 4 reviews the status of the benchmark data. Section 5 describes the simulation scenarios and simulation results. Finally, Section 6 provides concluding remarks.

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[1] GTAP-E is a CGE model provided by the GTAP for climate change policy analysis.

2. Model and Data

Table 1: List of regions.

Symbol	Regions	Symbol	Regions
EUR	EU	CHN	China
JPN	Japan	BRA	Brazil
USA	United States	ASE	ASEAN 10
GBR	United Kingdom	TUR	Turkey
OEU	Other European regions	IND	India
RUS	Russia	OEX	Other oil exporters
ANZ	Australia and New Zealand	MIC	Other middle income countries
CAN	Canada	LIC	Other low income countries
KOR	Korea		

Table 2: List of sectors.

Symbol	Sectors	Symbol	Sectors
I_S	Iron and steel industry	COA	Coal transformation
NFM	Non-ferrous metals	OIL	Crude oil
CHM	Chemical products	AGR	Agricultural products
OCH	Other chemical products	CNS	Construction
NMM	Non-metallic minerals nec	MAC	Machinery
PPP	Paper products, publishing	OMF	Other manufacturing
P_C	Petroleum and coal products	ATP	Air transport
ELY	Electricity and heat	TRN	Other transport
GAS	Natural gas works	SER	Services

This study uses simulation with the CGE model. Our model is similar to the CGE model used by Böhringer et al. (2021). The model is a multiregional, multisector global static CGE model. It is a perfectly competitive model in which economic agents act as price takers in all markets, and prices are determined to equalize supply and demand. We divide regions and sectors into 17 regions and 18 sectors in Table 1 and Table 2.[2] The following provides an overview of the

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[2] As explained below in Section 2.3, this study uses GTAP 10 data for the benchmark data. The original sector and region classification of the GTAP 10 data consisted of 65 sectors and 121 regions. In our data, the original sectors and regions are aggregated into 18 sectors and 17 regions. Please contact the authors for more information on the aggregation of sectors and regions.

model.[3]

2.1. Production Side

All producers determine the level of output and input to maximize their profits. The production function assumes a multistage nested constant elasticity of substitution (CES) function for all sectors. We divide production sectors into two types: the three primary fossil fuel sectors (OIL, COA, and GAS) and the nonfossil fuel sector (all other sectors), and we use different functional forms for each type. The factors of production are divided into four categories: labor, capital, land, and natural resources. Land is a specific factor used only in the agricultural sector (AGR), and natural resources are specific to only the fossil fuel sectors. The factors of production are assumed not to be internationally mobile.

Fossil fuel production is treated similarly to (Böhringer et al. 2021).[4] Fossil fuel production activities include the extraction of coal, oil, and gas and are structured as shown in Figure 1. Fossil fuel output is produced as a CES aggregate of natural resources and a nonnatural resource input composite, where σ_{ir}^{R} is the elasticity of substitution.[5] The nonnatural resource input is a Leontief composite of capital, labor, and other intermediate inputs.

Nonfossil fuel production (including electricity) has the structure shown in Figure 2. Output is produced by the CES aggregate of nonenergy intermediate inputs and an energy-primary factor composite. The energy-primary factor composite is a nested CES function of energy inputs and primary factors.

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[3] Due to space limitations, the main text provides only an overview of the model; Appendix 2 describes the structure of the model using mathematical formulas.

[4] The same approach is used in, for example, Takeda et al. (2011, 2014, 2019).

[5] All values of elasticity of substitution are reported in Appendix 2.

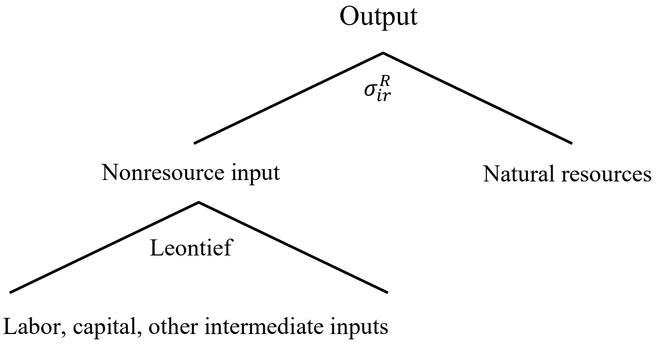

Figure 1: Production function of the fossil fuel sector.

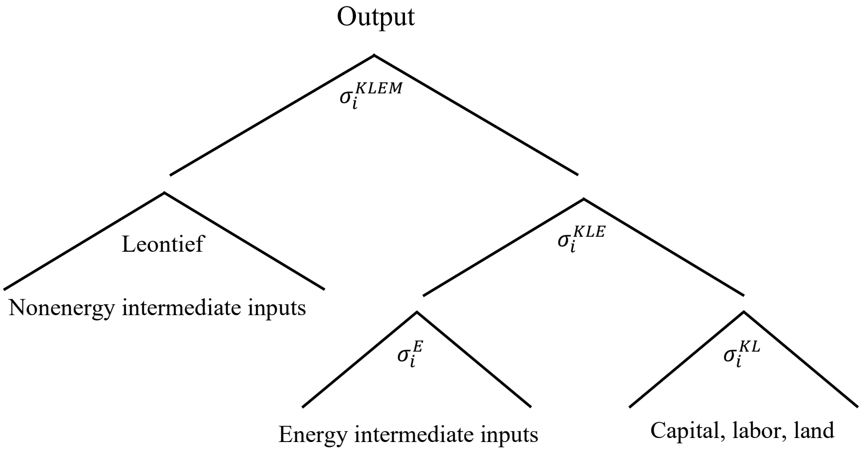

Figure 2: Production function of the nonfossil fuel sector.

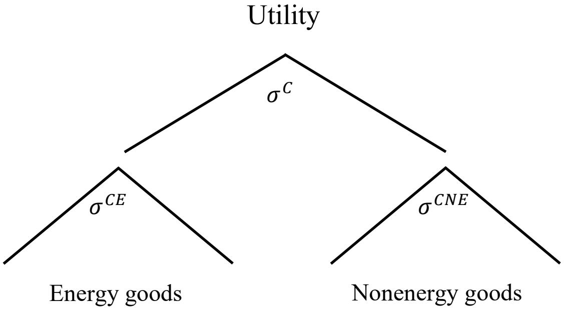

Figure 3: Utility function.

2.2. Demand Side

The representative household's utility has the structure depicted in Figure 3. The representative household aims to maximize its utility subject to budget constraints. The household's income consists of factor income minus tax payments. We assume that the endowments of primary factors are exogenously constant. The international trade in goods is treated in the same way as the GTAP model (Hertel, 1999), and there is no international movement of primary factors. In addition, we assume that government expenditure and investment are held constant at the benchmark values.

2.3. Benchmark Data

We use GTAP 10 data for the benchmark data (Aguiar, 2019). GTAP data are a standard dataset for multiregional CGE analysis. For the CO_2 emission data, we also use the GTAP 10 data. To use the GTAP data in GAMS, we use GTAPinGAMS provided by Lanz and Rutherford (2016). Although we basically use the original GTAP 10 data, we make some adjustments to the CO_2 data of Japan. More specifically, we adjust the CO_2 emissions from Japan's iron and steel sector (I_S) because they are significantly underestimated. In addition to CO_2 from fossil fuels, we consider process emissions from cement production, which are included in the NMM sector. We use UNFCCC data for these process CO_2 emission data.

3. Emission Regulations in the EU and the CBAM

3.1. Emission Regulations in the EU

In the simulations, we assume that the EU introduces a cap-and-trade emissions trading scheme. The initial allocation of emission permits is determined through an auction, with the auction revenue rebated to the representative household in a lump-sum way. CO_2 emissions are from the use and consumption of the following four fossil fuel goods in Table 2: OIL, COA, GAS, and P_C. In addition, CO_2 emissions are generated from NMM industrial processes, which include cement production.

Under emissions trading, the price of fossil fuel i used in sector j in region r is given by the following equation:

$$p_{ir}^{A} + \phi_{ijr} p_{r}^{CO2}$$

where p_{ir}^{A} is the demand price of good i in region r, ϕ_{ijr} is the emission coefficient for fossil fuel i used in sector j in region r, and p_{r}^{CO2} is the price of an emission permit in region r. In addition, the price of NMM is given by the following equation:

$$p_{NMM,r} + \psi_{NMM,r} p_{r}^{CO2}$$

where p_{ir} is the producer price of good i in region r and ψ_{ir} is the CO_2 emissions per unit of output of good i in region r.[6] The permit price is determined so that the demand for permits from various sectors and the household equals the supply of permits determined by the government.

3.2. CBAM

The CBAM is a policy aimed at reducing carbon leakage and suppressing the loss of international competitiveness that asymmetric environmental regulations among regions may cause. This paper analyzes the effects of CBAMs that the EU plans to introduce. The EU CBAM has the following characteristics.

- It includes both indirect and direct emissions to calculate carbon content.
- It applies only to the import side and not to the export side.
- The value of CO_2 emissions on the exporting region side is used to calculate carbon content.
- It applies only to specific sectors with high CO_2 emissions.

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[6] We assume that NMM industrial process emissions are proportional to the NMM output level.

- Some countries are exempt from the EU CBAM.

This section describes how to introduce the CBAM into the model. The method of introducing the CBAM is based on Takeda et al. (2012). The carbon tariff is determined according to the carbon content based on direct and indirect emissions.[7] q_{ir}^{CO2T} denotes the total amount of CO₂ emitted from a given sector i 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 CO₂ emissions of sector i in region r, respectively. Direct emissions of CO₂ are defined as the amount of CO₂ emitted from fossil fuel use plus CO₂ from industrial processes. Thus, direct emissions are given by the following equation:

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

where q_{eir}^{INT} is the amount of fossil fuel used in sector i of region r and q_{ir} is the level of output of sector i of region r. Note that we have $\psi_{ir} > 0$ only for $i = NMN$ and otherwise $\psi = 0$. Indirect emissions are the amount of CO₂ embodied in purchased electricity (CO₂ emitted from power plants where electricity is generated by burning fossil fuels). We calculate the indirect emissions from sector i in the following manner. First, θ_{ir}^{ELY} is defined 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 emissions of CO₂ from the electricity sector, we calculate the indirect emissions of CO₂ from sector i by multiplying $q_{ELY,r}^{CO2D}$ by θ_{ir}^{ELY}:

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

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[7] In this paper, indirect emissions mean emissions embodied in electricity. We do not consider emissions embodied in intermediate inputs because it is difficult (perhaps impossible) to calculate them in a CGE model, which assumes substitution among inputs.

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 by the following equation:

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

Let us assume that in the EU, emissions trading is introduced with a carbon price of p^{CO2} and the CBAM is implemented. Then, the following tariffs are imposed on the EU's imports of good i from region r:

$$t_{ir}^{M} + p^{CO2}\xi_{ir}$$

where t_{ir}^{M} is the original tariff rate imposed on good i and $p^{CO2}\xi_{ir}$ is the tariff rate introduced as the CBAM tariff. The introduction of the CBAM will generate additional tax revenues, which will be rebated to the representative household in a lump-sum way. In all simulations, we assume that the value of ξ_{ir} is assumed to remain constant at the benchmark value.[8]

As explained in the introduction, the EU CBAM is applied only to the following goods: steel, fertilizer, chemicals, polymers, aluminum, cement, and electricity. In our sector classification, steel is included in I_S, fertilizer and chemicals are included in CHM, polymers is included in OCH, aluminum in included in NFM, cement is included in NMM, and electricity is included in ELY. Therefore, we assume that the CBAM is applied to the following goods (sectors): I_S, NFM, CHM, OCH, NMM, P_C, and ELY. In the following, except for ELY, these sectors will be referred to as EITE sectors.[9] In addition, we assume that GBR and OEU are exempted from the EU CBAM because these regions are likely to be linked to the EU emission market.

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[8] Since ξ_{ir} depends on q_{ir}^{CO2T} and q_{ir}, ξ_{ir} will change as q_{ir}^{CO2T} and q_{ir} change, but we assume that ξ_{ir} will remain constant at the benchmark year value.

[9] The PPP sector is usually included in EITE sectors, but since it is not a sector covered by the CBAM, we exclude it from EITE sectors.

4. Benchmark Data

This section describes the characteristics of the benchmark data. Our simulation analyzes the effect of introducing emissions trading and the CBAM on the benchmark equilibrium represented by the benchmark data. Since the effects of these policies strongly depend on the initial state of the economy, we check the characteristics of the benchmark data.

Table 3: Trade with the EU.

	EU imports by region		Share of each country's export to the EU (%)
	Value	Share (%)	Export
GBR	309.5	11.1	44.5
OEU	273.4	9.8	45.1
JPN	95.4	3.4	10.4
USA	402.9	14.4	20.1
RUS	177.7	6.4	41.9
CAN	37.7	1.3	7.3
ANZ	23.9	0.9	7.0
KOR	61.6	2.2	9.1
CHN	435.5	15.6	16.4
IND	83.1	3.0	19.8
BRA	41.3	1.5	16.0
TUR	71.2	2.5	35.8
ASE	187.4	6.7	13.4
OEX	85.0	3.0	8.9
MIC	450.7	16.1	19.4
LIC	58.9	2.1	22.8
World	2,795.4	100.0	

The unit of value is billions of dollars.

The second and third columns of Table 3 show the value of EU imports from each country and its share. For example, GBR has a value of 11.1%, meaning that EU imports from GBR account for 11.1% of all EU imports. This figure indicates which regions are important to the EU as trading partners. It shows that GBR, OEU, USA, CHN, and MIC are particularly important to the EU as trading partners. Thus, if the CBAM is introduced, these regions will likely be strongly affected. EU imports from Japan (JPN) account for only 3.4% of total imports. This suggests that the economic ties with Japan are tiny from the EU's perspective.

The fourth column of Table 3 shows the share of each country's exports to the EU. For example, the value for GBR is 44.5%, which means that GBR's exports to the EU account for 44.5% of all GBR exports. This figure shows how important the EU is as a trading partner for regions outside the EU. Regions with a high share of exports to the EU include GBR, OEU, RUS, USA, and TUR. Japan's (JPN) share of exports to the EU is 10.4%, indicating that the EU's share as a trading partner is not that large. These data suggest that if the EU introduces the CBAM, the impact on Japan would likely be small.

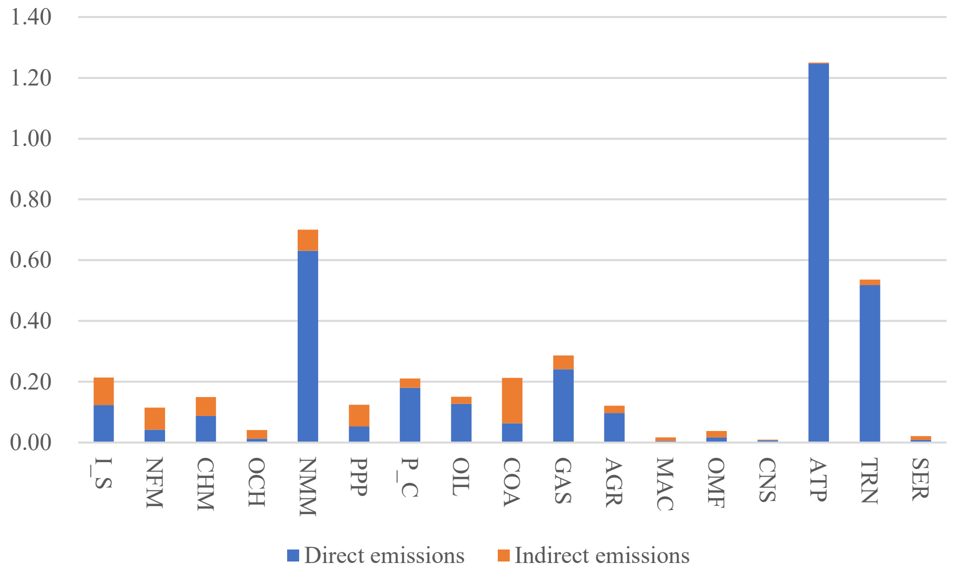

Figure 4: Sectoral carbon intensity in the EU (CO_2/output).

The CBAM planned by the EU is limited to EITE (and electricity) sectors that emit large amounts of CO_2. Here, we check the carbon intensity of each sector. Under the EU CBAM, emissions from the production of goods are counted in terms of not only direct emissions but also indirect emissions, which are CO_2 emitted from the generation of electricity. Figure 4 illustrates the carbon intensity by sector for the EU (the blue area is the carbon intensity based on direct emissions, and the orange area is the carbon intensity based on indirect emissions). EITE sectors (I_S, NFM, CHM, OCH, NMM, and P_C), energy sectors, and transportation sectors have high-intensity values. These sectors are likely to be strongly (negatively) affected by emission regulations and the EU CBAM.

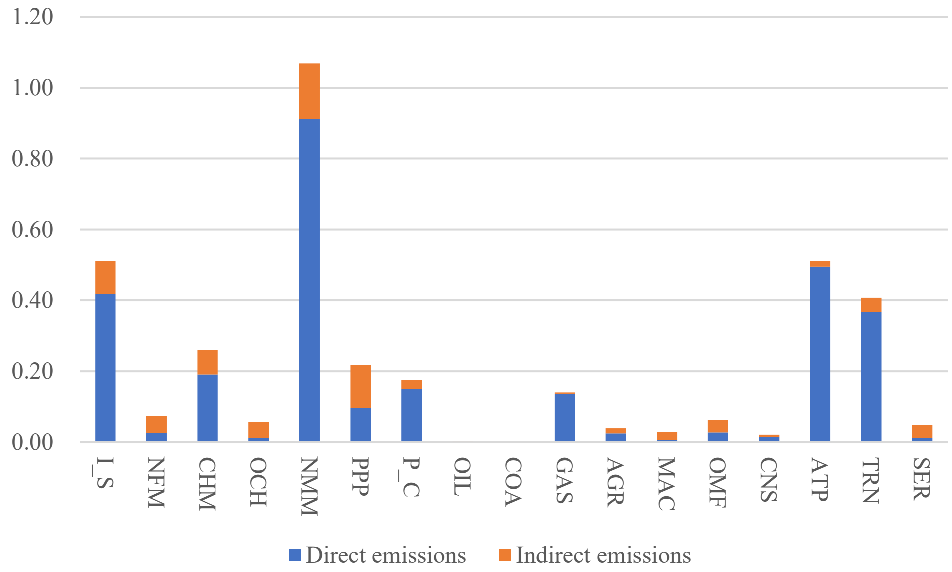

Figure 5: Sectoral carbon intensity in the EU (CO_2/output).

Figure 5 shows the carbon intensity by sector in Japan. Even in the same sector, the values are often very different from those of the EU sector. However, we see that the high carbon intensity of the EITE, energy, and transportation sectors is the same in Japan.

When the CBAM is introduced, additional tariffs will be imposed on imports according to their carbon content (carbon intensity). Figure 6 shows a graph of the tariff rates (ad valorem rates) for the CBAM, listing the seven sectors (goods) subject to the CBAM.[10] Tariff rates are calculated by $p^{CO2}\xi_{ir}$ in Section 3.2, assuming that the EU's carbon price (p^{CO2}) is US$100.[11] The more carbon intensive a good is, the higher the tariff rate. In addition, the EU CBAM determines tariff rates according to carbon intensity based on the CO_2 emissions in the exporting country. Thus, tariff rates will be higher for countries with a higher carbon intensity for the same goods. For example, a CBAM tariff rate of 5.1% is applied to I_S imports from Japan, while 27.3% is applied to imports from India. Since there are substantial differences in the carbon intensity of the production of the same good in different regions, there are also substantial differences in CBAM tariff rates.

While tariff rates vary by good and region, CBAM tariff rates for developing countries tend to be higher. The reason is that developing countries tend to have looser environmental regulations and lower levels of technology, which results in higher carbon intensity, even for the same goods. The high CBAM tariff rates for developing countries suggest that EITE sectors, especially in developing countries, are likely to be significantly affected when the EU introduces the CBAM.

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[10] As explained in Section 3.2, GBR and OEU are exempt from the EU CBAM, but values are calculated and listed for reference.

[11] See Section 5.1 for the reason we assume a carbon price of US$100.

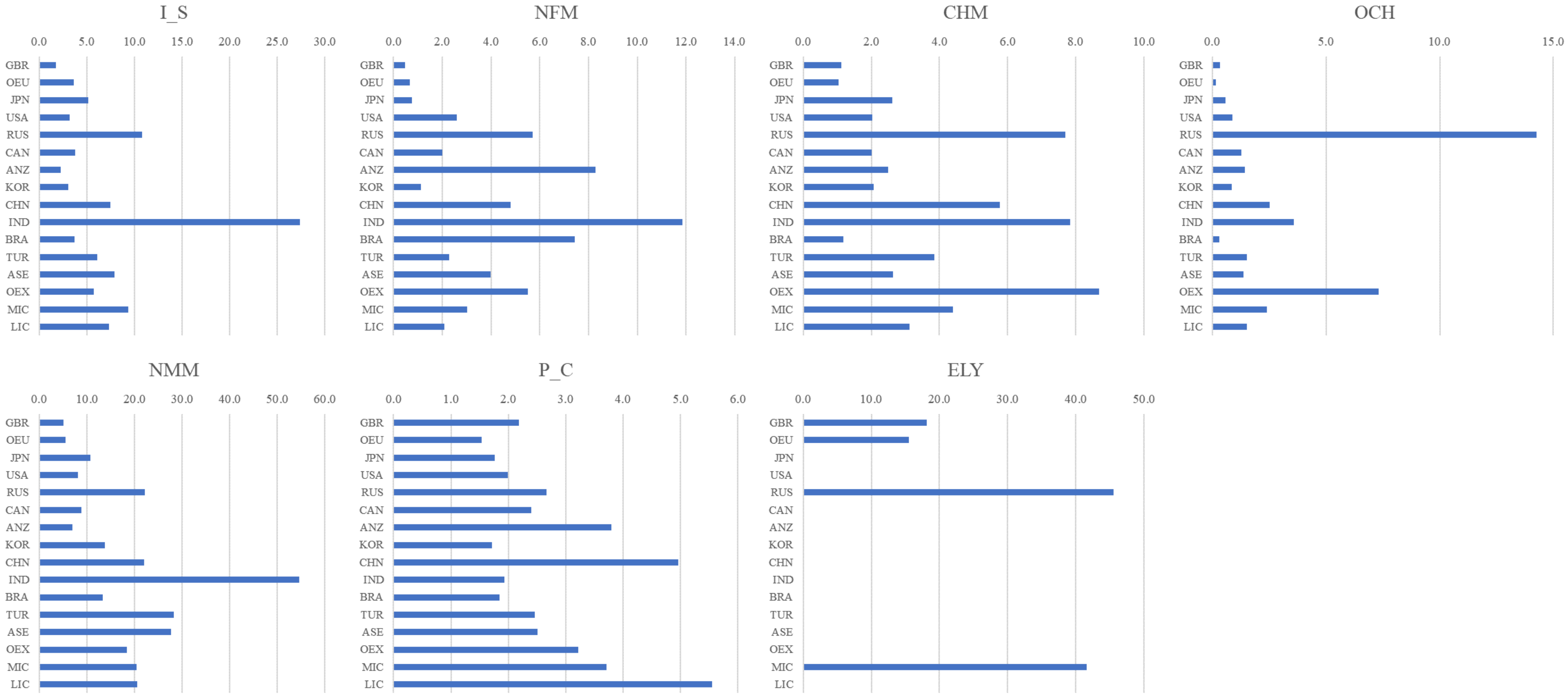

Figure 6: Tariff rates induced by the CBAM (%).

Table 4: Supply of EITE sectors in Japan (%).

Sector	Supply to the domestic market	Supply to regions other than the EU	Supply to the EU	Total
I_S	87.8	12.0	0.2	100.0
NFM	78.2	21.2	0.7	100.0
CHM	67.4	29.7	2.9	100.0
OCH	83.4	14.7	1.9	100.0
NMM	86.8	12.1	1.1	100.0
P_C	94.6	5.3	0.0	100.0

As already noted, EITE sectors are likely to be strongly affected by the introduction of the CBAM. Therefore, let us take a closer look at EITE sectors in Japan. Table 4 shows the share of supply of Japan's EITE sectors by destination. For example, concerning I_S, 87.8% of total output is supplied to the domestic market, 12.0% to non-EU regions, and only 0.2% to the EU. The values in Table 4 show that most of Japan's EITE goods are supplied to the domestic market or non-EU regions, with very few exports to the EU. We have already seen that the EU is not very important as a trading partner for Japan, and these data also suggest that the introduction of the EU CBAM will have a small impact on Japan.

5. Simulation

5.1. Simulation Scenarios

Table 5: Simulation scenarios.

Scenario	Carbon regulation in EU	CBAM
BM	No regulation	
NCBAM	Yes	No CBAM
WCBAM	Yes	With CBAM

Based on the UNCTAD (2021), the simulations in this study consider the three scenarios shown in Table 5.[12] First, BM is a scenario that represents an initial equilibrium without policy changes. The initial equilibrium represents the state of the benchmark data (2014 data). In this scenario, no explicit emission regulations are introduced in any region.

The NCBAM scenario represents the equilibrium with emission regulation (cap-and-trade) in the EU. Cap-and-trade is a policy that sets emission limits exogenously. Here, we assume that the emissions limit (cap) is set at a level where the carbon price (= price of emission permits) equals US$100 per ton of CO_2. Setting a carbon price of US$100 reflects the current situation in the EU emission permit market, where a price of approximately US$100 has recently been established. The extent to which cap-and-trade will reduce CO_2 emissions in the EU is explained in the next section. In the last scenario (WCBAM), we add the CBAM to the NCBAM scenario. Since we want to analyze the effects of the implementation of the EU CBAM, the simulation analysis is mainly concerned with the impact from the NCBAM scenario to the WCBAM scenario.[13]

5.2. Main Results[14]

In this section, we examine the simulation results. First, Table 6 shows the CO_2 emissions of each country in each scenario. The EU's introduction of cap-and-trade emission regulations would reduce CO_2 emissions in the EU by 19.5%, from 2,984 $MtCO_2$ to 2,402 $MtCO_2$. On the other hand, carbon leakage would increase CO_2 emissions in other regions. CO_2 emissions would decrease by 583 $MtCO_2$ in the EU. At the same time, they would increase by 204 $MtCO_2$ in regions outside the EU. Thus, the carbon leakage rate is approximately 35%, indicating that introducing emission regulations in the EU alone without the CBAM would result in

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[12] However, the difference is that the UNCTAD assumes a carbon tax while we assume emissions trading.

[13] To make the NCBAM and WCBAM scenarios comparable, the EU CO2 emissions in the WCBAM scenario are set equal to the emissions in the NCBAM scenario. Thus, the carbon price in the WCBAM scenario will be different from the carbon price in the NCBAM scenario (i.e., US$100).

[14] The dataset and programs for the simulation are are available from the authors upon request.

considerably high carbon leakage.[15]

Table 6: CO_2 emissions and the leakage rate.

	CO2 (MtCO2)		
	BM	NCBAM	WCBAM
EUR	2,984	2,402	2,404
GBR	434	441	442
OEU	193	201	203
JPN	1,180	1,188	1,189
USA	5,224	5,264	5,266
RUS	1,455	1,467	1,458
CAN	582	586	586
ANZ	413	417	417
KOR	532	537	537
CHN	9,009	9,039	9,030
IND	2,048	2,059	2,052
BRA	484	487	487
TUR	345	349	346
ASE	1,414	1,429	1,429
OEX	1,606	1,614	1,612
MIC	3,743	3,785	3,771
LIC	287	290	290
World	31,933	31,555	31,519
Leakage rate (%)		35.0	28.5

If the EU further introduces the CBAM, EU emissions will remain the same, while non-EU emissions will decrease. Therefore, the carbon leakage rate relative to the BM scenario will decrease to 28.5%, 6.5 percentage points lower than that without the CBAM. Thus, the CBAM effectively controls carbon leakage, as the EU intended.

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[15] Note that this carbon leakage includes not only competitiveness channel leakage but also fossil-fuel-price channel leakage. See Böhringer et al. (2012) for competitiveness and fossil-fuel-price channel leakage.

Table 7: Leakage rates by region (%).

	Leakage rate	Change in leakage rate (% point)
	NCBAM	WCBAM
GBR	1.2	0.2
OEU	1.4	0.2
JPN	1.3	0.2
USA	6.9	0.4
RUS	2.2	-1.6
CAN	0.6	0.0
ANZ	0.6	0.1
KOR	0.8	0.1
CHN	5.2	-1.6
IND	2.0	-1.2
BRA	0.5	0.0
TUR	0.7	-0.5
ASE	2.7	-0.1
OEX	1.4	-0.3
MIC	7.2	-2.4
LIC	0.5	0.0
Total	35.0	-6.5

Next, let us see how carbon leakage changes in more detail. Table 7 shows the values of carbon leakage from the EU expressed by region; the second column (NCBAM) displays the carbon leakage rate of 35.0% under the NCBAM scenario broken down by region. Looking at this column, we see how much CO_2 has increased in each region instead of decreasing in the EU. Large carbon leakages are found in USA, CHN, ASE, RUS, and IND. This means that if there is no CBAM, the production of EITE sectors will move to these regions.

The third column (WCBAM) shows the percentage point change in the carbon leakage rate due to the introduction of the CBAM. As already seen in Table 6, the overall carbon leakage rate decreases by 6.5 percentage points with the EU CBAM. Table 7 shows that the CBAM does not reduce leakage rates for all regions uniformly and, instead, increases the leakage rates in some regions. For example, the leakage rates to RUS, CHN, IND, and MIC decrease, while those to

USA and JPN increase. One reason for this large difference in the impact of the CBAM across regions is that the EU CBAM tariff rates significantly vary from region to region. While the leakage rates for developing countries tend to decrease, those for CBAM-exempt or developed countries tend to increase. The reason is that CBAM tariff rates tend to be higher for developing countries.

Table 8: Percentage change in the exports, imports, and output of EITE sectors in the EU (%).

	Export	Import	Output
I_S	3.48	-1.93	2.43
NFM	1.63	-0.71	1.54
CHM	1.26	-0.95	1.32
OCH	-0.09	-0.47	-0.01
NMM	5.81	-6.19	2.78
P_C	1.50	-1.61	1.07
ELY	5.62	-6.00	0.92

All values are percentage changes from values in the NCBAM scenario.

One of the EU's objectives in introducing the CBAM is to limit the negative impact of carbon regulation on EITE sectors. Table 8 shows how the CBAM has changed the EU's EITE (and electricity) sectors' exports, imports, and output (all values are percentage changes from the NCBAM scenario to the WCBAM scenario). For all sectors except for OCH, we see that the volume of exports increases, the volume of imports decreases, and consequently, the volume of output increases. These results indicate that the CBAM generally has the effect of protecting EITE sectors, as intended. Furthermore, for I_S and NMM, output increases by more than 2%, indicating that the protective effect is also reasonably large.

Table 9: Impacts on the EU.

	NCBAM	CBAM
Carbon price ($/tCO2)	100.0	102.3
CO2 emissions (MtCO2)	2,402	2,404
GDP		-0.01
Welfare		0.07
Export		-0.30
Import		-0.19
Terms of trade		0.35

All figures without units represent the percentage change from the NCBAM scenario to the WCBAM scenario.

Table 10: Impacts on GDP and welfare (%).

	GDP	Welfare
EUR	-0.006	0.068
GBR	0.007	0.020
OEU	0.007	0.022
JPN	0.002	0.026
USA	0.000	-0.005
RUS	-0.064	-0.151
CAN	-0.002	-0.042
ANZ	-0.001	-0.034
KOR	0.003	0.049
CHN	-0.005	-0.038
IND	-0.004	-0.050
BRA	0.000	-0.009
TUR	-0.012	-0.053
ASE	-0.001	-0.025
OEX	-0.001	-0.251
MIC	-0.004	-0.059
LIC	-0.004	-0.056
World	-0.004	-0.010

All figures represent the percentage change from the NCBAM scenario to the WCBAM scenario.

Table 9 summarizes the values of the effects on the EU. All figures without units represent the percentage change from the NCBAM scenario to the WCBAM scenario. “Welfare” indicates the percentage change in the utility level of the representative household, and “Export” and “Import” are the percentage change in total exports and total imports, respectively.

We have already seen that the CBAM has the effect of deterring carbon leakage and protecting EITE sectors. However, this does not necessarily mean that this is the desired outcome for the EU as a whole. Therefore, we also check the effects on GDP and welfare to see the overall effect. First, the household’s welfare has increased with the introduction of the CBAM. Therefore, from the perspective of the welfare indicator, the CBAM is desirable for the EU as a whole. On the other hand, GDP has decreased, indicating that the CBAM is not necessarily a desirable policy from the perspective of the EU economy as a whole. However, the rates of change, whether in welfare or GDP, are very small (less than 0.1% in absolute terms). Therefore, we can say that the CBAM will not significantly affect the EU as a whole.

Having looked at the impact on the EU, let us now look at the impact on other regions. Table 10 shows the percentage change in GDP and welfare for other regions (both from the NCBAM scenario to the WCBAM scenario). While GDP and welfare move in opposite directions in some regions, in many regions, they move in the same direction. It can be seen that some regions have increases in GDP and welfare, while others have decreases. In particular, GDP and welfare in CBAM-exempt and developed countries tend to increase (with some exceptions), while those in developing countries often decrease. Thus, the introduction of the CBAM in the EU is likely to have a positive effect on CBAM-exempt and developed countries but a negative effect on developing countries. However, the absolute rate of change in GDP and welfare of regions outside the EU is generally less than 0.1%, which means that the effect on GDP and welfare of regions outside the EU is small. Therefore, it follows that the EU CBAM will have only a small impact on non-EU regions.

Table 11: Impacts on Japan (%).

	WCBAM
CO2 emissions	0.088
GDP	0.002
Welfare	0.026
Export	-0.039
Import	0.024
Terms of trade	0.064

All figures represent the percentage change from the NCBAM scenario to the WCBAM scenario.

One of the main objectives of this study is to analyze the impact of the EU CBAM on Japan. Therefore, we will take a closer look at the impact on Japan. Table 11 summarizes the impact on Japan. All figures represent the percentage change from the NCBAM scenario to the WCBAM scenario. Both Japan's GDP and welfare have increased with the introduction of the CBAM, indicating that Japan as a whole is positively affected by the EU CBAM. However, as we have already seen in Table 10, the rates of change in GDP and welfare are very small for Japan as well. In this sense, the EU CBAM is not a policy that will significantly impact Japan.

Table 12: Percentage change in the exports, imports, output, and prices of EITE sectors in Japan.

	Export	Import	Output	Price
I_S	-0.32	0.03	-0.05	-0.06
NFM	0.08	0.15	0.00	0.01
CHM	-0.54	-0.34	-0.13	-0.26
OCH	0.06	-0.20	0.07	-0.01
NMM	-3.16	-0.09	-0.42	-0.10
P_C	0.03	0.08	0.07	-0.76

While we have seen that Japan as a whole will be positively (but very minimally) affected by the EU CBAM, the impact on Japan's EITE sectors may be significant. Therefore, let us now examine the impact of the introduction of the EU CBAM on Japan's EITE sectors. Table 12 shows the percentage change in exports, imports, output, and output prices in Japan's EITE sectors. The EU CBAM has resulted in lower output for three goods and lower prices for five goods. Therefore, the introduction of the EU CBAM is likely to harm Japan's EITE sectors. In this sense, Japanese industries' concern about the EU CBAM is correct, but the changes in output and prices are still minimal. Even for NMM, which will see the largest decrease in output, the change in output is only a 0.42% decrease. As we have already seen in Section 4, Japan's EITE sectors originally supplied most of their output to Japan and non-EU regions, and supplies to the EU were very small. While it is true that a negative impact is likely to occur, it is clear that the impact will be very small. Therefore, it cannot be said that the EU CBAM is a policy that needs to be of strong concern.

5.3. Sensitivity Analysis

In Section 5.2, we examined the impact of the EU CBAM. While we were able to obtain a set of results, the results may depend on various assumptions that we made for our analysis. One of these assumptions is the type of CBAM. In the simulation in Section 5.2, we assume the CBAM policy that the EU is planning to introduce. However, there are various types of CBAMs, and they are not necessarily limited to those planned by the EU. Therefore, in this section, we perform a sensitivity analysis by changing the settings concerning the CBAM.[16]

For convenience, we will refer to the case that we have dealt with thus far (WCBAM scenario) as "the reference case." In the reference case, we assume that not only direct emissions but also indirect emissions are included in calculating carbon content. However, since more data are necessary for calculating indirect CO_2 emissions, there will likely be cases where

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[16] Similar analysis was conducted in Takeda et al. (2012).

only direct emissions will be considered in the CBAM. Therefore, we will address the scenario where only direct emissions are used for calculating carbon content.

In the reference case, the CBAM is applied only to the import side. However, the original border adjustment was applied not only to the import side but also to the export side. In other words, the original border adjustment policy included a rebate of the amount paid for the carbon price when goods are exported. Therefore, we will discuss a scenario in which the CBAM is applied not only to the import side but also to the export side.

In the reference case, CO_2 emissions in the exporting country are used for calculating carbon content. While doing so makes sense in that it reflects the actual CO_2 emitted in production, it may be difficult to make the exporting country report accurate carbon content. In addition, calculating CBAM tariff rates based on carbon content in the exporting country would mean that tariff rates would vary from country to country. Such discriminatory tariff rates may violate WTO rules. An alternative measure is to use the carbon content in EU production as a proxy variable. In this way, carbon content can be calculated relatively accurately, and the same uniform tariff may be applied to imports from all regions.

Finally, we consider a scenario in which the sectors covered by the CBAM are changed. In the reference case, EITE plus electricity sectors were covered by the CBAM. However, it may not be appropriate to specifically protect only EITE sectors and the electricity sector. Therefore, we will also consider a scenario in which the sectors covered by the CBAM are changed.

Table 13 summarizes the scenarios of the sensitivity analysis: WCBAM is the reference case scenario; CBAM_2 is the scenario where only direct emissions are included when calculating carbon content; CBAM_3 is the scenario where the CBAM is applied not only to the import side but also to the export side; CBAM_4 is the scenario where EU emissions are used when calculating carbon content; CBAM_5 is the scenario where electricity (ELY) is excluded from the CBAM; and CBAM_6 is the scenario where all sectors in the EU are covered by the CBAM.

The detailed simulation results of the sensitivity analysis are presented in Appendix 1. Here, we provide a brief explanation of the results. First, the leakage rate decreased significantly for CBAM_3, in which the CBAM is also applied to the export side. On the other hand, CBAM_4, which uses EU values for calculating carbon content, showed a smaller decrease in the leakage rate, indicating that the introduction of the CBAM does not change the fact that leakage is reduced. However, the magnitude of the effect can vary greatly depending on the type of CBAM used.

The impact on the GDP and welfare of the EU may improve or worsen depending on the type of CBAM, but in any case, the rate of change in absolute terms is very small, which is the same as in the reference case. The size of the impact on regions outside the EU also varies slightly depending on the type of CBAM. Japan's GDP and welfare will still increase with the introduction of the CBAM (except for one scenario), even if the type of CBAM is changed. The results will also remain the same in that the CBAM tends to negatively impact Japan's EITE sectors, and the fact that the magnitude of the effect on Japan is small also remains unchanged. In sum, we found that changing the type of CBAM does not significantly change the reference case results, except for the leakage rate and the effect on EITE sectors in the EU. Therefore, it can be said that the analysis in Section 5.2 is robust.

Table 13: List of scenarios in the sensitivity analysis.

Scenario	Direct emissions or direct+indirect emissions	Trade covered by CBAM	CO2 coefficient used for CBAM	Sectors covered by CBAM
WCBAM	Direct+indirect	Only import	Exporting region	EITE+ELY
CBAM_2	Only direct	Only import	Exporting region	EITE+ELY
CBAM_3	Direct+indirect	Import+Export	Exporting region	EITE+ELY
CBAM_4	Direct+indirect	Only import	EU CO2 coefficient	EITE+ELY
CBAM_5	Direct+indirect	Only import	Exporting region	Only EITE
CBAM_6	Direct+indirect	Only import	Exporting region	All sectors

6. Concluding Remarks

In this study, we have analyzed the impact of the introduction of the EU CBAM, especially on Japan, using a CGE model. The model is a global multiregional, multisector model with 17 regions and 18 sectors. With this model, we analyze a scenario in which the EU introduces the CBAM under an emissions trading regulation with a US$100 carbon price. The main findings of the analysis are as follows.

First, the EU CBAM results in a significant reduction in carbon leakage from the EU, which indicates that CBAM is very effective as a carbon leakage control measure. Second, the impact of the EU CBAM on GDP was examined, with the result that GDP increases in countries exempted from CBAM and some developed countries, while GDP decreases in many developing countries. Therefore, the EU CBAM policy is rather unfavorable to developing countries. However, the magnitude of change in GDP is generally small, less than 0.1%, and we can say that the CBAM does not significantly impact the GDP of regions outside the EU. We also analyzed the impact on welfare in each country and found a trend similar to the impact on GDP.

From the Japanese perspective, the EU CBAM results in increases in both GDP and welfare, which means that the CBAM is a policy that has a positive impact on Japan as a whole. On the other hand, the output of Japan's EITE sectors tends to decrease due to the CBAM, and the CBAM will harm the EITE sectors. However, we found that the negative impact on the EITE sectors is very small.

In response to various concerns raised over the EU CBAM plan, this study conducted an ex ante and quantitative analysis of the effects of the EU CBAM. We found that, as feared, the introduction of the EU CBAM would have a negative impact on Japan's EITE sectors but that it would have a rather positive impact on the GDP and welfare of Japan. It was also found that the magnitude of the effect, whether positive or negative, is so small that the EU CBAM is not a policy that should be of strong concern. However, the CBAM may have more significance in the future when more stringent emission regulations are introduced in various regions. Therefore, it is desirable to continue research on the CBAM in the future.

7. Acknowledgments

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Appendix

Appendix 1: Results of sensitivity analysis

Table A-1: Leakage rate.

	Leakage rate	Change in leakage rate (% point)					
	NCBAM	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
GBR	1.2	0.2	0.2	0.0	0.1	0.2	0.3
OEU	1.4	0.2	0.2	0.1	0.1	0.1	0.4
JPN	1.3	0.2	0.1	0.1	0.0	0.1	0.4
USA	6.9	0.4	0.2	0.3	0.0	0.4	-0.8
RUS	2.2	-1.6	-0.9	-1.9	-0.6	-1.1	-1.6
CAN	0.6	0.0	0.0	-0.1	0.0	0.0	-0.2
ANZ	0.6	0.1	0.0	0.0	0.0	0.0	0.0
KOR	0.8	0.1	0.0	0.0	0.0	0.0	0.1
CHN	5.2	-1.6	-1.3	-2.8	-0.6	-1.4	-1.3
IND	2.0	-1.2	-1.0	-1.5	-0.2	-1.3	-1.2
BRA	0.5	0.0	0.0	-0.1	0.0	0.0	0.0
TUR	0.7	-0.5	-0.5	-0.7	-0.2	-0.4	-0.5
ASE	2.7	-0.1	-0.1	-0.4	-0.1	-0.1	-1.3
OEX	1.4	-0.3	-0.3	-0.6	-0.1	-0.3	-0.7
MIC	7.2	-2.4	-2.2	-4.0	-1.5	-0.7	-3.0
LIC	0.5	0.0	0.0	-0.2	0.0	0.0	-0.1
Total	35.0	-6.5	-5.7	-11.6	-3.0	-4.3	-9.5

All values except the values in column NCBAM are change in the leakage rate.

Table A-2: Percentage change in output of EITE sectors in EU

	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
I_S	2.43	1.44	3.74	0.55	2.55	1.36
NFM	1.54	-0.21	3.32	0.38	1.74	-0.68
CHM	1.32	0.62	3.39	0.33	1.46	-0.31
OCH	-0.01	-0.14	0.19	-0.10	0.05	-1.04
NMM	2.78	2.60	6.83	1.26	2.84	2.18
P_C	1.07	0.65	2.02	0.79	1.20	0.39
ELY	0.92	0.83	2.63	0.58	0.19	0.59

All values are percentage change from NCBAM values.

Table A-3: Impacts on the EU

	NCBAM	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
Carbon price ($/tCO2)	100.0	102.3	101.9	106.8	100.8	101.0	103.6
CO2 emissions (MtCO2)	2,402	2,404	2,404	2,408	2,403	2,404	2,404
GDP		-0.01	-0.01	-0.02	-0.01	0.00	-0.01
Welfare		0.07	0.04	-0.01	0.03	0.07	0.21
Export		-0.30	-0.22	-0.02	-0.14	-0.23	-1.20
Import		-0.19	-0.15	0.01	-0.09	-0.14	-0.91
Terms of trade		0.35	0.22	0.20	0.14	0.31	0.77

All values are percentage change from NCBAM values unless otherwise indicated.

Table A-4: Impacts on GDP (%)

	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
EUR	-0.006	-0.007	-0.019	-0.005	0.001	-0.006
GBR	0.007	0.004	0.019	0.002	0.006	0.016
OEU	0.007	0.004	0.027	0.003	0.006	0.024
JPN	0.002	0.001	0.000	0.000	0.002	0.007
USA	0.000	0.000	0.000	0.000	0.000	-0.002
RUS	-0.064	-0.035	-0.070	-0.012	-0.059	-0.079
CAN	-0.002	-0.001	-0.003	-0.001	-0.001	-0.007
ANZ	-0.001	-0.001	-0.002	-0.001	-0.001	-0.003
KOR	0.003	0.002	0.004	0.000	0.002	0.005
CHN	-0.005	-0.003	-0.004	-0.001	-0.005	-0.011
IND	-0.004	-0.003	-0.004	0.000	-0.004	-0.001
BRA	0.000	0.000	0.004	0.000	0.000	0.001
TUR	-0.012	-0.007	0.001	-0.005	-0.013	-0.027
ASE	-0.001	-0.001	0.000	-0.001	-0.001	-0.003
OEX	-0.001	-0.001	0.000	-0.001	-0.001	-0.002
MIC	-0.004	-0.003	-0.004	-0.002	-0.004	-0.013
LIC	-0.004	-0.002	-0.005	-0.002	-0.003	-0.005
World	-0.004	-0.003	-0.005	-0.002	-0.002	-0.006

All values are percentage change from NCBAM values.

Table A-5: Impacts on welfare (%)

	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
EUR	0.068	0.040	-0.007	0.031	0.068	0.206
GBR	0.020	0.009	0.087	0.004	0.020	0.032
OEU	0.022	0.008	0.235	0.015	0.019	0.296
JPN	0.026	0.014	0.030	0.004	0.020	0.049
USA	-0.005	-0.003	0.003	-0.006	-0.005	-0.025
RUS	-0.151	-0.090	-0.137	-0.038	-0.142	-0.462
CAN	-0.042	-0.029	-0.058	-0.021	-0.033	-0.107
ANZ	-0.034	-0.023	-0.044	-0.013	-0.027	-0.077
KOR	0.049	0.034	0.070	0.010	0.040	0.072
CHN	-0.038	-0.023	-0.031	-0.010	-0.039	-0.108
IND	-0.050	-0.031	-0.039	-0.007	-0.055	-0.119
BRA	-0.009	-0.008	0.015	-0.007	-0.009	-0.025
TUR	-0.053	-0.036	0.027	-0.028	-0.058	-0.141
ASE	-0.025	-0.018	-0.014	-0.012	-0.020	-0.124
OEX	-0.251	-0.167	-0.299	-0.083	-0.219	-0.426
MIC	-0.059	-0.040	-0.036	-0.023	-0.048	-0.182
LIC	-0.056	-0.033	-0.044	-0.028	-0.047	-0.078
World	-0.010	-0.007	-0.011	-0.003	-0.008	-0.022

All values are percentage change from NCBAM values.

Table A-6: Impacts on Japan.

	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
CO2 emissions	0.088	0.043	0.044	0.012	0.060	0.194
GDP	0.002	0.001	0.000	0.000	0.002	0.007
Welfare	0.026	0.014	0.030	0.004	0.020	0.049
Export	-0.039	-0.032	-0.055	-0.030	-0.037	-0.044
Import	0.024	0.003	0.030	-0.015	0.013	0.065
Terms of trade	0.064	0.036	0.088	0.015	0.052	0.115

All values are percentage change from NCBAM values.

Table A-7: Impacts on output of EITE sectors in Japan.

	WCBAM	CBAM_2	CBAM_3	CBAM_4	CBAM_5	CBAM_6
I_S	-0.05	-0.04	-0.24	-0.01	-0.05	-0.09
NFM	0.00	-0.02	-0.20	-0.04	0.01	-0.06
CHM	-0.13	-0.14	-0.57	-0.16	-0.17	0.14
OCH	0.07	0.07	0.04	0.01	0.06	0.17
NMM	-0.42	-0.37	-1.02	-0.32	-0.42	-0.39
P_C	0.07	0.03	-0.02	-0.01	0.04	0.18

All values are percentage change from NCBAM values.

Appendix 2: Model Description

In this appendix, we provide the algebraic representation of the model.

A-2.1. Notes

- All taxes except lump sum taxes and CBAM-related taxes are omitted for notational simplicity.
- All functions are written in calibrated share form. For the details of calibrated share form, see Böhringer et al. (2003).
- All reference prices are omitted for notational simplicity.

A-2.2. Notations

Sector and primary factor Index

Symbol	Description
OIL	Crude oil.
GAS	Gas.
COA	Coal.
P_C	Petroleum and coal products.
ELY	Electricity.
LND	Land which is a specific factor used only in sector AGR.
RES	Natural resources which are specific factors used only in fossil fuel sectors.

Sets

Symbol	Description
i, j	Index of sectors and goods.
r, s	Index of regions.
EG	Set of all energy goods: OIL, GAS, COA, P_C and ELY.
FF	Set of primary fossil fuels: OIL, GAS, COA.
ES	Set of CO_2 emissions sources: OIL, GAS, COA and P_C.
NRF	Set of primary factors except natural resources: capital, labor and land.

Activity variables

Symbol	Description
Y_{ir}	Output of sector i and region r.
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^I_{ir}	Armington aggregate for good j used for investment in region r
A^G_{ir}	Armington aggregate for good j used for government consumption in region r
M_{ir}	Aggregate imports of good i in region r
U_r	Household utility in r
Y^T_i	Global transport services
INV_r	Investment in region r.
G_r	Government consumption in region r.

Price variables

Symbol	Description
p_{ir}^{Y}	Output price of goods i produced in region r.
p_{ir}^{KLE}	Price of energy-primary factor composite for sector i in region r $(i \notin FF)$.
p_{ir}^{KL}	Price of primary factor composite for sector i in region r $(i \notin FF)$.
p_{ir}^{E}	Price of energy composite for sector i in region r $(i \notin FF)$
p_{jir}^{EF}	Price of energy intermediate goods j for sector i in region r $(j \in ES,\ i \notin FF)$
p_{ir}^{M}	Price of aggregated import for good i imported to region r
p_{irs}^{MM}	CIF price of goods i imported from r to region s.
p_{ijr}^{AF}	Price of Armington good i used for sector j in region r.
p_{ir}^{AP}	Price of Armington good i used for private consumption in region r.
p_{ir}^{AI}	Price of Armington good i used for investment region r.
p_{ir}^{AG}	Price of Armington good i used for government consumption in region r.
p_{r}^{CE}	Price of energy consumption composite in region r
p_{r}^{CNE}	Price of non-energy consumption composite in region r
p_{ir}^{EP}	Price of energy consumption goods i in region r
p_{r}^{U}	Price of household utility in region r
p_{fr}^{F}	Price of primary factor f in region r.
p_{jr}^{R}	Price of natural resources used in sector j in region r
p_{r}^{INV}	Price of investment in region r.
p_{r}^{G}	Price of government consumption in region r.
p_{i}^{T}	Price of global transport service i.
p_{r}^{CO2}	Price of emissions permit for region r.

Cost shares

Symbol	Description
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 intermediate inputs j for sector i and region r $(i \in FF)$
θ_{ir}^{KLE}	Share of energy-primary factor composite for sector i in region r $(i \notin FF)$
θ_{ir}^{KL}	Share of primary factor composite for sector i in region r $(i \notin FF)$
θ_{ir}^{KLE}	Share of energy-primary factor composite for sector i in region r $(i \notin FF)$
θ_{fir}^{F}	Share of primary factor f for sector i and region r $(i \notin FF)$
θ_{jir}^{EG}	Share of energy intermediate input j for sector i and region r $(j \in EG, i \notin FF)$
θ_{ijr}^{AF}	Share of domestic goods in Armington good i used for sector j of region r.
θ_{ir}^{AP}	Share of domestic goods in Armington good i for private consumption in region r.
θ_{ir}^{AI}	Share of domestic goods in Armington good i for investment in region r.
θ_{ir}^{AG}	Share of domestic goods in Armington good i for government consumption in region r.
θ_{isr}^{M}	Share of imports of good i from region s to region r.
θ_{r}^{C}	Share of energy consumption composite in household consumption in region r.
θ_{ir}^{CE}	Share of non-energy good i in non-energy household consumption demand in region r $(i \notin EG)$.
θ_{ir}^{CNE}	Share of energy good i in energy household consumption demand in region r $(i \in$

	EG).
θ_{ir}^{T}	Share of supply from region r in global transport sector i.
θ_{ir}^{INV}	Share of Armington good i in investment in region r.
θ_{ir}^{G}	Share of Armington good i in government consumption in region r.

Income and policy variables

Symbol	Description
H_r^H	Household income in region r
H_r^G	Government income 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
$\overline{INV}_r$	Exogenous level of investment in region r.
$\bar{G}_r$	Exogenous level of government consumption in region r.

Endowments and emissions coefficients

Symbol	Description
$\overline{E}_{fr}$	Total endowment of primary factor f in region r
$\overline{E}_{RES,jr}$	Total endowment of natural resource for sector j in region r ($j \in FF$)
$\overline{B}_r$	Balance of payment deficit or surplus in region r $\left(\sum_r \overline{B}_r = 0\right)$.
$\overline{CO2}_r$	Carbon emission limit for region r.
ϕ_{ijr}	Carbon emissions coefficient for fossil fuel i used for sector j in region r ($i \in ES$).
ϕ_{ir}^{C}	Carbon emissions coefficient for fossil fuel i used for private consumption in region r ($i \in ES$).
ψ_{jr}	Carbon emissions coefficient for industrial process emissions of sector i in region r ($j = NMM$).
τ_{jirs}	Amount of global transport service j required for the shipment of goods i from r to s.

Variables for CBAM

Symbol	Description
τ_{irs}^{M}	CBAM import tariff on import of goods i from r to s.
τ_{ir}^{X}	CBAM export rebate rates on export of goods i from r.
ξ_{ir}	Emissions coefficient (CO_2 per unit of output) including indirect emissions of sector i in region r.

Elasticities of substitution (EOS)

Symbol	Description	Value	Source
σ_{ir}^{R}	EOS between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_i^{FF} ($i \in FF$)	$\mu_i^{FF} = 1$	Böhringer et al. (2021)
σ_i^{KLEM}	EOS between energy-primary factor composite and non-energy intermediate input ($i \notin FF$)		Koesler and Schymura (2015)
σ_i^{KLE}	EOS between energy and primary factor ($i \notin FF$)		Koesler and Schymura (2015)

σ_i^{KL}	EOS between primary factors ($i \notin FF$)		Koesler and Schymura (2015)
σ_i^{E}	EOS between energy intermediate inputs ($i \notin FF$)	$\sigma_i^{E} = 0.5$	Böhringer et al. (2021)
σ_i^{A}	EOS between the import aggregate and the domestic input		Aguiar (2019)
σ_i^{M}	EOS between imports from different regions		Aguiar (2019)
σ^{C}	EOS between energy and non-energy consumption in household utility.	$\sigma^{C} = 0.3$	Böhringer et al. (2021)
σ^{CE}	EOS between energy consumption goods.	$\sigma^{CE} = 0.5$	Böhringer et al. (2021)
σ^{CNE}	EOS between non-energy consumption goods.	$\sigma^{CNE} = 1$	Böhringer et al. (2021)

A-2.3. Model

Zero profit conditions and price variables.

Zero profit for production of fossil fuels ($i \in FF$)

$$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{R} p_{ir}^{R\,1-\sigma_{ir}^{R}} + \left(1 - \theta_{ir}^{R}\right) \left(\sum_{f \in NRF} \theta_{fir}^{FF} p_{fr}^{F} + \sum_{j \notin ES} \theta_{jir}^{NR} p_{jir}^{AF} + \sum_{j \in ES} \theta_{jir}^{NR} p_{jir}^{EF} \right)^{1-\sigma_i^{R}} \right]^{\frac{1}{1-\sigma_i^{R}}} = 0 \qquad \{Y_{ir}\}$$

Zero profit for production of goods except fossil fuels ($i \notin FF$)

$$\Pi_{ir}^{Y} = p_{ir}^{Y} - \left[\theta_{ir}^{KLE} \left(p_{ir}^{KLE}\right)^{1-\sigma_i^{KLEM}} + \left(1 - \theta_{ir}^{KLE}\right) \left\{ \sum_{j \notin EG} \theta_{jir}^{NEG} p_{jr}^{AF} \right\}^{1-\sigma_i^{KLEM}} \right]^{\frac{1}{1-\sigma_i^{KLEM}}} - p_r^{CO2} \psi_{ir} = 0 \qquad \{Y_{ir}\}$$

Price of energy-primary factor composite ($i \notin FF$).

$$p_{ir}^{KLE} = \left[\theta_{ir}^{KL} \left(p_{ir}^{KL}\right)^{1-\sigma_i^{KLE}} + \left(1 - \theta_{ir}^{KL}\right) \left(p_{ir}^{E}\right)^{1-\sigma_i^{KLE}} \right]^{\frac{1}{1-\sigma_i^{KLE}}} \qquad \{p_{ir}^{VA}\}$$

Price of primary factor composite ($i \notin FF$)

$$p_{ir}^{KL} = \left[\sum_{f \in NRF} \theta_{fir}^{F} \left(p_{fr}^{F}\right)^{1-\sigma_i^{KL}}\right]^{\frac{1}{1-\sigma_i^{KL}}} \qquad \{p_{ir}^{VA}\}$$

Price of energy composite ($i \notin FF$)

$$p_{ir}^{E} = \left[\theta_{ELY,ir}^{EG} (p_{ELY,ir}^{AF})^{1-\sigma_i^{E}} + \sum_{j \in ES} \theta_{jir}^{EG} \left(p_{jir}^{EF}\right)^{1-\sigma_i^{E}}\right]^{\frac{1}{1-\sigma_i^{E}}} \qquad \{p_{ir}^{E}\}$$

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

$$p_{ijr}^{EF} = p_{ijr}^{AF} + p_r^{CO2} \phi_{ijr} \qquad \{p_{ijr}^{EF}\}$$

Zero profit for Armington aggregation for intermediate inputs

$$\Pi_{ijr}^{AF} = p_{ijr}^{AF} - \left[\theta_{ijr}^{AF} \left(p_{ir}^{Y}\right)^{1-\sigma_i^{A}} + \left(1 - \theta_{ijr}^{AF}\right)\left(p_{ir}^{M}\right)^{1-\sigma_i^{A}}\right]^{\frac{1}{1-\sigma_i^{A}}} = 0 \qquad \{A_{ijr}^{F}\}$$

Zero profit for Armington aggregation for private consumption

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

Zero profit for Armington aggregation for investment

$$\Pi_{ir}^{AI} = p_{ir}^{AI} - \left[\theta_{ir}^{AI} \left(p_{ir}^{Y}\right)^{1-\sigma_i^{A}} + \left(1 - \theta_{ir}^{AI}\right)\left(p_{ir}^{M}\right)^{1-\sigma_i^{A}}\right]^{\frac{1}{1-\sigma_i^{A}}} = 0 \qquad \{A_{ir}^{I}\}$$

Zero profit for Armington aggregation for government consumption

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

Zero profit for aggregation of imports from different regions

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

CIF price of imports

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

Zero profit for the household utility

$$\Pi_r^U = p_r^U - \left[\theta_r^C \, (p_r^{CE})^{1-\sigma^C} + (1-\theta_r^C)(p_r^{CNE})^{1-\sigma^C}\right]^{\frac{1}{1-\sigma^C}} = 0 \qquad \{U_r\}$$

Price of energy consumption composite

$$p_r^{CE} = \left[\theta_{ELY,r}^{CE}\left(p_{ELY,r}^{AP}\right)^{1-\sigma^{CE}} + \sum_{i \in ES} \theta_{ir}^{CE}\left(p_{ir}^{EP}\right)^{\theta_{ir}^{1-\sigma^{CE}}}\right]^{\frac{1}{1-\sigma^{CE}}} \qquad \{p_r^{CE}\}$$

Price of non-energy consumption composite

$$p_r^{CNE} = \left[\sum_{i \notin EG} \theta_{ir}^{CNE}\left(p_{ir}^{EP}\right)^{\theta_{ir}^{1-\sigma^{CNE}}}\right]^{\frac{1}{1-\sigma^{CNE}}} \qquad \{p_r^{CNE}\}$$

Price of energy consumption goods ($i \in ES$)

$$p_{ir}^{EP} = p_{ir}^{AP} + p_r^{CO2}\phi_{ir}^C \qquad \left\{p_{ir}^{EP}\right\}$$

Zero profit for global transport sector

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

Zero profit for investment

$$\Pi_r^{INV} = p_r^{INV} - \sum_i \theta_{ir}^{INV} p_{ir}^{AI} = 0 \qquad \{INV_r\}$$

Zero profit for government consumption

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

Market Clearance Conditions

Markets for capital and labor ($f = K, L$)

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

Market for land

$$\bar{E}_{LND,r} = -Y_{AGR,r} \frac{\partial \Pi_{AGR,r}^Y}{\partial p_{LND,r}^F} \qquad \left\{p_{LND,r}^F\right\}$$

Markets for natural resources ($j \in FF$)

$$\bar{E}_{RES,jr} = -Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{jr}^{R}} \qquad \{p_{jr}^{R}\}$$

Output

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

Aggregated import

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

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 private consumption

$$A_{ir}^{P} = -U_{r} \frac{\partial \Pi_{r}^{U}}{\partial p_{ir}^{AP}} \qquad \{p_{ir}^{AP}\}$$

Armington aggregate for investment

$$A_{ir}^{I} = -INV_{r} \frac{\partial \Pi_{r}^{INV}}{\partial p_{ir}^{AI}} \qquad \{p_{ir}^{AI}\}$$

Armington aggregate for government consumption

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

Household utility

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

Investment

$$INV_{r} = \overline{INV_{r}} \qquad \{p_{r}^{INV}\}$$

Government consumption

$$G_{r} = p_{r}^{G} H_{r}^{G} \qquad \{p_{r}^{G}\}$$

Global transport service

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

Emissions permit

$$\overline{CO2}_r = \sum_{i \in ES} \left[\sum_{j} A^F_{ijr}\phi_{ijr} + A^P_{ir}\phi^C_{ir} \right] + Y_{NMM,r}\psi_{NMM,r} \qquad \{p_r^{CO2}\}$$

Income definition.

Income of the representative household

$$H_r^H = \sum_{f \in MF} p^F_{fr}\, \bar{E}_{fr} + \sum_{j \in FF} p^R_{jr} \bar{E}_{RES,j} + p_r^{INV} INV_r + p^C_{USA} \overline{B}_r - p_r^C T_r^{LUMP} \qquad \{H_r^H\}$$

Government income

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

Lump-sum transfer (tax) to household

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

Permit revenue

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

Equations for CBAM

CBAM import tariff rates (WCBAM)

$$\tau^M_{isr} = p_r^{CO2} \xi_{is} \qquad \{\tau^M_{isr}\}$$

CBAM import tariff rates (CBAM_4)

$$\tau^M_{isr} = p_r^{CO2} \xi_{ir} \qquad \{\tau^M_{isr}\}$$

CBAM export rebate rates (CBAM_3)

$$\tau^X_{ir} = p_r^{CO2} \xi_{ir} \qquad \{\tau^X_{ir}\}$$