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EU Carbon Border Adjustment Mechanism:

A Game-Theoretic Analysis of Impact on the Republic of Korea

Master Thesis

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Abstract

In July 2021, the European Union (EU) announced a Carbon Border Adjustment Mechanism (CBAM) as part of the 'Fit for 55' packages. It seeks to achieve a new ambitious target for 2030 of reducing greenhouse gas emissions by 55% compared to the 1990 level as well as to become the first climate-neutral continent in the world by 2050. Implementing the EU CBAM is anticipated to negatively affect the exports and welfare of several countries that actively trade with the EU, including the Republic of Korea. Thus, finding an appropriate policy option for each country becomes crucial to ensuring its welfare and competitiveness in international trade.

In this thesis, we provide a qualitative assessment of the EU CBAM and suggest the best response for Korea and the rest of the world (RoW). We adapted a model originally established by Eichner & Pethig (2013), which allows us to analyze the international trade of CBAM products. Using the game-theoretic model, we examine the impact of the EU CBAM on non-EU countries under two policy options: The non-EU countries may (1) exempt domestic GHG emission tax on CBAM exports to the EU, or (2) tax all domestic production of CBAM products and get a remission of carbon border tax from the EU. Our numerical illustration has shown that the EU's CBAM exports increase, but Korea's and the RoW's decrease under the EU CBAM. In addition, the EU's and Korea's welfare are better off with the second policy option than the other, while the RoW's welfare is better off with the first policy option. Our sensitivity analysis also shows that global GHG emissions and welfare of each country are sensitive to the EU-ETS prices. Therefore, we suggest that the EU should be careful in designing the CBAM and set a proper level of EU-ETS price to ensure its welfare and to achieve the reduction target of global GHG emissions.

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List of Abbreviations

CBAM	Carbon Border Adjustment Mechanism
CBT	Carbon Border Tax
CGE	Computable General Equilibrium
EU	European Union
EU-ETS	European Union Emissions Trading System
FOC	First-order condition
GATT	General Agreement on Tariffs and Trade
GHG	Greenhouse Gas
K-ETS	Korean Emissions Trading System
MRV	Measurement, Reporting, and Verification
NDCs	Nationally Determined Contributions
RoW	the Rest of the World
SSP	Shared Socio-economic Pathway
WTO	World Trade Organization

Chapter 1. Introduction

1.1 Climate Crisis and EU Carbon Border Adjustment Mechanism (CBAM)

The 17th edition of the Global Risks Report (World Economic Forum, 2022) showed that 'Climate action failure' and 'Extreme weather' were ranked as the top two critical risks. These risks will threaten the world's societies and economies over the medium (2~5 years) and the long (5~10 years) term with the high probability. The World Economic Forum (2022) also highlighted that half of the ten most critical risks in the world over the next decade are environmental risks. Besides, the European Commission (2019b) warned that the EU would lose €190 billion annually when the global average temperature increases by 3℃. Moreover, they pointed out that the EU could experience a 20% rise in food prices by 2050 and spend more than €40 billion of economic costs annually on heat-related mortality.

Most countries already have agreed that anthropogenic climate change is a serious issue. Hence, they have been trying to avoid the climate crisis by joining the well-known 2015 Paris Agreement. Its goal is to limit the increase of global average temperature to well below 2℃ and pursue efforts to restrict it to 1.5℃ compared to pre-industrial levels by reducing Greenhouse Gas (GHG) emissions (United Nations, 2015). Additionally, 197 countries achieved an alignment on the Glasgow Climate Pact and made other pledges at the United Nations Climate Change Conference (COP26) in 2021 (United Nations, 2021). One of the main goals of the Glasgow Climate Pact is to reduce GHG emissions. They plan to reduce emissions by 45% compared to 2010 by 2030 and achieve carbon neutrality by 2050 to meet the Paris Agreement goal (UNFCCC, 2021).

However, during the COP26, the Climate Action Tracker (2021) warned that the global temperature would increase by 2.1℃ compared to the pre-industrial level, even if all parties would achieve 2030 Nationally Determined Contributions (NDCs) and long-term targets, as shown in Figure 1. Moreover, the IPCC's recent Sixth Assessment Report (2021) highlighted that global surface temperature will keep rising until 2050 under all Shared Socio-economic

Pathways (SSP), despite our efforts. As climate change risks become more complex and difficult to handle, the IPCC (2021 & 2022) called for strong, rapid, and sustained global efforts to limit global warming.

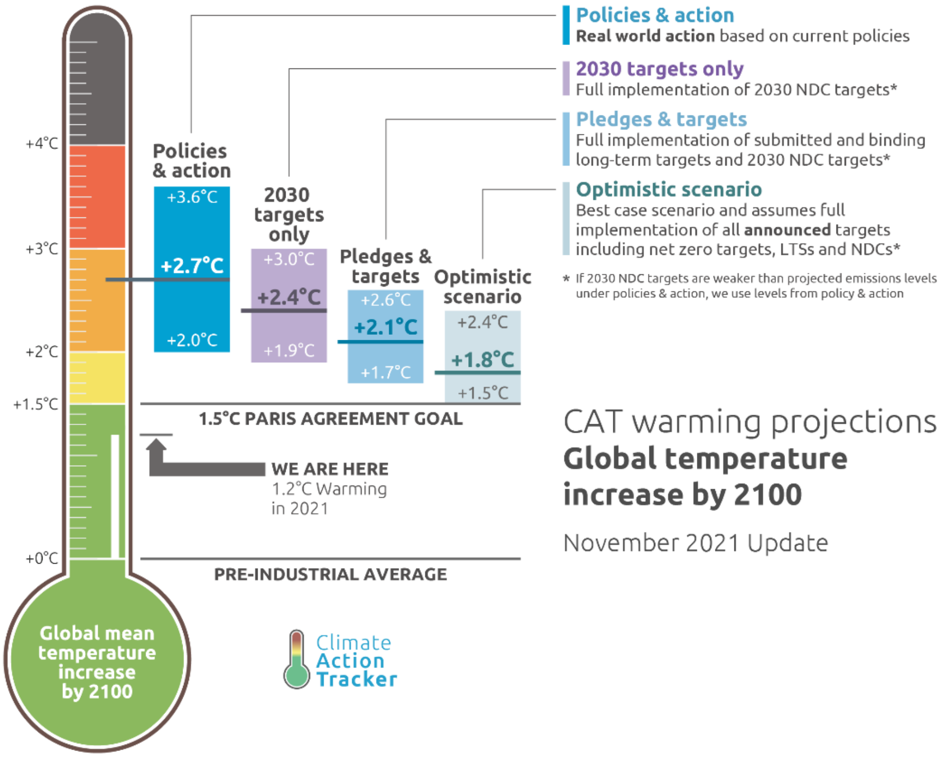

Figure 1. Updated comparison of global mean temperature increases by scenario (Climate Action Tracker, 2021)

Since it becomes imperative and urgent to reach net-zero anthropogenic GHG emissions for stabilizing global surface temperature increases, the European Commission (2021b) proposed a Carbon Border Adjustment Mechanism (CBAM) as part of the 'Fit for 55 Package' in July 2021. The EU CBAM aims to achieve a climate-neutral EU by 2050 and a new ambitious EU target for 2030 of reducing GHG emissions by 55% compared to the 1990 level (European Commission, 2021a). Under the CBAM regime, EU importers will purchase CBAM certificates mirroring the carbon price under the EU Emissions Trading System (ETS) (European Commission, 2021a). If a producer from a non-EU country proves that a carbon price has already been paid in the origin country, the corresponding cost may be deducted from the carbon border tax (CBT) (European Commission, 2021a & 2021c). This mechanism will be initiated gradually from 2023 onward and be applied first to goods with a high risk of GHG emissions and carbon leakages, such as cement, aluminum, fertilizers, iron and steel, and electrical energy (European Commission, 2021a). It is expected to decrease carbon leakage and aims to increase the welfare of the country that operates stricter climate policies (Felbermayr et al., 2020).

As the implementation of CBAM is officially confirmed, previous studies have shown that the EU CBAM will negatively affect the exports and welfare of the Republic of Korea (hereafter 'Korea'). Greenpeace (2021) warned that Korea would face a large amount of CBT since Korea's economy is export-oriented and relies heavily on carbon-intensive industries. They highlighted that the CBT on the iron and steel sector might account for 12.26% of its total exports under the $75/t$CO_2$ CBT scenario in 2030 based on the export data in 2019 (Greenpeace, 2021).

Moon et al. (2020) showed that the EU's consumer welfare would rise due to increased trade within the EU and increased production of CBAM products. However, they mentioned that EU trading partners' exports to the EU and their welfare would decrease. For example, if the EU imposes a CBT on cement, iron and steel, Korea's consumer welfare will reduce by $12.6 million, but the EU's welfare will increase by $82.0 billion (Moon et al., 2020).

Kim and Son (2021) pointed out that Korea's steel and aluminum sectors would be considerably affected by the CBAM since these are the major exporting industries to the EU. They argued that producers who are not subject to the EU CBAM or have no exports to the EU should not be indifferent to this international environmental regulation because international trade is interconnected through the value chain and climate policies usually affect the entire world. They also predicted that the scope of EU CBAM could extend to indirect emissions, other industrial sectors, and services such as transportation. Furthermore, Korea's welfare and exports will suffer more negative effects when other countries like the United States implement CBAM as well. Then, Korea will be significantly affected in the mid-to-long term (Kim & Son, 2021).

1.2 Research Questions and Structure

Despite the approaching implementation of the EU CBAM, research on this issue has not been sufficient. Most of the studies dealt with the compatibility with the World Trade Organization (WTO) General Agreement on Tariffs and Trade, shortly GATT, and analyzed the impact of the EU CBAM on Korea's economy using outdated data or not reflecting recently updated regulations. Furthermore, some argued that the Korean government should link Korean Emissions Trading System (K-ETS) to the EU-ETS to get a remission of CBT, but not much detailed research has been conducted to support this. Therefore, we would like to overcome these limitations by mirroring the latest CBAM regulation updated in 2022 and recent trade data from 2016 to 2020.

We aim to provide a qualitative assessment of the EU CBAM and propose the best response for Korea and the rest of the world (hereafter 'the RoW') by considering two policy options in non-EU countries: (1) Tax exemption on exports to the EU and (2) Taxation on all domestic production, through the following two research questions:

(a) When the EU implements a CBAM regime, how much will Korea and the RoW be affected compared to the current situation?

(b) Will Korea's welfare really be better off if Korea links the K-ETS to the EU-ETS and gets a remission of CBT for exports to the EU as the previous studies recommended?

To answer these questions, we first introduce a simple game-theoretic model of strategic international trade with specific assumptions and find the Nash equilibrium in each policy option. Then, we conduct a numerical illustration with Eurostat trade data for five years from 2016 to 2020 to examine how each country's welfare changes in response to policy options and the EU-ETS prices.

Our study shows three meaningful results. First, when the EU CBAM is implemented, exports of CBAM products increase in the EU, but exports decrease in Korea and the RoW. Second, the second policy option is better for the EU and Korea, while the first policy option is better for the RoW. Last but not least, the EU should be careful in setting an appropriate level of EU-ETS price to ensure its own welfare and to reach the reduction goal of global GHG emissions. This is because the EU-ETS prices impact both global GHG emissions and the EU's welfare. For example, global GHG emissions decrease as the EU-ETS price increases. In terms of EU welfare, the higher EU-ETS price leads to lower welfare in the first policy option but higher welfare in the second policy option.

This master's thesis is structured as follows. Chapter 2 offers an overview of the EU CBAM with its background, objectives, and updated operation plans. This chapter also provides the status of Korea, including the K-ETS. Chapter 3 describes how we establish the game-theoretic model without and with the CBAM regime, and Chapter 4 shows a numerical illustration. Chapter 5 discusses the results of the numerical illustration and compares them with previous studies. Finally, Chapter 6 concludes the thesis.

Chapter 2. Literature Review

2.1 EU Carbon Border Adjustment Mechanism (CBAM)

2.1.1 Background

In December 2019, the European Commission (hereafter 'the Commission') announced the European Green Deal, the aim of which is to become the first climate-neutral continent by 2050. The European Green Deal is a comprehensive roadmap to preserve the EU's natural resources and protect its citizens from environmental risks and impacts (Kim & Kim, 2020; European Commission, 2021c). The strategy includes reducing GHG emissions, decarbonizing the energy sector, renovating buildings to increase energy efficiency, and supporting sustainable mobility and innovative industries (European Commission, 2019a). The Commission also heralded the implementation of EU CBAM as a toolbox to meet its goal by 2050. In the following year, the European leaders agreed to raise its GHG emissions reduction target in 2030 from 40% to 55% compared to 1990 levels (European Commission, 2021c), and the EU's ambitious goal of 2050 climate neutrality was legislated by the European Climate Law in June 2021 (Kim & Kim, 2020).

In July 2021, the Commission (2021b) announced the 'Fit for 55' package with the CBAM, as mentioned previously. The 'Fit for 55' consists of 12 inter-connected proposals to achieve the EU's GHG reduction goal in 2030 (Faggiano, 2021). These policy proposals are well-balanced between pricing (including CBAM), targets, rules, and support measures (European Commission, 2021b).

2.1.2 Carbon Border Adjustment Mechanism (CBAM)

As a part of the 'Fit for 55' package, the CBAM is expected to be a practical economic tool to accomplish climate neutrality by 2050, since the EU is the world's largest GHG emissions net importer (Felbermayr et al., 2020; European Commission, 2021c). The CBAM has economic, environmental, and political objectives (Kim & Kim, 2020). Firstly, the economic objective of the CBAM is to protect the EU's industrial competitiveness. Since the EU is increasing its climate ambitions, producers in the EU have to expend more costs than before, which increases consumer prices. It leads to a decline in the EU's industrial competitiveness in the international market (Kim & Kim, 2020). Therefore, the CBAM implementation would re-establish fair competition with foreign firms (Faggiano, 2021).

Secondly, the environmental objective is to prevent carbon leakage (European Commission, 2021c). Carbon leakage happens when the EU producers move their carbon-intensive installations to foreign countries having less or no environmental regulations to avoid the EU's stringent environmental regulations (direct leakage). In addition, it occurs when the world price of fossil fuels declines due to the reduction of the EU's fossil fuel consumption, causing incentives to increase fossil fuel consumption in non-EU countries (indirect leakage) (Felbermayr et al., 2020; Kim & Kim, 2020; European Commission, 2021a). According to Felbermayr et al. (2020), the embodied carbon imports increased by 8% from non-committed countries to committed countries under the Kyoto Protocol. Hence, the CBAM is proposed to avoid offsetting the EU's efforts to reduce global GHG emissions (European Council, 2022a).

Lastly, the political objective is to invite foreign countries to raise their climate ambitions (Kim & Kim, 2020). Climate change depends on global GHG emissions, and we need international efforts to solve this issue (European Commission, 2021a; Lee et al., 2022). However, it is hard to achieve the ambitious global GHG emission reduction goal, as countries are lukewarm about climate change due to free-riding incentives (Kim et al., 2021). The CBAM reduces the free-riding benefits and, thus, gives incentives to other countries to reduce their GHG emissions, too (European Commission, 2021a & 2021c; Rocchi et al., 2018). Therefore, this mechanism will be an essential economic tool for becoming climate-neutral by reducing carbon leakage (European Commission, 2021c).

The CBAM works by imposing a tariff on imports from non-EU countries having weaker environmental regulations than the EU. It is not a unilateral tariff, because adjustments can take place based on explicit carbon pricing, such as carbon tax and ETS, in foreign countries (Moon et al., 2020). For example, when the EU's carbon price is t_{EU} and country A's carbon price is t_A, the fully adjusted CBT τ is $t_{EU} - t_A$ (Moon et al., 2020). Therefore, companies from both countries can compete fairly in the EU, as they face the same tax burden.

Products under the EU CBAM are determined by three criteria, whether the sector is: (1) one of the largest sources of GHG emissions, (2) at a considerable risk of carbon leakage, and (3) needs to balance GHG emissions while limiting administrative burdens and complexity (European Commission, 2021c). Based on these criteria, the Commission announced five industrial sectors: cement, aluminum, fertilizers, iron and steel, and electricity (European Commission, 2021c). During the transitional period, the EU may consider only direct emissions, but there is a possibility of expanding to indirect emissions, according to the European Parliament (2022a) in June 2022. Here, 'direct emissions' mean GHG emissions during the production processes of goods, and 'indirect emissions' mean GHG emissions from electricity production to produce goods (European Commission, 2021a; European Council, 2022b).

If the CBAM is implemented as planned, importers need to apply for authorization before importing goods from foreign countries to the EU from January 2023 (European Commission, 2021c). By May 31st every year, the EU importers have to submit CBAM declarations and carbon certificates (European Commission, 2021a & 2021c). The price of CBAM certificates is calculated based on the average EU-ETS closing prices, and it applies from the next working day until the first working day of the following week (European Commission, 2021c). The embedded emissions of goods are calculated according to the regulation, but if actual emissions cannot be measured, default values will be applied (European Commission, 2021c). The EU has not yet decided on how to calculate the default values.

According to Article 9 of the CBAM regulation, the carbon price already paid in the country of origin can be subtracted from the CBT of the EU (Assous et al., 2021). An agreement with the EU is required to get a remission of CBT or an exemption from the CBAM obligation (European Commission, 2021c). The EU will only reduce the carbon price considering any rebate or compensation in the country of origin (European Council, 2022b). Free allocation will be applied to the EU CBAM, but it will phase out depending on the finalized CBAM regulation.

Recently, the European Parliament decided its position on the CBAM regulation, showing higher climate ambition than the Commission's and the EU Council's (European Parliament, 2022a). The negotiation with member states for the final draft of the CBAM regulation is still going, but it implies that the EU will expand the scope of goods and emissions and phase out free allocations for sure. Table 1 shows the summary of positions of the Commission, the EU Council, and the EU Parliament.

	EU Commission	*EU Council*	*European Parliament*
Released date	July 2021	March 2022	June 2022
Industrial Sectors	Cement Aluminum Fertilizers Iron and steel Electrical energy	Cement Aluminum Fertilizers Iron and steel Electrical energy	Cement Aluminum Fertilizers Iron and steel Electrical energy Organic chemicals Plastics Hydrogen Ammonia
Emissions	Direct	Direct	Direct + Indirect
Transitional period	2023 ~ 2025 (3 years)	2023 ~ 2025 (3 years)	2023 ~ 2026 (4 years)
Free allocation plan	Phase-out by 10% each year from 2026 to 2035	95% in 2026 90% in 2027 85% in 2028 77.5% in 2027 70% in 2030 60% in 2031 50% in 2032 35% in 2033 20% in 2034 0% in 2035	100% in 2023~2026 93% in 2027 84% in 2028 69% in 2029 50% in 2030 25% in 2031 0% in 2030

Table 1. Summary of positions of the EU Commission, the EU Council, and the EU Parliament (European Commission, 2021c; European Council, 2022b; European Parliament, 2022a; KOTRA, 2022)

The European Parliament (2022b) gave a briefing that the CBAM will be implemented from 2023 as planned, as shown in Figure 2. During the transitional period, foreign countries do not have to pay carbon border taxes to the EU. Instead, they need to submit quarterly reports, including quantities of imports, direct and indirect emissions, and carbon prices paid in the countries of origin (KOTRA, 2021).

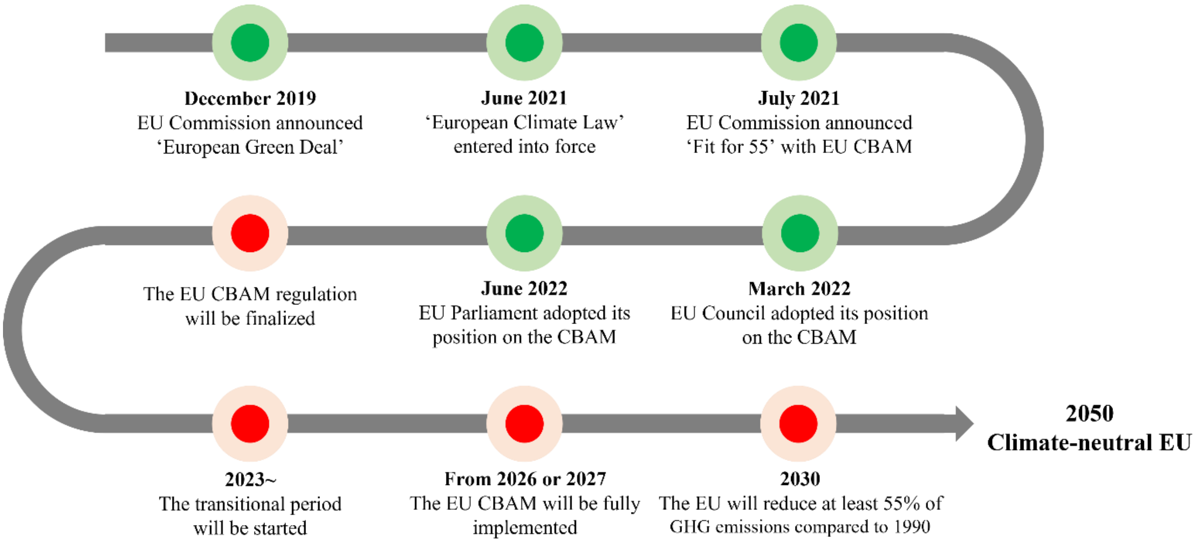

Figure 2. The EU CBAM timeline from European Green Deal to 2050 climate-neutral EU

2.1.3 Controversies about EU CBAM

There are some controversies regarding the compatibility of the CBAM with the WTO GATT. Some claim that the EU CBAM violates Article III of the GATT, the National Treatment Principle, which states that there should be no discrimination between domestic goods and imports (Assous et al., 2021). However, Assous et al. (2021) and Böhringer et al. (2022) pointed out that there is no discrimination against non-EU countries since the price of the CBAM certificates mirrors the EU-ETS price. Lee et al. (2021) also argued that it is not necessary to accurately identify the measurements applied to the EU goods and imports, according to the judgments of DS161 (Korea-various measures on beef) and DS26 (EC-Hormones).

Lee et al. (2021) stated that the EU CBAM is working in a compatible way with WTO in general. Nonetheless, they are concerned that there is a possibility of violating the GATT regarding the default value of carbon intensity of goods. If an exporting company lacks technology, capability, and financial resources for measurement, reporting, and verification (MRV) of its emissions, the default value will be applied according to the CBAM regulation (Lee et al., 2021; European Commission, 2021c; European Council, 2022b; European Parliament, 2022b). Here, the problem is that the default value of carbon intensity is based on the average carbon intensity of the 10% worst performing installations in the EU, according to the Commission (2021c). Since this default value is not applied to the EU producers, the non-EU producers can be disadvantaged (Lee et al., 2021). Therefore, the EU should ensure opportunities for importers to prove that their actual emissions are better than default values and guarantee that imports are not treated more unfavorably than domestic EU products (Lee et al., 2021).

2.2 Status of Korea

Korea's economy is export-oriented (Choi et al., 2017). According to Greenpeace (2021)'s report, approximately 40% of Korea's GDP accounts for exports in 2019, much higher than the world average of 30%. Hence, Korea is sensitive to changes in the global trade environment. In addition, Korea's total energy consumption is around 1.7 times higher than OECD countries' average, because its major exporting industries, such as iron and steel, heavy chemicals, and electrical and electronic products, exhibit energy-intensive production processes (Choi et al., 2017). Moreover, in 2019, 40.4% of Korea's total power production relied on coal power, higher than other developed countries like Germany (30%) and the United States (24%) (Greenpeace, 2021). On the other hand, renewable energy generation in Korea accounts for only 4.8%, much lower than in Germany (41.2%) (Greenpeace, 2021). Consequently, relying heavily on exports, carbon-intensive industries, and coal power generation has lead Korea to become the 6th largest CO_2 net exporter based on the average CO_2 embodied in gross exports to the world between 2016 and 2018, as shown in Table 2. Korea is also one of the top 10 CO_2 net exporters to the EU27 among non-EU countries (Table 3). The average CO_2 embodied in gross exports is calculated based on the data from OECD Statistics (2021). Additionally, Dumitru et al. (2021) have shown that Korea is the 6th largest exporter of CBAM products to the EU27, following Russia, Turkey, the United Kingdom, China, and Ukraine (Figure 3). In this regard, Korea should pay attention to the EU's decision on the EU CBAM and prepare for it in advance.

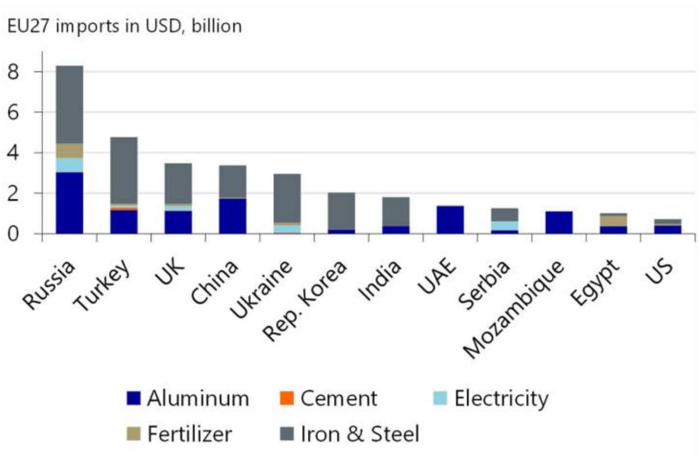

Figure 3. Korea is the 6th largest exporter of CBAM products to the EU27 (Dumitru et al., 2021)

	Country	*CO_2 embodied in gross exports to the World [mil. tCO_2]*			
		2016	***2017***	***2018***	***3yrs Average***
1	China	870.6	945.2	895.5	903.8
2	Russia	342.8	301.9	343.5	329.4
3	South Africa	138.4	135.2	122.5	132.0
4	India	132.4	102.1	106.1	113.5
5	Taipei	72.8	81.0	77.0	77.0
6	South Korea	80.4	53.5	54.3	62.7
7	Singapore	58.3	60.3	62.2	60.3
8	Thailand	66.0	55.9	41.8	54.6
9	Canada	42.3	41.1	53.1	45.5
10	Malaysia	46.3	40.7	46.5	44.5

Table 2. Top 10 CO_2 net exporters to the world. Data from OECD. Stat, Carbon dioxide emissions embodied in international trade (2021 ed.)

	Country	*CO_2 embodied in gross exports to the EU27 [mil. tCO_2]*			
		2016	***2017***	***2018***	***3yrs Average***
1	China	157.9	166.5	178.4	167.6
2	Russia	150.0	134.6	137.5	140.7
3	India	32.5	34.5	40.8	35.9
4	Kazakhstan	16.5	18.7	20.3	18.5
5	South Africa	16.4	16.8	14.6	15.9
6	Turkey	11.8	12.1	22.5	15.5
7	Viet Nam	11.9	13.5	15.9	13.8
8	Thailand	13.4	13.6	13.6	13.6
9	South Korea	9.7	10.2	9.9	9.9
10	Taipei	8.2	9.4	9.9	9.2

Table 3. Top 10 Non-EU CO_2 net exporters to the EU27. Data from OECD. Stat, Carbon dioxide emissions embodied in international trade (2021 ed.)

Park et al. (2021) highlighted that Korea faces transition risks upon the EU CBAM implementation due to its carbon-intensive industry-oriented economy. Transition risks appear when the climate policies to mitigate physical risks affect the real economy (Park et al., 2021). Korea does not have significant physical risks from natural disasters, but the physical risks of other countries can be transferred through the global supply chain and make Korea's competitiveness weaker and decrease its exports (Park et al., 2021).

Magacho et al. (2022) explained the potential impacts of the CBAM on five industrial sectors (HS2523, HS2716, HS3102, HS72, and HS76), which are listed on the CBAM regulation. They assumed an EU carbon tax of $60/tCO2 and no tax in non-EU countries. They concluded that the iron and steel industry would be the most impacted sector in Turkey, the United States, Brazil, India, South Africa, and Korea.

Greenpeace (2021) analyzed the impact of the EU CBAM on Korea's industries when the EU is imposing \$75/tCO_2, \$100/tCO_2, and \$300/tCO_2 of CBT each in 2030. They demonstrated that Korea would face additional costs of $347.7 million on iron and steel and $229.8 million on petrochemicals under the \$75/tCO_2 CBT scenario. In particular, they mentioned that the CBT on the iron and steel sector might account for 12.26% of its total exports in 2030 based on the export data in 2019. Under the \$100/tCO_2 CBT scenario, Korean firms would need to pay an additional $825.1 million to the EU. Moreover, $2.48 billion of CBT would be charged to Korean firms under the \$300/tCO_2 CBT scenario (Greenpeace, 2021).

Lee et al. (2021) showed that the iron and steel sector accounts for 95.2% and aluminum for 4.8% of goods listed on CBAM in terms of average exports to the EU from 2017 to 2019. Among iron and steel products, HS7210 accounts for 33.5%, HS7208 for 15.4%, and HS7219 for 9.4%. They mentioned that the export of iron and steel (HS7210 and HS7208) to the EU has increased rapidly since 2015. Therefore, they warned that companies exporting those goods to the EU would be seriously hit. On the other hand, Korea exports only a small amount of cement and no electricity to the EU (Lee et al., 2021). Moon et al. (2021) also warned about the iron and steel industry. They conducted research on the economic impact of EU CBAM by using a Computable General Equilibrium (CGE) model, assuming a €30/tCO_2 CBT. The result showed that iron and steel production in Korea would decrease by 0.25% (Moon et al., 2021).

Moon et al. (2020) carried out a study on changes in consumer welfare when the EU imposes CBT on iron and steel, and cement by using a CGE model. They showed that the trade between EU countries would increase, and the consumer welfare of the EU would also increase by $82.03 million. However, Korea's consumer welfare would decrease by $12.6 million because of the decline in production and exports (Moon et al., 2020). They emphasized that Korea's iron and steel industry would face a decrease in production by 0.25% and exports to the EU by 11.69%.

Yoon (2022) recently published a research paper about the economic effect of CBAM. He analyzed 2014 GTAP data with a CGE model. He targeted 14 industries and ten countries, including EU28, Korea, and Japan. He analyzed two policy scenarios and compared them with the baseline scenario, which is the case without CBAM. The first scenario is when the EU imposes a €30/tCO_2 CBT on every import. In this case, the EU's consumer welfare increases significantly, but the other countries' welfares decrease except for Japan because of its low carbon emissions. The second scenario is when the EU imposes €30/tCO_2 on five industrial sectors based on the current CBAM regulation draft (Yoon, 2022). The EU's welfare also increases in this case. Besides, Korea's welfare increases slightly, because exports to other countries increase, despite a drop in exports to the EU. For example, fertilizer exports to the EU fall by 0.22 percent, but exports to China, Russia, and the United States rise by 0.26 percent (Yoon, 2022).

Kim et al. (2021) from the Bank of Korea stated that if Korea increases the K-ETS price and gets a CBT reduction from the EU, the negative impact will be reduced. They assumed an EU's CBT of $50/t$CO_2$ and a K-ETS's price of $15/t$CO_2$. Then, they compared the results regarding whether Korea received a CBT reduction. When Korea got a reduction and paid only $35/t$CO_2$ as CBT to the EU, the exports decreased by 0.3% per year, which is 0.2% per year lower than without getting a reduction. Moreover, they found that if Korea's CBT burden is relatively small compared to its export competitors, its market share in the EU will rise, and exports to the EU will increase. Korea's export to the EU will rise by 0.06% since the competitiveness of China, the world's largest CO_2 emitter, will decrease (Kim et al., 2021).

Many of these previous studies have shown that the EU CBAM will have a negative impact on Korea's economy, and it is important to reduce CBT by signing an agreement with the EU in recognition of K-ETS being equal to EU-ETS to overcome the negative impact. We will see whether Korea can link K-ETS to EU-ETS in the next chapter.

2.3 EU-ETS and K-ETS

Since the K-ETS has benchmarked the EU-ETS from the beginning, the Korean government is trying to promote K-ETS to demonstrate similarities with EU-ETS and to get a CBT remission for its exports. According to the European Commission (2016), the EU supported Korea's first implementation of a national emissions trading system in East Asia through a €3.5 million cooperation project from 2016 to 2019. The EU provided technical support such as emissions trading, GHG emissions verification, and allocation methods at the beginning of the K-ETS (European Commission, 2016).

	EU-ETS	***K-ETS***
Phases	Phase 1: 2005~2007 Phase 2: 2008~2012 Phase 3: 2013~2020 **Phase 4: 2021~2030**	Phase 1: 2015~2017 Phase 2: 2018~2020 **Phase 3: 2021~2025**
GHG Coverage	CO_2, N_2O, PFCs	CO_2, CH_4, N_2O, SF_6, HFCs, PFCs
GHG emissions	Direct	Direct + Indirect
Sector Coverage	Power Industry Transport (Aviation in the EU)	Power Industry Transport (Domestic Aviation) Buildings Waste Public services/other sectors
Coverage of total GHGs	36%	68%
Free allocation	Power 0% Industry 30% Aviation 82%	90%
ETS Price in 2021	\$50/tCO_2	\$16/tCO_2

Table 4. Comparison between the EU-ETS and the K-ETS (Niederhafner & Lee, 2013; Son & Kim, 2021; Greenhouse Gas Inventory and Research Center, 2022)

As shown in Table 4, the EU-ETS and K-ETS have many similarities with each other, and Korea is stricter in some areas than the EU. For instance, K-ETS covers more greenhouse gases and sectors than the EU-ETS. Therefore, the coverage of total GHGs is 32% larger than in the EU. Moreover, K-ETS covers both direct and indirect emissions, which makes it easier to get a remission of CBT in the future. However, there are huge differences making it difficult to connect K-ETS to the EU-ETS in terms of ETS price and free allocation ratio. Nevertheless, Shin (2022) argued that Korea could overcome this gap between the price of K-ETS and EU-ETS. He analyzed that the current price of the K-ETS is much lower than the EU due to the earlier closure of coal power generation than expected and restrictions on coal power generation to reduce fine dust, causing a decrease in permit demand. Therefore, Shin (2022) recommended operating the Market Stability Reserve (MSR) in Korea to narrow the price gap with the EU ETS. Here, the MSR is a system to prevent major fluctuations in permit prices, as shown in Figure 4 (Dutch Emissions Authority, 2015). It stabilizes the permit market by setting aside emission allowances if a surplus is larger than the upper limit and returning the emissions allowances to the auctions if a surplus is smaller than the lower limit (Dutch Emissions Authority, 2015).

Figure 4. EU's Market Stability Reserve (MSR) (Dutch Emissions Authority, 2015)

Chapter 3. Model

To answer the two research questions in Chapter 1.2, we adapt an international trade model framework developed by Eichner and Pethig (2013 & 2015), which allows for international trade of fossil fuels and composite consumer goods between identical countries. We select this model to examine the impact of the EU CBAM on CBAM supply, exports, and welfare of each country, where there is an international trade of CBAM products (dirty goods) and clean goods. Scenarios with two possible policy options, which the non-EU countries can choose under the EU CBAM, are outlined.

3.1 Model Economy

We build a simple game-theoretic model of strategic international trade based on the model by Kaufmann (2021), which differs from Eichner and Pethig (2013 & 2015) in three ways. Firstly, we suppose there are three heterogeneous countries $(n = 3)$ in the world economy rather than identical. Secondly, we set a GHG emission tax t_i, for $i = 1, 2, 3$, to regulate the GHG emissions of each country and collect taxes from producers instead of consumers based on the CBAM (Kaufmann, 2021; Rocchi, 2018). Lastly, we use a linear damage function, not a quadratic one, based on Golosov et al. (2014)'s paper mentioning that the damage function is almost linear.

Let us suppose the world economy consists of three heterogeneous countries, the EU27 $(i = 1)$, Korea $(i = 2)$, and the RoW $(i = 3)$. Here, we consider 27 countries of the EU, excluding the United Kingdom as a single country. We assume that each country has a representative consumer and a representative producer because we cannot represent every individual's preference and cannot conduct economic analysis without generalization. The representative producer from each country produces two types of consumer goods (Böhringer et al., 2014; Eichner & Pethig, 2013; Keen & Kotsogiannis, 2014). One is a clean good not listed on the EU CBAM regulation, and its quantity is denoted by x_i. The other one is called a dirty good, which will be regulated under the EU CBAM, such as cement, aluminum, fertilizers, iron and steel, and electrical energy. The quantity of GHG emissions generated from the dirty good's production is denoted by e_i, which leads to climate change. We set the price of the clean good to $p_x \equiv 1$ and denote the price of the dirty good as p.

The representative producer of each country maximizes its profits, $1 \cdot x_i^s + (p - t_i) \cdot e_i^s$, based on the incomes from selling goods excluding GHG emission tax imposed on every dirty good. The production possibility frontier introduced by Eichner and Pethig (2013) specifies the production technology of each country as follows:

$$x_i^s = T_i(e_i^s) = \overline{x_i} - \frac{1}{2\alpha_i}(e_i^s)^2. \quad (1)$$

This quadratic function shows an efficient combination of the supply quantity of clean goods and GHG emissions from the dirty goods in the country i. The function implies that both goods are produced by domestic productive factors like labor and capital (Eichner & Pethig, 2015). Here, superscript s stands for the quantity of supplied goods, and the positive parameter $\overline{x_i}$ indicates the fixed quantity of clean goods x_i that can be produced in each country when no dirty goods are produced. The positive parameter α_i indicates the carbon efficiency, which is a measurement of the amount of GDP per unit of GHG emissions that country i can produce. More developed countries generally have higher carbon efficiencies since they have more advanced low-carbon technologies than developing countries and rely more on service-based industries than carbon-intensive ones.

The representative consumer of country i maximizes its consumption utility, $x_i^d + V_i(e_i^d)$, without considering climate change caused by consuming dirty goods. It is because the influence of individual consumers is too small and inconsequential to internalize negative externalities. The consumer's utility of consuming dirty goods is characterized by:

$$V_i(e_i^d) = a_i e_i^d - \frac{1}{2b_i}(e_i^d)^2. \quad (2)$$

It is a quadratic function and superscript d indicates the quantity of demanded goods. The positive parameter a_i means marginal utility's upper limit, and b_i represents a marginal benefit change when a unit of dirty goods is consumed in addition. (Eichner & Pethig, 2013; Kaufmann, 2021). A higher b_i refers to a higher preference for spending on dirty goods over clean goods. Therefore, $a_i b_i$ represents the emissions' quantity, which country i's consumer can get the highest benefits (Kaufmann, 2021).

Climate change is transboundary and depends on global GHG emissions (Böhringer et al., 2014; European Commission, 2021a). Hence, we suppose a damage function, as Golosov et al. (2014) suggested:

$$D_i(E) = \delta_i E. \tag{3}$$

This function has a linear relationship with total GHG emissions from all three countries. Here, the global GHG emissions E can be characterized by:

$$E = \sum_{i=1}^{3} e_i \,, \quad i = 1, 2, 3. \tag{4}$$

We can interpret the damage function eq. (3) as a willingness-to-pay of each country to prevent the damage from climate change. The parameter δ_i is constant marginal damage, which means a measurement of country i's willingness to pay (WTP) per unit of GHG emissions. The WTP for GHG emission reduction in developed countries, such as the EU27, is generally higher than that in developing countries.

Each country maximizes its welfare function, which is the utility of the representative consumer minus climate damage:

$$W_i = x_i^d + V_i(e_i^e) - D_i(E). \tag{5}$$

In all scenarios, we suppose that the EU sets its CBT, which mirrors the EU-ETS price, independently of any strategic considerations, while Korea and the RoW decide their domestic GHG emission taxes strategically at the level of maximizing their own welfare.

Based on the model economy, first, we build a game-theoretic model without the CBAM as a baseline scenario.

3.2 Model without EU CBAM

Recall that the dirty good price is denoted by p and the GHG emission tax by t_i for $i = 1, 2, 3$. The producer price is $p - t_i$ because the emission tax is levied by each country on every dirty good. Each country's representative producer maximizes its profits considering GHG emission tax, $1 \cdot x_i^s + (p - t_i) \cdot e_i^s$ with eq. (1). Then, we derive the following supply quantity of GHG emissions from dirty goods from the first-order condition (FOC):

$$e_i^s = \alpha_i(p - t_i). \tag{6}$$

The representative consumer also maximizes its utility of consumption, $x_i^d + V_i(e_i^d)$ with eq. (2) and the consumer's budget constraint $x_i^d = y_i - pe_i^d$. The FOC leads to

$$e_i^d = b_i(a_i - p). \tag{7}$$

The income y_i from the budget constraint is the sum of producer profits and the government's tax revenues from the domestic dirty good production: $y_i = x_i^s + (p - t_i) \cdot e_i^s + t_i \cdot e_i^s$. Therefore, we obtain the demand quantity of clean goods as follows:

$$x_i^d = x_i^s + p(e_i^s - e_i^d). \tag{8}$$

The perfectly competitive markets for clean goods and dirty goods are in equilibrium if,

$$\sum_{j=1}^{3} x_j^s = \sum_{j=1}^{3} x_j^d, \tag{9}$$

and

$$E = \sum_{j=1}^{3} e_j^s = \sum_{j=1}^{3} e_j^d. \tag{10}$$

By inserting eqs. (6) and (7) into eq. (10), we derive the dirty good price p:

$$p = \frac{C + \sum_{j=1}^{3} \alpha_j t_j}{A+B}. \tag{11}$$

where

$$A = \sum_{j=1}^{3} \alpha_j, \; B = \sum_{j=1}^{3} b_j, \; C = \sum_{j=1}^{3} b_j a_j. \tag{12}$$

Then, we obtain e_i^s and e_i^d by inserting eq. (11) into eqs. (6) and (7), respectively:

$$e_i^s = \alpha_i \left[\frac{C + \sum_{j=1}^{3} \alpha_j t_j - t_i(A+B)}{A+B}\right], \tag{13}$$

$$e_i^d = b_i \left[\frac{a_i(A+B) - C - \sum_{j=1}^{3} \alpha_j t_j}{A+B}\right]. \tag{14}$$

We insert eqs. (13) and (14) into eq. (10) to obtain the total GHG emissions E:

$$E = \frac{1}{A+B}\left(AC - B\sum_{j=1}^{3} \alpha_j t_j\right). \tag{15}$$

The welfare of each country can be determined with eqs (5) and (8) as follows:

$$W_i = V_i(e_i^d) + \underbrace{T_i(e_i^s) + p(e_i^s - e_i^d)}_{terms\ of\ trade} - D_i(E). \tag{16}$$

The eq. (16) shows the country i's equilibrium welfare for given GHG emission tax profiles t_1, t_2, and t_3 and includes the terms of trade (Eichner & Pethig, 2015).

Now, under the Business as Usual (BAU) scenario, we suppose the EU decides on GHG emission tax t_1 unilaterally, not considering the other countries' GHG emission tax levels. Korea and the RoW choose their GHG emission tax at the level of maximizing their domestic welfare $W_i\ (t_1, t_2, t_3)$, taking all other countries' tax levels as given:

$$\max_{t_i} W_i = \max_{t_i} V_i(e_i^d) + T_i(e_i^s) + p(e_i^s - e_i^d) - D_i(E), \quad i = 2,3. \tag{17}$$

$$\overset{FOC}{\longrightarrow} \quad V_i'(e_i^d)\frac{\partial e_i^d}{\partial t_i} + T_i'(e_i^s)\cdot\frac{\partial e_i^s}{\partial t_i} + \frac{\partial p}{\partial t_i}(e_i^s - e_i^d) + p\left(\frac{\partial e_i^s}{\partial t_i} - \frac{\partial e_i^d}{\partial t_i}\right) - D_i'(E)\frac{\partial E}{\partial t_i} = 0. \tag{18}$$

Here, we can derive the **Business as Usual (BAU) emission taxes** for Korea and the RoW in the Nash equilibrium (see Appendix A.1 for details):

$$\widehat{t_2} = \frac{X_2Y(C + \alpha_1 t_1) + X_2\cdot\alpha_3\cdot Z_3 + (Y^2 - X_3\alpha_3)\cdot Z_2}{Y^3 - X_2\alpha_2 Y - X_3\alpha_3 Y}, \tag{19}$$

$$\widehat{t_3} = \frac{X_3Y(C + \alpha_1 t_1) + X_3\cdot\alpha_2\cdot Z_2 + (Y^2 - X_2\alpha_2)\cdot Z_3}{Y^3 - X_2\alpha_2 Y - X_3\alpha_3 Y}, \tag{20}$$

where

$$\alpha_i + b_i = X_i$$

$$A + B = Y$$

$$\delta_i B - b_i a_i = Z_i.$$

By inserting the BAU emission tax $\widehat{t_i}$ into eqs. (13) and (14) each, we obtain the **BAU supply and demand of GHG emissions** from dirty goods:

$$\widehat{e_i^s} = \alpha_i \cdot \left[\frac{C + \sum_{j=1}^{3}\alpha_j\widehat{t_j} - \widehat{t_i}(A + B)}{A + B}\right], \tag{21}$$

$$\widehat{e_i^d} = b_i \cdot \left[\frac{a_i(A + B) - C - \sum_{j=1}^{3}\alpha_j\widehat{t_j}}{A + B}\right]. \tag{22}$$

This leads to the following **BAU welfare** of each country:

$$\widehat{W_i} = \bar{x} - \frac{1}{2\alpha_i}(\widehat{e_i^s})^2 + p \cdot (\widehat{e_i^s} - \widehat{e_i^d}) + a_i\widehat{e_i^d} - \frac{1}{2b_i} \cdot (\widehat{e_i^d})^2 - \delta_i\hat{E}. \tag{23}$$

3.3 Model with EU CBAM

Next, we build a game-theoretic model with the EU CBAM using the equations from (1) to (5) in Chapter 3.1. The representative producer of each country pays the GHG emission tax t_i to their countries. However, in this model, the EU 27 unilaterally imposes the CBT on imported dirty goods into the EU from non-EU countries, which is equal to the GHG emission tax when produced in the EU (Ismer & Neuhoff, 2007). Therefore, EU producers have no incentive to move their installations of dirty goods to foreign countries. Under the principle of CBAM, producers of Korea and the RoW get a refund on the GHG emission taxes they pay during production in their home country, according to Ismer and Neuhoff (2007).

For trade to happen, we assume that every country has the same producer price, $q = p_i - t_i$. Hence, the dirty good price is now $p_i = q + t_i$ for $i = 1, 2, 3$, which differs across countries and depends on the CBT. The representative producer of country i wants to maximize profits $1 \cdot x_i^s + (p_i - t_i) \cdot e_i^s$. We can obtain the supply quantity of GHG emissions from dirty goods from the FOC after inserting eq. (1) into x_i^s of the producer profits as follows:

$$e_i^s = \alpha_i(p_i - t_i) = \alpha_i \cdot q. \tag{24}$$

The representative consumer of country i seeks to maximize consumption utility, $x_i^d + V_i(e_i^d)$ subject to eq. (2) and the consumer's budget constraint $x_i^d = y_i - p_i e_i^d$. The FOC leads to the demand quantity of GHG emissions from dirty goods:

$$e_i^d = b_i(a_i - p_i) = b_i[a_i - (q + t_i)]. \tag{25}$$

Using eqs. (24) and (25), the market equilibrium condition (10) yields the following producer price q by:

$$q = p_i - t_i = \frac{C - \sum_{j=1}^{3} b_j t_j}{A+B}. \quad (26)$$

From eq. (26), we obtain the dirty good price of each country as follows:

$$p_i = \frac{C - \sum_{j=1}^{3} b_j t_j + (A+B)t_i}{A+B}. \quad (27)$$

We derive the supply and demand quantity of dirty goods by inserting eq. (26) into eqs. (24) and (25), respectively.

$$e_i^s = \alpha_i \cdot \left(\frac{C - \sum_{j=1}^{3} b_j t_j}{A+B}\right), \quad (28)$$

$$e_i^d = b_i \cdot \left(\frac{(A+B)(a_i - t_i) - C + \sum_{j=1}^{3} b_j t_j}{A+B}\right). \quad (29)$$

From eq. (10) the total GHG emissions E is obtained as:

$$E = \frac{1}{A+B}\left(AC - A\sum_{j=1}^{3} b_j t_j\right). \quad (30)$$

In the next part, we will extend the model by distinguishing between two possible policy options that Korea and the RoW can take, based on Helm et al. (2012)'s international trade game (Figure 5). The first policy option is when Korea and the RoW exempt their domestic GHG emission taxes on exported dirty goods to the EU, and the EU imposes its domestic GHG emission tax on imports of dirty goods from non-EU countries. The second policy option is when Korea and the RoW levy their GHG emission taxes on all domestic production of dirty goods and the EU imposes the CBT, which is the EU's GHG emission tax minus country i's emission tax already paid by producers to their countries. According to Article 9 of the EU CBAM regulation, Korea and RoW need to sign agreements with the EU to get a remission of CBT, respectively (European Commission, 2021c).

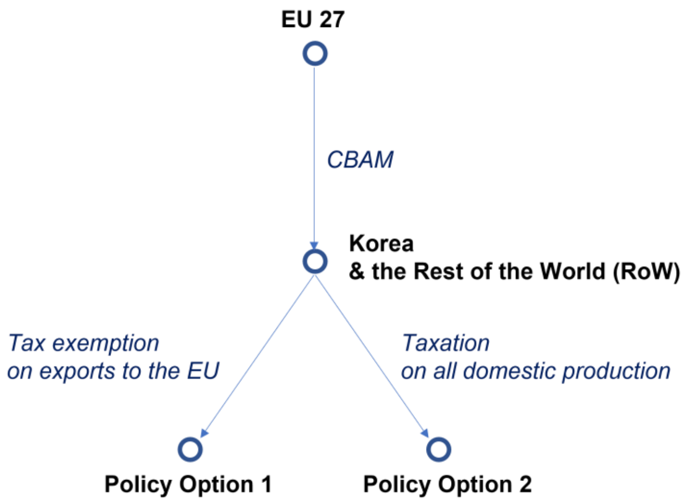

Figure 5. International trade game with carbon border adjustment, based on Helm et al. (2012)

3.3.1 Policy Option 1: Tax Exemption on Exports to the EU

In the first policy option, Korea and the RoW impose their domestic taxes on each country's demand for dirty goods and exempt taxes on exports to the EU. Then, the EU levies its domestic GHG emission tax on both domestic dirty goods production and imported dirty goods. We calculate the taxes in both countries in the Nash equilibrium given the tax t_1 in the EU.

The EU27 $(\boldsymbol{i} = \mathbf{1})$

The **tax revenue** of the EU under policy option 1 is as follows:

$$\underbrace{e_1^s \cdot t_1}_{domestic\ revenue} + \underbrace{\left(e_2^s - e_2^d\right) \cdot t_1}_{Tax\ revenue\ from\ Korea} + \underbrace{\left(e_3^s - e_3^d\right) \cdot t_1}_{Tax\ revenue\ from\ the\ RoW} . \quad (31)$$

The budget of the EU is the sum of EU's producer profits, $1 \cdot x_1^s + (p_1 - t_1) \cdot e_1^s$, and its tax revenues, eq. (31). Therefore, the EU budget is:

$$y_1 = x_1^s + e_1^s \cdot p_1 + \left(e_2^s - e_2^d\right) \cdot t_1 + \left(e_3^s - e_3^d\right) \cdot t_1. \quad (32)$$

We can obtain the demand quantity of clean goods from the consumer's budget constraints, $x_1^d = y_1 - p_1 e_1^d$, by inserting eq. (32):

$$x_1^d = x_1^s + (e_1^s - e_1^d) \cdot p_1 + (e_2^s - e_2^d) \cdot t_1 + (e_3^s - e_3^d) \cdot t_1. \tag{33}$$

The EU unilaterally decides on GHG emission tax $\widehat{t_1}$, not taking the other countries' GHG emission tax levels as given under the CBAM. Therefore, the **BAU supply and demand of GHG emissions** from production of dirty goods in the Nash equilibrium are:

$$\widehat{e_1^s} = \alpha_1 \cdot \left(\frac{C - \sum_{j=1}^{n} b_j \widehat{t_j}}{A+B}\right), \tag{34}$$

$$\widehat{e_i^d} = b_1 \cdot \left(\frac{(A+B)(a_1 - \widehat{t_1}) - C + \sum_{j=1}^{n} b_j \widehat{t_j}}{A+B}\right). \tag{35}$$

Based on the welfare function introduced in Chapter 3.1, the **BAU welfare** of the EU is:

$$\widehat{W_1} = T_1(\widehat{e_1^s}) + \left(\widehat{e_1^s} - \widehat{e_1^d}\right) \cdot p_1 + \left(\widehat{e_2^s} - \widehat{e_2^d}\right) \cdot \widehat{t_1} + \left(\widehat{e_3^s} - \widehat{e_3^d}\right) \cdot \widehat{t_1} + V_1\left(\widehat{e_1^d}\right) - \delta_1 \widehat{E}. \tag{36}$$

Korea $(i = 2)$ and the Rest of the World $(i = 3)$

The **tax revenue** of Korea and the RoW under policy option 1 is $e_i^d \cdot t_i$ for $i = 2, 3$ because each country's GHG emission tax imposed on exports of dirty goods is exempted. The budget of each county is the producer's profits plus the government's tax revenue. Therefore, the country i's budget for $i = 2, 3$ is:

$$y_i = \underbrace{x_i^s + e_i^d \cdot (p_i - t_i)}_{Domestic\ profits} + \underbrace{(e_i^s - e_i^d) \cdot (p_1 - t_1)}_{Profits\ of\ export\ to\ the\ EU} + \underbrace{e_i^d \cdot t_i}_{Tax\ revenue}. \tag{37}$$

Since the producer price is $q = p_i - t_i$, the eq. (37) can be simplified as follows:

$$y_i = x_i^s + e_i^s \cdot q + e_i^d \cdot t_i, \quad i = 2, 3. \tag{38}$$

We can calculate the demand quantity of clean goods from the consumer's budget constraint, $x_i^d = y_i - p_i e_i^d$, by inserting it into eq. (38):

$$x_i^d = x_i^s + (e_i^s - e_i^d) \cdot q, \quad i = 2, 3. \tag{39}$$

We suppose that Korea and the RoW decide their GHG emission tax at the level of maximizing each domestic welfare, $W_i = x_i^d + V_i(e_i^d) - D_i(E)$ for $i = 2, 3$, taking all other countries' tax levels as given:

$$\max_{t_i} W_i = \max_{t_i} x_i^d + V_i(e_i^d) - D_i(E), \quad i = 2, 3. \tag{40}$$

$$\xrightarrow{FOC} T_i'(e_i^s)\cdot\frac{\partial e_i^s}{\partial t_i}+\left(\frac{\partial e_i^s}{\partial t_i}-\frac{\partial e_i^d}{\partial t_i}\right)\cdot q+\left(e_i^s-e_i^d\right)\cdot\frac{\partial q}{\partial t_i}+V_i'\left(e_i^d\right)\frac{\partial e_i^d}{\partial t_i}-D_i'(E)\frac{\partial E}{\partial t_i}=0, \quad (41)$$

$$i=2,3.$$

Then, we can obtain the **BAU emission tax** of each country in the Nash equilibrium (see Appendix A.2 for details):

$$t_2=\frac{Y^2Z_2-X_2YC+X_2Z_3b_3-X_3Z_2b_3+X_2Yb_1t_1}{Y(Y^2-X_2b_2-X_3b_3)}, \quad (42)$$

$$t_3=\frac{Y^2Z_3-X_3YC+X_3Z_2b_2-X_2Z_3b_2+X_3Yb_1t_1}{Y(Y^2-X_2b_2-X_3b_3)}, \quad (43)$$

where

$$\alpha_i+b_i=X_i$$

$$A+B=Y$$

$$\delta_iA+\ b_i\alpha_i=Z_i.$$

We insert BAU emission tax $\widehat{t_i}$ into eqs. (28) and (29) each, and obtain the **BAU supply and demand of GHG emissions** from dirty goods production:

$$\widehat{e_i^s}=\alpha_i\cdot(\frac{C-\sum_{j=1}^{n}b_j\widehat{t_j}}{A+B}),\quad i=2,3, \quad (44)$$

$$\widehat{e_i^d}=b_i\cdot(\frac{(A+B)(a_i-\widehat{t_i})-C+\sum_{j=1}^{n}b_j\widehat{t_j}}{A+B}),\quad i=2,3. \quad (45)$$

We lead to the **BAU welfare** of Korea and the RoW as follows:

$$\widehat{W_i}=T_i(\widehat{e_i^s})+\left(\widehat{e_i^s}-\widehat{e_i^d}\right)\cdot q+V_i\left(\widehat{e_i^d}\right)-\delta_i\hat{E},\quad i=2,3. \quad (46)$$

3.3.2 Policy Option 2: Taxation on all domestic production

Under the second policy option, Korea and the RoW levy domestic GHG emission tax t_i on all domestic production of dirty goods e_i^s, including exports to the EU. Then, the EU imposes a CBT on the imports of dirty goods from non-EU countries, subtracting the GHG emission tax already paid in each country, according to Article 9 of the EU CBAM regulations.

The EU27 $(\boldsymbol{i=1})$

The **tax revenue** of the EU under policy option 2 is as follows:

$$\underbrace{e_1^s \cdot t_1}_{domestic\ revenue} + \underbrace{\left(e_2^s - e_2^d\right)\cdot(t_1 - t_2)}_{Tax\ revenue\ from\ Korea} + \underbrace{\left(e_3^s - e_3^d\right)\cdot(t_1 - t_3)}_{Tax\ revenue\ from\ the\ RoW}. \tag{47}$$

The EU budget is the sum of EU's producer profits, $1 \cdot x_1^s + (p_1 - t_1)\cdot e_1^s$, and its tax revenues, eq. (47). Therefore, the EU budget is given by

$$y_1 = x_1^s + e_1^s \cdot p_1 + \left(e_2^s - e_2^d\right)\cdot(t_1 - t_2) + \left(e_3^s - e_3^d\right)\cdot(t_1 - t_3). \tag{48}$$

We obtain the demand quantity of clean goods from the consumer's budget constraint, $x_1^d = y_1 - p_1 e_1^d$, by inserting eq. (48):

$$x_1^d = x_1^s + \left(e_1^s - e_1^d\right)\cdot p_1 + \left(e_2^s - e_2^d\right)\cdot(t_1 - t_2) + \left(e_3^s - e_3^d\right)\cdot(t_1 - t_3). \tag{49}$$

Like the first policy option, the EU levies GHG emission tax $\widehat{t_1}$ on dirty goods without considering the GHG emission taxes of the other countries. Hence, the **BAU supply and demand of GHG emissions** from production of dirty goods in the Nash equilibrium are:

$$\widehat{e_1^s} = \alpha_1 \cdot \left(\frac{C - \sum_{j=1}^{n} b_j \widehat{t_j}}{A+B}\right), \tag{50}$$

$$\widehat{e_i^d} = b_1 \cdot \left(\frac{(A+B)(a_1 - \widehat{t_1}) - C + \sum_{j=1}^{n} b_j \widehat{t_j}}{A+B}\right). \tag{51}$$

The **BAU welfare** of the EU is:

$$\widehat{W_1} = T_1\left(\widehat{e_1^s}\right) + \left(\widehat{e_1^s} - \widehat{e_1^d}\right)\cdot p_1 + \left(\widehat{e_2^s} - \widehat{e_2^d}\right)\cdot\left(\widehat{t_1} - \widehat{t_2}\right) + \left(\widehat{e_3^s} - \widehat{e_3^d}\right)\cdot\left(\widehat{t_1} - \widehat{t_3}\right) + V_1\left(\widehat{e_1^d}\right) - \delta_1 \hat{E}. \tag{52}$$

Korea $(\boldsymbol{i=2})$ **and the Rest of the World** $(\boldsymbol{i=3})$

Korea and the RoW impose GHG emission taxes on all production of domestic dirty goods under policy option 2 to get a remission of CBT from the EU. Therefore, the **tax revenue** of Korea and the RoW is $e_i^d \cdot t_i + \left(e_i^s - e_i^d\right)\cdot t_i = e_i^s \cdot t_i$ for $i = 2, 3$. The budget of each country is the producer's profits plus the government's tax revenue:

$$y_i = \underbrace{x_i^s + e_i^d \cdot (p_i - t_i)}_{Domestic\ profits} + \underbrace{\left(e_i^s - e_i^d\right)\cdot(p_1 - t_1)}_{Profits\ of\ export\ to\ the\ EU} + \underbrace{e_i^s \cdot t_i}_{Tax\ revenue}. \tag{53}$$

Since the producer price is $q = p_i - t_i$, eq. (53) can be simplified as follows:

$$y_i = x_i^s + e_i^s \cdot p_i, \quad i = 2, 3. \tag{54}$$

We calculate the demand quantity of clean goods from the consumer's budget constraint, $x_i^d = y_i - p_i e_i^d$, by inserting it into eq. (54):

$$x_i^d = x_i^s + \left(e_i^s - e_i^d\right) \cdot p_i, \quad i = 2, 3. \tag{55}$$

Again, we suppose that Korea and the RoW decide their GHG emission tax at the level of maximizing their domestic welfare, $W_i = x_i^d + V_i\left(e_i^d\right) - D_i(E)$ for $i = 2, 3$, taking all other countries' tax levels as given:

$$\max_{t_i} W_i = \max_{t_i} x_i^d + V_i\left(e_i^d\right) - D_i(E), \quad i = 2, 3. \tag{56}$$

$$\xrightarrow{FOC} T_i'(e_i^s) \cdot \frac{\partial e_i^s}{\partial t_i} + \left(\frac{\partial e_i^s}{\partial t_i} - \frac{\partial e_i^d}{\partial t_i}\right) \cdot p_i + \left(e_i^s - e_i^d\right) \cdot \frac{\partial p_i}{\partial t_i} + V_i'\left(e_i^d\right) \frac{\partial e_i^d}{\partial t_i} - D_i'(E) \frac{\partial E}{\partial t_i} = 0, \quad i = 2, 3. \tag{57}$$

Then, we obtain the **BAU emission tax** of Korea and the RoW in the Nash equilibrium (see Appendix A.3 for details):

$$\hat{t_2} = \frac{(X_3-Y)(Y-b_2)[(C-b_1t_1)X_2-Ya_2b_2]-(Y-b_3)(Y-b_2)(X_3a_2b_2-X_2a_3b_3)+[(X_3-Y)Y+(Y-b_3)X_3]b_2\delta_2A-(Y-b_2)X_2b_3\delta_3A}{b_2[Y(X_3-Y)(X_2-Y)+(X_2-Y)(Y-b_3)X_3+(X_3-Y)(Y-b_2)X_2]}, \tag{58}$$

$$t_3 = \frac{(X_2-Y)(Y-b_3)[(C-b_1t_1)X_3-Ya_3b_3]-(Y-b_2)(Y-b_3)(X_2a_3b_3-X_3a_2b_2)+[(X_2-Y)Y+(Y-b_2)X_2]b_3\delta_3A-(Y-b_3)X_3b_2\delta_2A}{b_3[Y(X_2-Y)(X_3-Y)+(X_3-Y)(Y-b_2)X_2+(X_2-Y)(Y-b_3)X_3]}. \tag{59}$$

where

$$\alpha_i + b_i = X_i$$

$$A + B = Y.$$

We insert BAU emission tax $\hat{t_\imath}$ into eqs. (28) and (29) each, and obtain the **BAU supply and demand of GHG emissions** from dirty goods production:

$$\widehat{e_\imath^s} = \alpha_i \cdot \left(\frac{C - \sum_{j=1}^n b_j \hat{t_\jmath}}{A+B}\right), \quad i = 2, 3, \tag{60}$$

$$\widehat{e_\imath^d} = b_i \cdot \left(\frac{(A+B)(a_i - \hat{t_\imath}) - C + \sum_{j=1}^n b_j \hat{t_\jmath}}{A+B}\right), \quad i = 2, 3. \tag{61}$$

We derive the **BAU welfare** of Korea and the RoW as follows:

$$\widehat{W_i} = T_i(\widehat{e_i^s}) + (\widehat{e_i^s} - \widehat{e_i^d}) \cdot p_i + V_i(\widehat{e_i^d}) - \delta_i \hat{E}, \quad i = 2, 3. \tag{62}$$

3.4 Summary of Welfare in Each Policy Option

In Chapters 3.2 and 3.3, we obtain BAU emissions tax, supply and demand of GHG emissions, and welfare of each country in the Nash equilibrium in each policy option. The welfare of country i are summarized in Table 5.

Scenario	*Country*	*BAU Welfare*
Baseline	EU27, Korea, RoW	$\widehat{W_i} = T_i(\widehat{e_i^s}) + p \cdot \left(\widehat{e_i^s} - \widehat{e_i^d}\right) + V_i\left(\widehat{e_i^d}\right) - \delta_i \hat{E}$
Policy op. 1	EU27	$\widehat{W_1} = T_1(\widehat{e_1^s}) + \left(\widehat{e_1^s} - \widehat{e_1^d}\right) \cdot p_1 + \left(\widehat{e_2^s} - \widehat{e_2^d}\right) \cdot \widehat{t_1} + \left(\widehat{e_3^s} - \widehat{e_3^d}\right) \cdot \widehat{t_1} + V_1\left(\widehat{e_1^d}\right) - \delta_1 \hat{E}$
	Korea, RoW	$\widehat{W_i} = T_i(\widehat{e_i^s}) + \left(\widehat{e_i^s} - \widehat{e_i^d}\right) \cdot q + V_i\left(\widehat{e_i^d}\right) - \delta_i \hat{E}$
Policy op. 2	EU27	$\widehat{W_1} = T_1(\widehat{e_1^s}) + \left(\widehat{e_1^s} - \widehat{e_1^d}\right) \cdot p_1 + \left(\widehat{e_2^s} - \widehat{e_2^d}\right) \cdot (\widehat{t_1} - \widehat{t_2}) + \left(\widehat{e_3^s} - \widehat{e_3^d}\right) \cdot (\widehat{t_1} - \widehat{t_3}) + V_1\left(\widehat{e_1^d}\right) - \delta_1 \hat{E}$
	Korea, RoW	$\widehat{W_i} = T_i(\widehat{e_i^s}) + \left(\widehat{e_i^s} - \widehat{e_i^d}\right) \cdot p_i + V_i\left(\widehat{e_i^d}\right) - \delta_i \hat{E}$

Table 5. Summary of welfare in each policy option

As shown in the table above, it is too complicated to derive and assess the general results, which makes it hard to investigate what is the best policy option for each country. In this regard, we will analyze these policy options numerically by using actual trade data in the next chapter.

Chapter 4. Numerical Illustration

In this chapter, we investigate how much the EU, Korea, and the RoW will be affected when the EU implements a CBAM regime compared to the baseline scenario. In addition, we explore whether Korea is better off by getting a CBT remission for exports of dirty goods to the EU, as previous studies recommended. Even though there is a limitation in choosing accurate parameter values for the numerical illustration, we determine plausible parameters based on empirical data on each country's supply and demand quantities. The game-theoretic model built in Chapter 3 is used for the analysis.

4.1 Data

We use the EU trade data with Korea and the RoW from 2016 to 2020, based on Eurostat (2021). The dirty goods are selected according to the EU CBAM regulations revised by the EU Council in March 2022, as shown in Table 6. The industrial sectors of dirty goods we analyzed are cement, fertilizers, iron and steel, and aluminum. Here, we exclude electrical energy from the list since it cannot be measured as weight, and Korea does not export electricity to the EU.

Industrial Sector	***CN Code***
Cement	2523 10 00, 2523 21 00, 2523 29 00, 2523 30 00, 2523 90 00
Fertilizers	2808 00 00, 2814, 2834 21 00, 3102, 3105 (except 3105 60 00)
Iron and Steel	7201~7229 (except 7202 & 7204), 7301, 7302, 7303 00, 7304~ 7311, 7326
Aluminum	7601, 7603, 7604, 7605, 7606, 7607, 7608, 7609 00 00, 7610, 7611 00 00, 7612, 7613 00 00, 7614, 7616

Table 6. List of the dirty (CBAM) goods (EU Council, 2022b)

For the country i's quantity of clean goods x_i, we use trade value in EUR. The quantity of clean goods is calculated as the value of total trading goods minus the value of dirty goods defined in Table 6. We set each country's supply and demand quantity of clean goods by using the average value for five years from 2016 to 2020 based on the reconstructed dataset, as shown in Table 7. The quantity of clean goods is measured in [mil. €].

	$EU27\ (i = 1)$	$Korea\ (i = 2)$	$RoW\ (i = 3)$	$Total$
x_i^s $(Supply)$	1,932,666.97	40,475.22	1,686,924.76	3,660,066.95
x_i^d $(Demand)$	1,727,399.98	41,915.63	1,890,751.33	3,660,066.95

Table 7. The average supply and demand quantity of clean goods from 2016 to 2020 [mil. €]

To obtain the GHG emissions quantity of dirty goods, we use the most recent carbon intensity data (base-year 2016) of iron and steel, and cement obtained from the Climate Action Tracker (2022a & 2022b), Climate Transparency (2020 & 2021), and Roh (2018). The carbon intensity data, which includes both direct and indirect emissions, are used since the EU Commission and the EU Council plan to expand CBAM's scope after the transitional period. Then, we calculate the average carbon intensity of each country according to the International Energy Agency (2019). They mentioned that the iron and steel industry accounts for 24% of total industrial emissions, and cement accounts for 26%. Therefore, we obtain the average carbon intensity based on this ratio, as shown in Table 8. In light of the lack of detailed data, we use the EU 28's average data, including the UK, as the EU 27's and the world's average as the RoW's.

	$Carbon\ Intensity\ (tCO_2/ton\ of\ product)$		
	$Cement$	$Iron\ and\ Steel$	$Average$
$EU27$	0.563	1.209	0.873
$Korea$	0.347	1.750	1.020
RoW	0.615	1.900	1.232

Table 8. Carbon intensity of each country for 2016 [tCO_2/ton of product]

The GHG emission quantity from the production of dirty goods e_i (Table 9) can be obtained by multiplying the weight of dirty goods [mil. ton] and carbon intensity of country i [tCO_2/ton of product] in Table 8. The weight of dirty goods is set as the average from 2016 to 2020, like the quantity of clean goods. The quantity of GHG emissions is measured in [mil. tCO_2].

	EU 27 $(\boldsymbol{i} = \mathbf{1})$	***Korea*** $(\boldsymbol{i} = \mathbf{2})$	***RoW*** $(\boldsymbol{i} = \mathbf{3})$	***Total GHG Emissions***
$\boldsymbol{e_i^s}$ $(\boldsymbol{Supply})$	60.23	3.15	92.76	156.14
$\boldsymbol{e_i^d}$ $(\boldsymbol{Demand})$	95.91	0.31	59.93	156.14

Table 9. The average supply and demand GHG emission quantity of dirty goods from 2016 to 2020 [mil. tCO_2]

4.2 Parametrization

δ_i means the willingness to pay per unit of GHG emissions in each country (see Chapter 3.1). According to the World Bank (2021) and Parry (2021), the EU's carbon price was \$50/tCO_2, Korea's \$16/tCO_2, and the world's \$3/tCO_2 in 2020. We convert the currency unit as 1 EUR = 0.90 USD (Feenstra et al., 2015). Therefore, plausible values for δ_i are chosen as δ_1 = 45.00, δ_2 = 14.40, and δ_3 = 2.70, based on the carbon price of each country.

The dirty good price p in the baseline model without the CBAM is selected based on the average dirty good price for five years from 2016 to 2020 in three countries. Thus, p = €807.45/tCO_2. This leads to obtaining plausible values for α_i, which indicates the carbon efficiency. Using $\alpha_i = e_i^s \cdot (p - t_i)^{-1}$ with carbon taxes in 2020 and the supply quantity of dirty goods in each country, we choose carbon efficiencies as $\alpha_1 = 0.079$, $\alpha_2 = 0.004$, and $\alpha_3 = 0.115$ with unit [mil. tCO_2^2/€]. Then, the positive parameter $\overline{x_i} = x_i^s + (e_i^s)^2 \cdot (2\alpha_i)^{-1}$ can be determined based on the supply quantity of clean and dirty goods in Table 7 and Table 9. Therefore, $\overline{x_1}$ = 1,955,629.19 [mil. €], $\overline{x_2}$ = 41,724.19 [mil. €], and $\overline{x_3}$ = 1,724,247.16 [mil. €].

The demand quantity of dirty goods is $e_i^d = b_i(a_i - p)$. a_i indicates the marginal utility's upper limit, and b_i indicates the preference for spending on dirty goods over clean goods. Finding these parameters are challenging to select. We assume a_i are higher than the dirty good price p = €807.45/tCO_2, so that a_i can have positive values. Then, we select the values of these parameters to match the demand quantity of dirty goods in Chapter 4.1 (Table 9). The plausibility of values is assessed by checking the total GHG emissions, which is the sum of the demand quantity of dirty goods in three countries. Therefore, the plausible values are chosen as shown in Table 10, which results in total GHG emissions of 156.00 [mil. tCO_2].

The following table shows all the plausible values described above:

Parameter	***Values***			***Unit***
	EU 27 $(\boldsymbol{i=1})$	***Korea*** $(\boldsymbol{i=2})$	***RoW*** $(\boldsymbol{i=3})$	
$\boldsymbol{\delta_i}$	45.000	14.400	2.700	€/tCO_2
$\boldsymbol{\alpha_i}$	0.079	0.004	0.115	mil. tCO_2^2/€
$\boldsymbol{a_i}$	850.000	808.000	810.000	€/tCO_2
$\boldsymbol{b_i}$	2.254	0.557	23.500	mil. tCO_2^2/€
$\boldsymbol{\bar{x}_i}$	1,955,629.191	41,724.190	1,724,247.159	mil. €

Table 10. Parameter values in the EU, Korea, and the RoW

4.3 Results

Using the economic models in Chapter 3 and parameter values in Table 10, we obtain the results for the numerical illustration as shown in Table 11. Here, the baseline scenario shows the status quo. Scenario 1 describes when Korea and the RoW choose policy option 1 under the EU CBAM, which is exempting domestic GHG emission tax on dirty good exports to the EU (see Chapter 3.3.1). Scenario 2 represents Korea and the RoW choosing policy option 2, which is imposing domestic GHG emission tax on all domestic production of dirty goods to get a remission of CBT (see Chapter 3.3.2).

We assume the EU imposes an EU-ETS price of €30/tCO_2, consistent with EU-ETS prices between 2016 and 2020 and previous studies by Moon et al. (2020), Moon et al. (2021), and Yoon (2022).

Scenario	Country	GHG Emissions Tax [€/tCO$_2$]	GHG emissions from Dirty Goods			Clean Goods		Welfare [mil. €]	Total GHG Emissions [mil. tCO$_2$]
			Price [€/tCO$_2$]	Supply [mil. tCO$_2$]	Demand [mil. tCO$_2$]	Supply [mil. €]	Demand [mil. €]		
Baseline	***EU***	30.00	807.41	61.41	95.99	1,931,757.01	1,903,837.18	1,976,315.00	157.18
	Korea	14.40	807.41	3.15	0.33	40,475.35	42,753.09	40,755.13	
	RoW	3.89	807.41	92.61	60.85	1,687,039.16	1,712,681.25	1,761,470.28	
Scenario 1	***EU***	30.00	829.79	63.18	45.56	1,930,363.04	1,944,456.64	1,975,588.25	158.54
	Korea	0.16	799.95	3.18	4.49	40,453.91	39,404.51	40,730.26	
	RoW	5.60	805.38	92.18	108.49	1,687,383.76	1,674,339.56	1,761,540.18	
Scenario 2	***EU***	30.00	816.07	62.10	76.48	1,931,222.41	1,919,617.56	1,976,318.17	155.82
	Korea	16.55	802.29	3.12	3.18	40,497.12	40,449.05	40,767.15	
	RoW	20.69	806.76	90.60	76.16	1,688,637.58	1,700,290.51	1,761,434.17	

Table 11. Numerical illustration results with the EU’s GHG emission tax of €30/tCO$_2$

4.3.1 Visual Comparisons by Scenario

Before investigating the impact of the EU CBAM on each country, we first assess which scenario is most effective in reducing global GHG emissions as the EU intended and benefiting the total welfare of the three countries for a general understanding.

The global GHG emissions are indicators of whether the EU CBAM can function successfully as the EU intended. Figure 6 compares the global GHG emissions with the world average GHG emission tax in each scenario. The lowest level of global GHG emissions occurs with the highest world average carbon price in Scenario 2, when non-European countries impose their domestic GHG emission taxes on all domestic production of dirty goods and get a remission of CBT from the EU. It implies that policy option 2 is more efficient than the others for reaching the climate change targets. On the contrary, the highest level of global GHG emissions occurs in Scenario 1. It confirms that policy option 1 leads to a lower world average carbon price, therefore, more global GHG emissions from producing dirty goods.

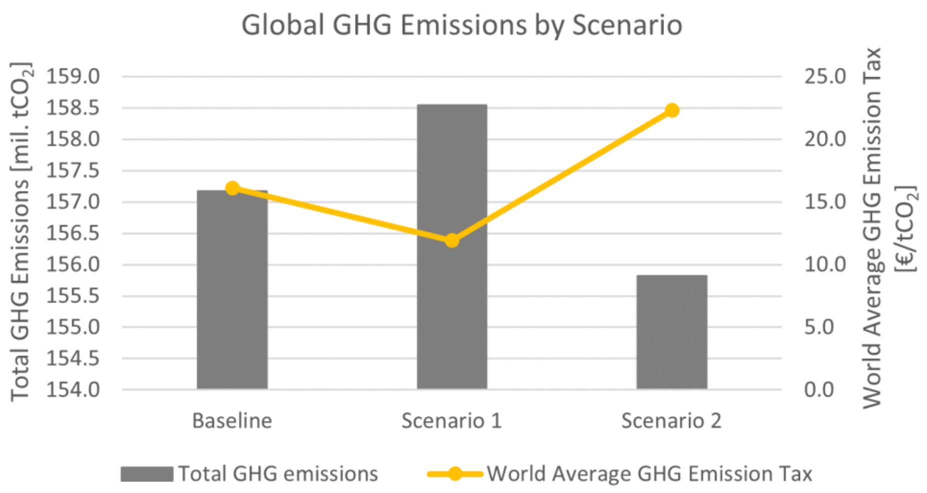

Figure 6. Total GHG emissions by Scenario with EU-ETS price of €30/tCO$_2$

Figure 7 compares the impact of EU CBAM on the total welfare of three countries in each scenario. The highest total welfare is in the baseline scenario, and the lowest total welfare is in Scenario 1. The total welfare in Scenario 2 is lower than the baseline, but the gap between the two scenarios is just 0.02 bil. €. This is because the level of global GHG emissions is lowest in Scenario 2, which leads to the lowest damage function level in the EU and Korea.

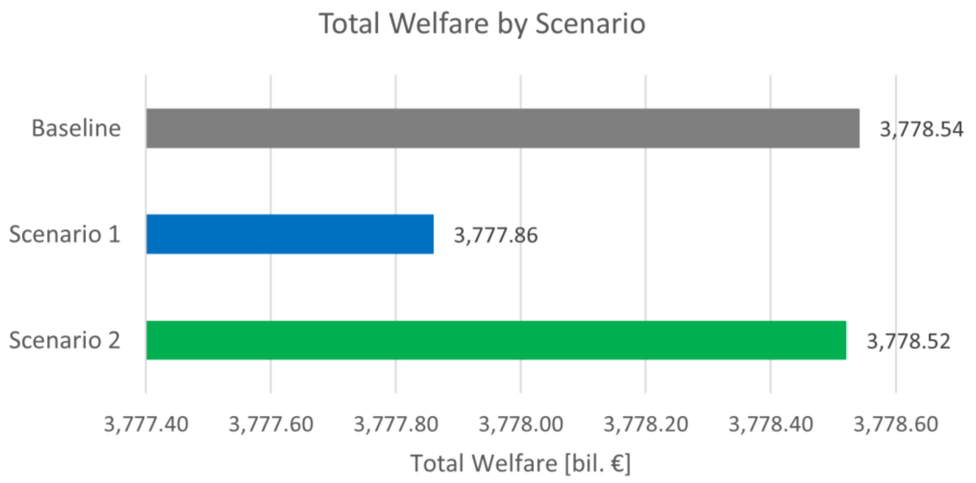

Figure 7. Total welfare by Scenario with EU-ETS price of €30/tCO_2

These two results demonstrate that the CBAM with policy option 2 is better than with policy option 1, considering both global GHG emissions and total welfare. In other words, policy option 2 gives us incentives to reduce global GHG emissions while almost maintaining the total welfare of the three countries.

4.3.2 Visual Comparisons by Country

In this part, we will compare the supply and export of GHG emissions from dirty goods production and welfare in each scenario by country. Figure 8 shows the GHG emissions supply changes compared to the baseline grouped by country. The EU's supply of dirty goods increases in both scenarios but increases more in Scenario 1. Korea's supply increases by 0.85% in Scenario 1 but decreases by 0.88% in Scenario 2. In contrast to the EU, the RoW's supply decreases in both scenarios but decreases more in Scenario 2. Three countries supply more GHG emissions in Scenario 1 than in Scenario 2 because of the negative linear relationship between GHG emissions supply from dirty goods and the world average carbon price (highest in Scenario 2). It is also associated with producer price, outlined in eq. (28). The higher producer price in Scenario 1 (€799.79/tCO_2) than in Scenario 2 (€786.07/tCO_2) leads to a higher supply of GHG emissions.

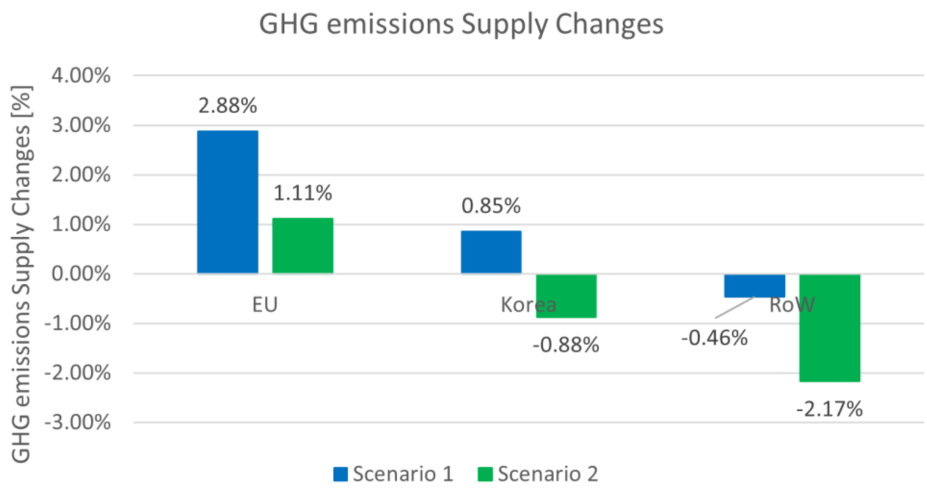

Figure 8. GHG emissions supply changes compared to the baseline scenario by country

Figure 9 displays GHG emissions export changes of each country compared to the baseline scenario. The EU exports more GHG emissions compared to the baseline in both scenarios, while Korea and the RoW export much less GHG emissions. It is because of the difference in producer price of each country, outlined in eqs. (24) and (25). The three countries' export changes in Scenario 1 are relatively more than in Scenario 2, as the difference in producer price between the baseline and Scenario 1 is higher than between the baseline and Scenario 2.

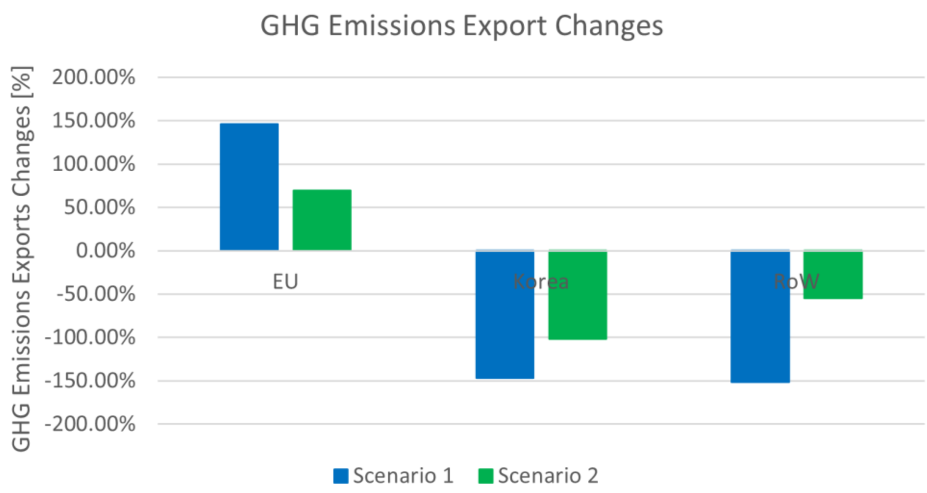

Figure 9. GHG emissions exports changes compared to the baseline scenario by country

Figure 10 shows how the welfare changes compared to the baseline scenario by country. It allows us to see how much Korea's and the RoW's welfare will be affected by the implementation of the EU CBAM and which policy option is better for Korea and the RoW at a glance.

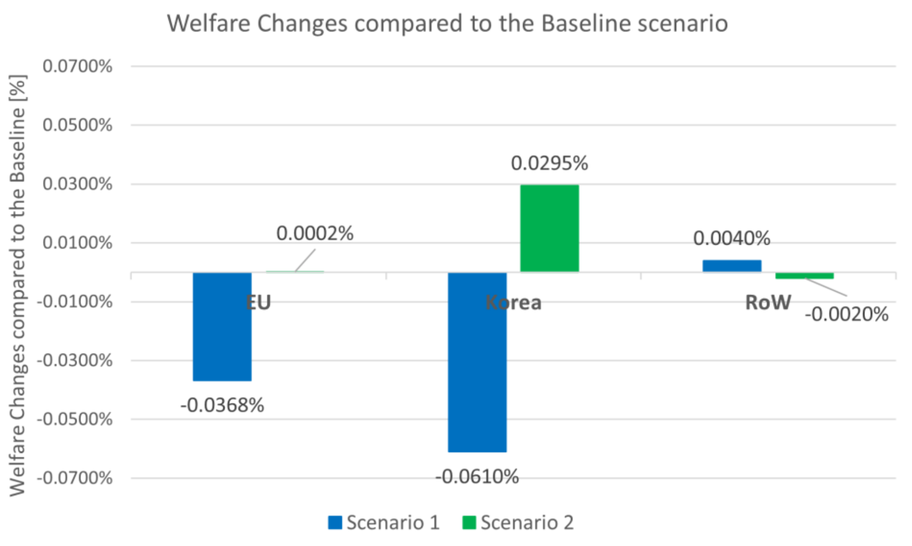

Figure 10. Welfare changes compared to the baseline scenario by country

Overall, the EU CBAM does not significantly affect the welfare of each country in percentage terms. The EU's and Korea's welfares drop compared to the baseline in Scenario 1 and increase in Scenario 2 because of the simple fact that global GHG emissions are the highest in Scenario 1 and the lowest in Scenario 2 (see Figure 6). Although Korea seems to be affected more than the other countries, it is actually because its economy is smaller than the EU and the RoW. The RoW's welfare slightly increases in Scenario 1 due to a combination of the lower dirty goods price than the baseline and its high preference for consuming dirty goods over clean goods. The RoW is much less affected by the global GHG emissions since its willingness to pay is relatively low.

Therefore, we can conclude that the EU's and Korea's welfare are better off in Scenario 1 than in Scenario 2, while the RoW's is better off in Scenario 1 than the other. Besides, it is clear that policy option 1 is not helpful to the EU since it increases the global GHG emissions and decreases the EU's welfare, contrary to what the EU intended.

4.4 Sensitivity Analysis

4.4.1 Global GHG Emissions Sensitivity to the EU-ETS Price

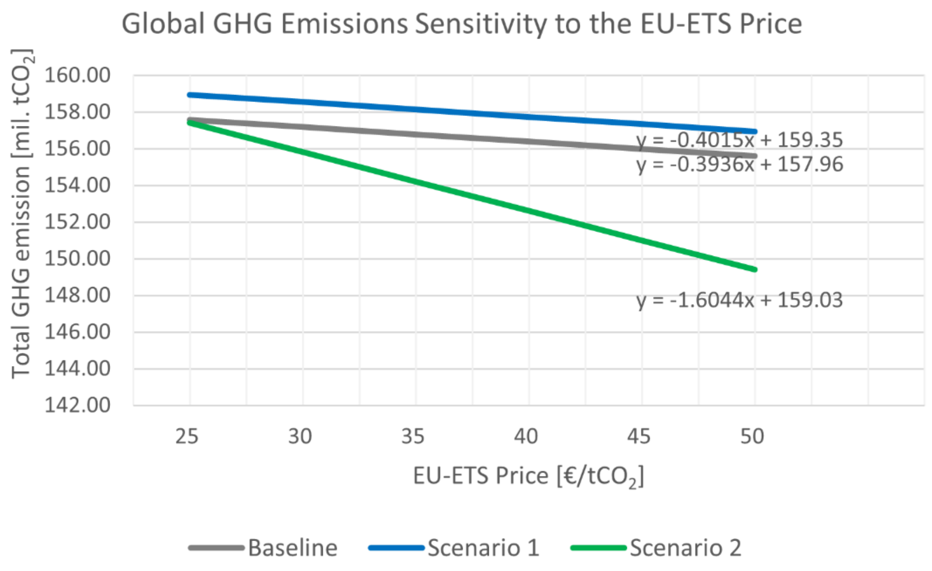

Figure 11. Global GHG Emissions Sensitivity to EU-ETS price

As we expected, the global GHG emissions change with the EU-ETS price, t_1, in all scenarios and decrease linearly with the higher price of the EU-ETS, as shown in Figure 11. The global GHG emissions sensitivity to the EU-ETS price is the most notable in Scenario 2, which decreases much steeper than in Scenario 1. It demonstrates that policy option 2 is a more effective way to reach the EU's ambitious climate goal than policy option 1.

4.4.2 Sensitivity of GHG Emissions Supply Changes to the EU-ETS Price

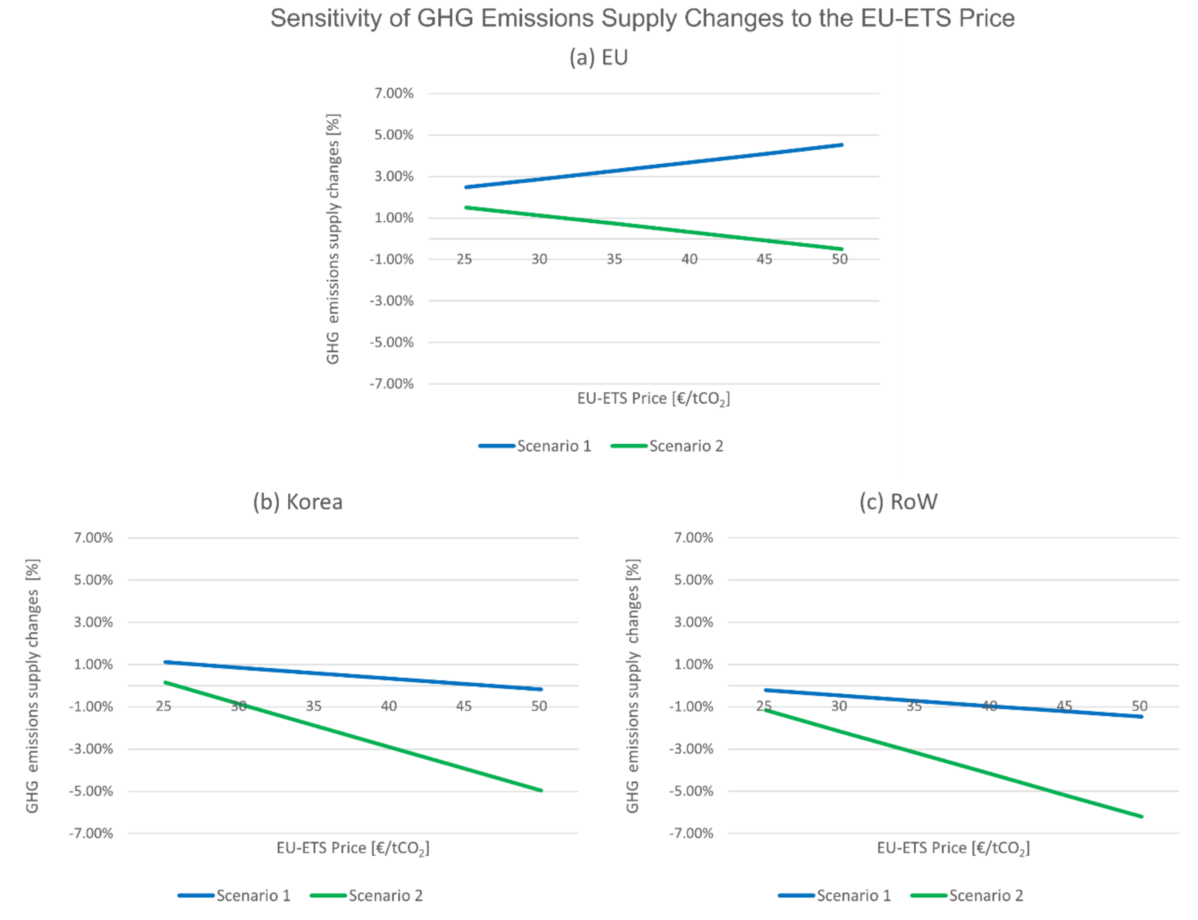

Figure 12. Sensitivity of GHG emissions supply changes to the EU-ETS price

Table 12 shows the sensitivity of GHG emissions supply changes to the EU-ETS price in each country. The EU's GHG emissions supply notably increases with higher EU-ETS prices under policy option 1. It is due to the re-establishment of fair competition with the non-EU countries under the EU CBAM, leading to a higher producer price than the baseline in the EU, therefore, a higher supply of dirty goods. On the other hand, Korea's and the RoW's GHG emissions supply decreases linearly with increasing EU-ETS prices. In Particular, Korea's GHG emissions supply changes negatively at certain higher EU-ETS prices. It highlights that the level of the EU-ETS price plays an important role in incentivizing the reduction of global GHG emissions. Without a high enough EU-ETS price, the producer price may be higher than the baseline in certain countries (here, Korea), which leads to emitting more GHG emissions.

4.4.3 Welfare Changes Sensitivity to the EU-ETS Price

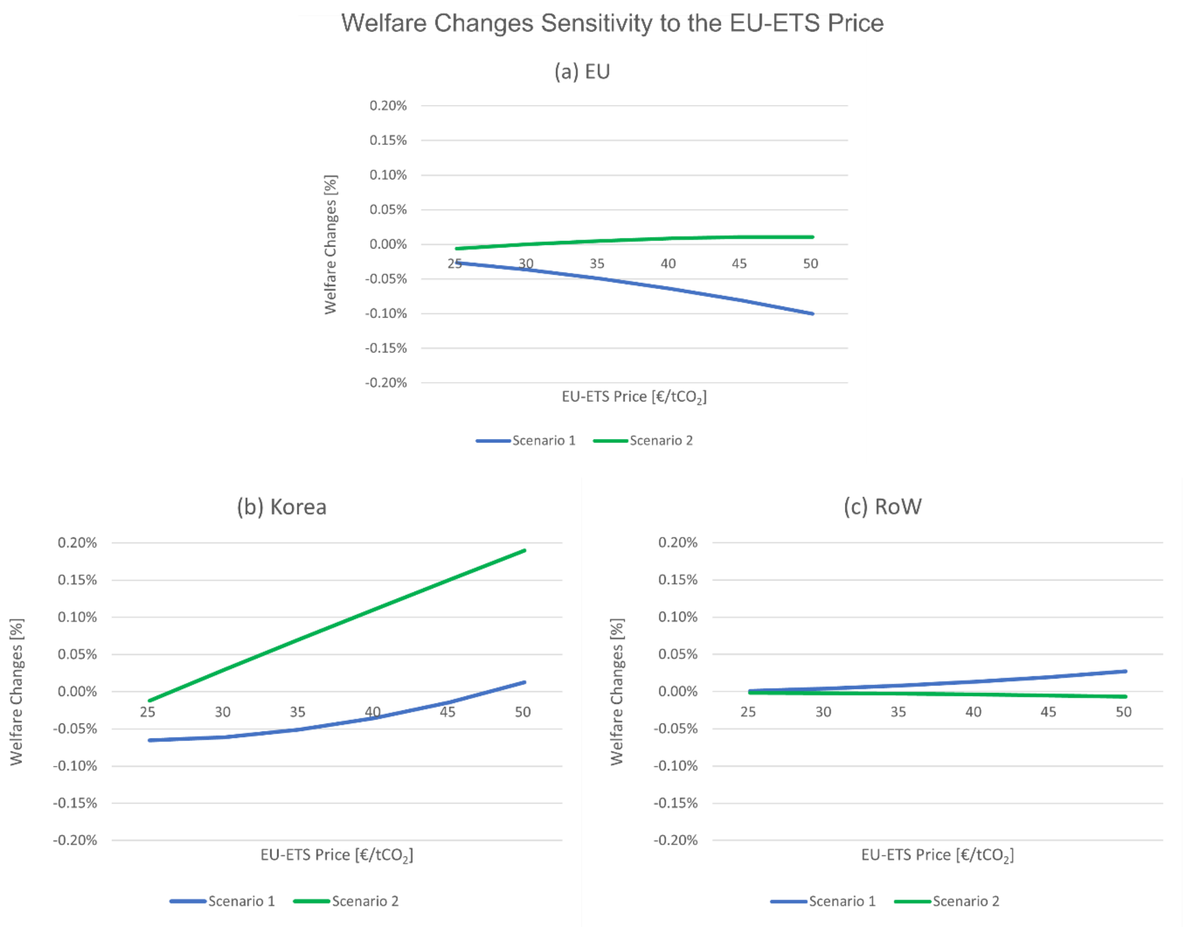

Figure 13. Welfare changes sensitivity to the EU-ETS price

As shown in Figure 13, there is a decrease in the EU's welfare with an increase in the EU-ETS price in Scenario 1. It is due to the highest level of global GHG emissions with policy option 1. In Scenario 2, the EU's welfare slightly increases and changes positively at a certain level of the EU-ETS price. It indicates that the EU should be careful to set a proper level of the EU-ETS price for its own welfare. Korea's welfare increases with the higher EU-ETS price in Scenario 2. In Scenario 1, its welfare changes positively with the EU-ETS price of over €47.8/tCO_2 because the dirty goods price is low enough to increase consumption utility and its welfare. The RoW's welfare increases with increased EU-ETS price in Scenario 1, while it decreases slightly in Scenario 2. This is because the demand for dirty goods in Scenario 1 is higher than in Scenario 2, with the lower price of dirty goods.

4.4.4 Welfare Changes Sensitivity to the Korea's Willingness-to-pay (WTP)

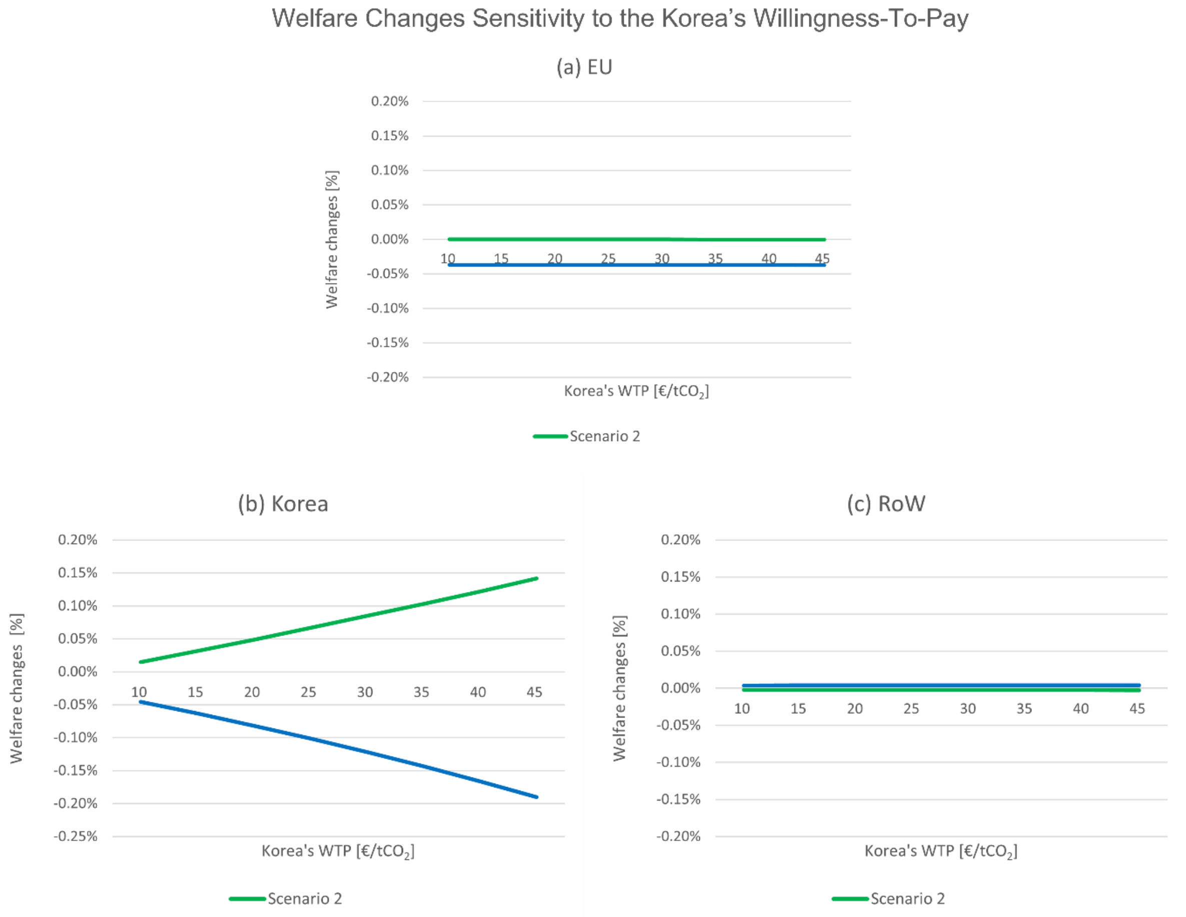

Figure 14. Welfare changes sensitivity to the Korea's Willingness-to-pay (WTP)

Korea's willingness to pay (WTP) to prevent climate damages, δ_2, does not have a significant effect on the EU's and the RoW's welfare in both scenarios. Korea's welfare significantly decreases with a higher Korea's WTP in Scenario 1, thanks to the linear relationship between damage function and willingness to pay. However, in the other scenario, its welfare increases as δ_2 gets larger due to the lowest level of global GHG emissions, as shown in Figure 6. Therefore, Korea's welfare increases with a higher WTP in Scenario 2 while it decreases in Scenario 1.

Chapter 5. Discussion

5.1 Economic Assumptions

Our results are based on reasonable economic assumptions regarding the EU CBAM, as described in Chapter 3.1. We adapted the game-theoretic model with plausible assumptions to find a Nash equilibrium, conduct the qualitative investigation of the impact of the EU CBAM under the two policy options that non-EU countries can take and provide an insight into the best response for this new carbon pricing system.

Our model differs from the model established by Eichner and Pethig (2013 & 2015), who assume the world economy consists of identical countries. We suppose there are three heterogeneous countries, the EU, Korea, and the RoW, in the world economy, and each country levies domestic GHG emission tax on the producers to prevent climate damage. In addition, we use quadratic consumption utility and linear damage functions.

For tractability, the general assumptions of our model may have some limitations to getting robustness of results. Firstly, we assume that every country levies a domestic GHG emission tax on emissions from dirty goods. The EU and Korea operate each ETS in the real world. However, most other countries do not have a carbon pricing system. According to the World Bank (2022), only 15 non-EU countries (excluding Iceland, Liechtenstein, Norway, and Switzerland) are operating explicit carbon pricing at the national level.

Secondly, we assume that both non-EU countries (here, Korea and the RoW) always choose the same policy option. Based on our results, Korea is better off with policy option 2, but the RoW is better off with policy option 1. Therefore, the same policy option is not necessarily in the best interests of both countries. Despite these limitations in our model, our research is still meaningful because it shows what would be the best response to the EU CBAM for each country.

5.2 Numerical Illustration

Korea's Exports of Dirty Goods to the EU

We compare our results with previous studies to assess the plausibility of our numerical illustration (see Table 11). Our results show that Korea's GHG emissions export to the EU will be reduced by 1.31 mil. tCO_2 in Scenario 1 and by 0.06 mil. tCO_2 in Scenario 2. It indicates that policy option 2 is better than the other option for Korea's producers. These results are in accordance with the earlier study by Kim et al. (2021) from the Bank of Korea. They assume that the EU imposes the CBT of \$50/tCO_2 in Scenario 1 and \$35/tCO_2 in Scenario 2 on Korea. Then, they calculated that the exports from Korea to the EU would decline by 0.5% per year in Scenario 1 and by 0.3% per year in Scenario 2. There may be a numerical difference because we assume the EU-ETS price as €30/tCO_2. In our model, the CBT of the EU is €30/tCO_2 in Scenario 1 and €13.78/tCO_2 in Scenario 2 for Korea. Aside from that, Kim et al. (2021) impose the CBT on all products, while we levy the CBT on dirty goods listed on the recent CBAM regulation.

Our findings can also be supported by Yoon (2022), who conducted research using the CGE model with the GTAP database (base-year 2014). He aggregated data from 12 countries, including the EU and Korea, and 14 industry sectors and assumed that a CBT of €30/tCO_2 was imposed on dirty goods listed on the CBAM regulation drafted by the EU Commission in 2021. He showed that exports of dirty goods to the EU would be reduced in Korea and the RoW, excluding the EU and Japan. Besides, he also proved that even though Korea's export to the EU would decline, export to other countries, such as the United States, China, and Turkey, would increase.

Korea's Welfare Changes

Our results demonstrate that Korea is better off with policy option 2 than policy option 1 since Korea's welfare declines by 0.06% in Scenario 1 but increases by 0.03% in Scenario 2 compared to the baseline scenario. This finding is comparable to estimates noted in the paper of Kim et al. (2021), as shown in Table 12. They also proved that Korea's welfare is better off in Scenario 2 than in the other and recommended linking K-ETS to the EU-ETS and getting a remission of CBT from the EU.

	Our results		Kim et al. (2021)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
CBAM products	Based on the regulation		All products	
Carbon Border Tax	€30	€13.78	$50	$35
Welfare Changes (compared to the baseline)	- 0.06%	+ 0.03%	- 0.13%	- 0.08%

Table 12. Comparison of Korea's welfare changes with previous study

In addition, the previous study by Moon et al. (2020) supports that our result in Scenario 1 is plausible. They conducted research targeting nine countries, including the EU and Korea, and industrial sectors classified by the OECD. They highlighted that if the EU imposes a CBT of €30/tCO_2 on the basic iron and cement, Korea's welfare will fall by 12.6 mil. $ in Scenario 1.

5.3 Model Implications

5.3.1 Climate Implications

As mentioned in Chapter 2.1.2, one of the EU CBAM's purposes is to reduce the free-riding benefits and incentivize other countries to reduce their GHG emissions. The effectiveness of each policy option in reducing GHG emissions can be evaluated using two quantities in our numerical illustration: global GHG emissions and each country's supply of GHG emissions from producing dirty goods.

Comparing the global GHG emissions in each scenario (Figure 6), policy option 1 shows the highest level of global GHG emissions. Policy option 1 without remission of CBT induces some countries to select a lower domestic GHG emission tax to maximize their welfare and protect their trade competitiveness, lowering global carbon prices. This lower global carbon price leads to a higher producer price and a higher GHG emission supply in the EU and Korea, as shown in Figure 8.

Global GHG emissions are lowest in Scenario 2. The remission of CBT under the CBAM incentivizes non-EU countries to raise their domestic GHG emission tax since each government can gain tax revenue and invest in low-carbon technologies. Furthermore, it drives down their supply of GHG emissions with the higher global carbon price, thereby reducing global GHG emissions. In addition, increasing EU-ETS prices lead to reductions in global GHG emissions (Figure 11).

Our numerical illustration suggests that the EU should be cautious in designing the CBAM since some countries (here, Korea) can increase their supply as a consequence of higher producer prices than their baseline. Besides, it implies that setting a proper level of CBT is also important to incentivize raising each country's domestic GHG emission tax and cutting GHG emissions.

5.3.2 Economic Implications

The welfare changes in each scenario allow us to determine the best policy option for each country. Unlike the concerns expressed by non-EU countries, the EU CBAM's impact on each country's welfare is not substantial, as illustrated in Figure 10.

The EU's and Korea's welfare drops in Scenario 1 compared to the baseline, thanks to the increase in global GHG emissions. It implies that there can be a backfire of the EU CBAM, which can lead to a lower world carbon price and declines in the welfare of some countries having a higher willingness to pay. On the other hand, the RoW's welfare slightly increases in Scenario 1. As policy option 1 creates the most competitive international trade environment, which allows dirty goods to be supplied at the lowest possible price in the RoW. The result of low dirty goods prices and high consumption utility is positive from a welfare perspective.

The EU's and Korea's welfare is the highest in Scenario 2, with the lowest level of global GHG emissions. The interesting fact to note is that in Scenario 2, the EU's and Korea's welfare increases with the higher EU-ETS prices leading to the lower global GHG emissions (See Figure 13). Especially, Korea's welfare is better off when its WTP gets higher, as shown in Figure 14. This suggests that the EU's welfare would be better off negotiating with non-EU countries that already have explicit carbon pricing and setting EU-ETS prices high enough. It further implies that Korea should negotiate with the EU to link K-ETS to the EU-ETS in order to get a remission of CBT and raise Korea's carbon tax for its own welfare.

In terms of tax revenue, Scenario 2 is the most advantageous for each country. In

Scenario 2, as the EU CBAM effectively raises global climate ambitions, each country imposes a higher domestic GHG emission tax than the baseline, receiving more tax revenue. For example, Korea collects 5.29 mil. € more in tax revenue than the baseline in Scenario 2. The EU also earns more tax revenue in Scenario 2 because more dirty goods are imported from non-EU countries than in Scenario 1.

5.3.3 Policy Implications

EU

Based on our results, we propose that the EU encourages non-EU countries to implement their own carbon-pricing initiatives and choose policy option 2 in order to reduce global GHG emissions and increase EU welfare and tax revenues. Under policy option 1, the EU's CBT can generate additional tax revenue of 0.05 bil. € than the baseline, as shown in Figure 15. However, its welfare is the lowest of the three scenarios because of the highest global GHG emissions level, as discussed in Chapter 5.3.2. Due to these factors, policy option 1 is not the best option for the EU, even if it can gain more tax revenue. On the other hand, the EU can accomplish the purpose of implementing the EU CBAM by reducing global GHG emissions and achieving the highest level of its welfare under policy option 2. In addition, it can gain 0.15 bil. € more tax revenue than the baseline and 0.10 bil. € more than policy option 1 (Figure 15). It is because non-EU countries have a heavier burden on CBT under policy option 1 than under policy option 2, making their exports to the EU much less.

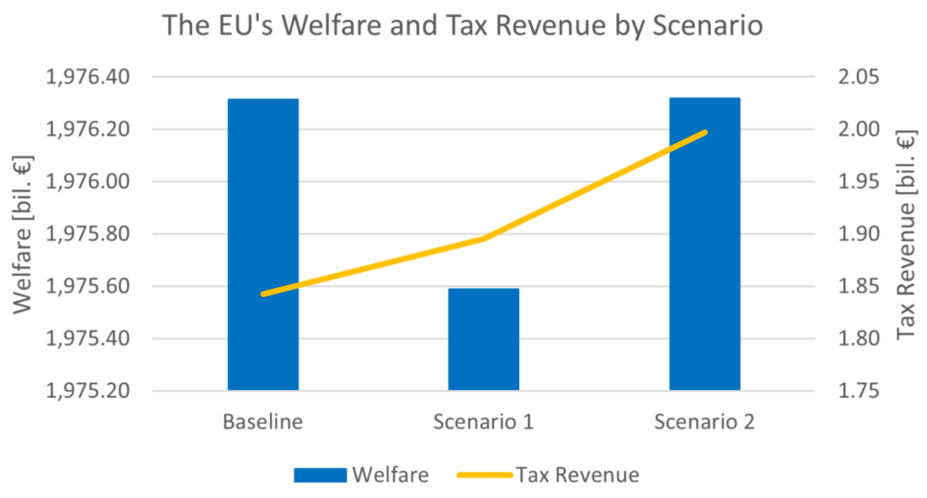

Figure 15. The EU's welfare and tax revenue by scenario

Besides, the EU should impose a CBT at an appropriate level and consider not to disadvantage its trading partners, which lack technology, capability, and financial resources for MRV of their emissions to avoid trade frictions, such as retaliatory tariffs. Wolf (2021) warned that moving ahead with the stringent environmental regulations may create trade frictions with Russia, Turkey, and some eastern European countries. Furthermore, he mentioned the EU might see a drop in exports as non-EU countries are expected to take some time to catch up with the EU's new carbon pricing system and its price. For example, Turkey and China are the largest importers of aluminum, and iron and steel from the EU, and these countries can switch to cheaper and carbon-intensive alternatives from non-EU countries until they implement their carbon pricing initiatives (Wolf, 2021).

In summary, the EU should incentivize non-EU countries to select policy option 2 and set an appropriate level of CBT because global GHG emissions and their welfare are sensitive to the EU-ETS prices. In addition, it is important that the EU CBAM should be designed carefully to avoid violating WTO GATT and thereby receiving trade retaliation.

Korea

Our numerical illustration suggests that Korea is better off when Korea links its ETS to the EU-ETS and raises its ETS price. Shin (2020) from Korea International Trade Association (KITA) also argued that Korea could be more competitive as the EU Parliament's CBAM amendment stipulated that only explicit carbon pricing can be subject to reduction or exemption from purchasing CBAM certificates. As shown in Figure 16, only 15 non-EU countries (excluding Iceland, Liechtenstein, Norway, and Switzerland) operate explicit carbon pricing at the national level, according to the World Bank (2022). Besides, Figure 17 shows that Uruguay, the United Kingdom, New Zealand, and Canada are the only countries that charge higher carbon prices than Korea among 15 non-EU countries in 2022 (World Bank, 2022). Hence, Korea should raise its ETS prices and the ratio of free allocation to increase its chances of negotiating with the EU more than other countries (see Chapter 2.3) and gain an advantageous position over its competitors such as Russia, Turkey, China, and Ukraine in the EU's CBAM market with policy option 2.

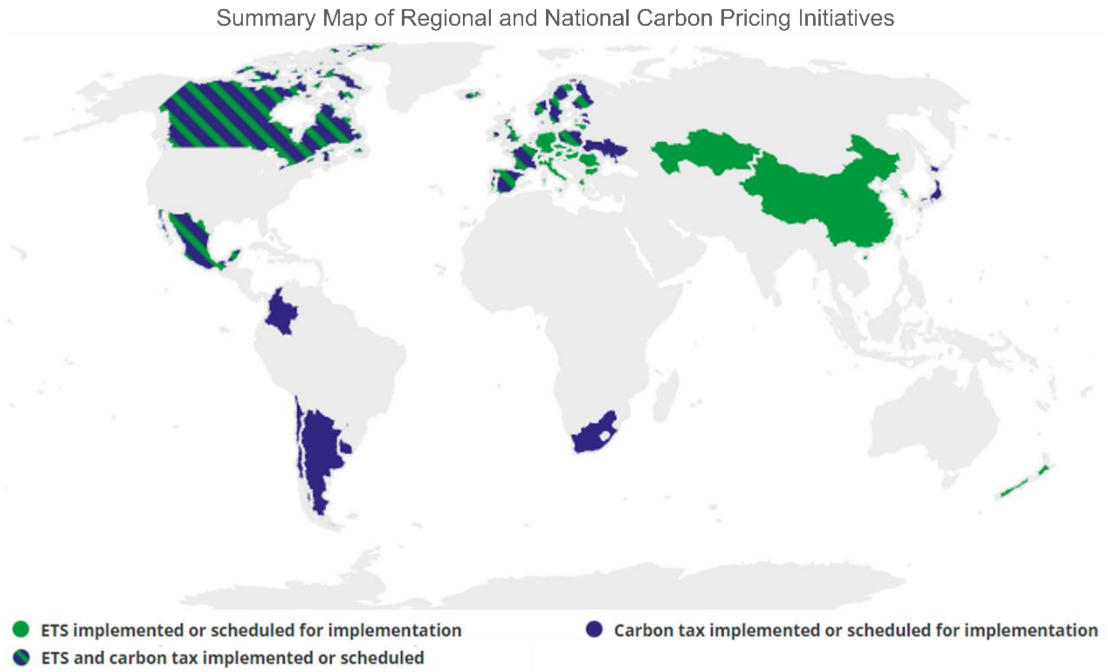

Figure 16. Summary map of regional and national carbon pricing initiatives (World Bank, 2022)

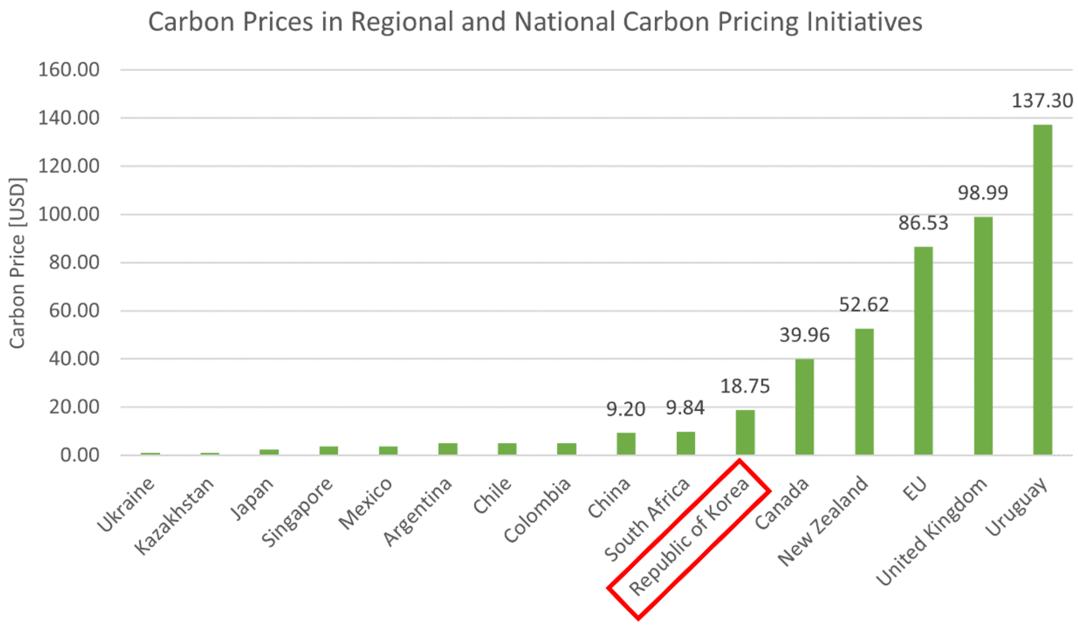

Figure 17. Carbon prices in regional and national carbon pricing initiatives (World Bank, 2022)

As well as getting a remission of CBT, it is necessary to develop low-carbon technologies and invest in low-carbon transitions (Moon et al., 2021). As stated in Chapter 2.2, Korea depends heavily on carbon-intensive industries and coal power generation. The Korean government should encourage CBAM industries to use low-carbon energies and support low-carbon technological innovation at the national level to encounter the weakened competitiveness caused by the introduction of EU CBAM (Moon et al., 2021). Although these environmental policies may negatively affect Korea's macroeconomy due to transition risks, they will increase its potential growth rate through advanced technologies related to low-carbon industries (Park et al., 2021).

In a nutshell, when the EU implements CBAM, Korea should try to get a remission of CBT by increasing its ETS prices while simultaneously undertaking low-carbon transitions and technology development for its welfare.

Chapter 6. Conclusion

It has been a year since the EU announced the implementation of CBAM. Nevertheless, even though Korea is a net exporter of GHG emissions to the EU, there is still a lack of research on the impact of EU CBAM on Korea and its policy options, as mentioned in Chapter 1. To fill this gap, we proposed a game-theoretic model of international trade, which quantitively investigates how much Korea and the RoW will be affected by the EU CBAM and explores whether Korea is better off with policy option 2 as previous studies recommended.

We conducted the numerical analysis by applying recent trade data from 2016 to 2020 and the CBAM regulations revised in March 2022. With the EU-ETS price of €30/tCO_2, our results first showed that the level of global GHG emissions in Scenario 1 is the highest, whereas it is the lowest in Scenario 2. In addition, global GHG emissions decline with the higher EU-ETS prices. Therefore, considering the EU's ambitious climate goal, it would be best to impose a sufficiently high EU-ETS price and remit CBT for imported dirty goods from countries having explicit carbon pricing.

We found the EU and Korea are better off in Scenario 2 than in Scenario 1. It is because their willingness to pay is much higher than the RoW and global GHG emissions are the lowest in Scenario 2. Moreover, Korea's welfare increases with its higher WTP with policy option 2. This finding implies that the EU CBAM with policy option 2 incentivizes Korea to increase its climate ambitions. Further, we found that policy option 1 provides a better welfare outcome for the RoW having a high preference for consuming dirty goods over clean goods since it causes competition, which lowers the price of dirty goods.

Our findings provide three potential implications that might be used for decision-making in the future. Firstly, the EU should not overlook the backfire effect of the EU CBAM with respect to policy option 1. Implementing CBAM does not always lead to successful carbon reduction. Secondly, it is necessary for the Korean government to increase its ETS price and negotiate with the EU to link the K-ETS to the EU-ETS. As a result of qualifying for CBT remission, Korea will be able to compete more effectively in the EU market. Last but not least, since Korea depends heavily on carbon-intensive industries and coal power production, it is crucial to invest in low-economy transition and technology development.

Even though our research provides qualitative insights regarding the EU CBAM, it has some limitations. First, we used a simple game-theoretic model for tractability, which cannot reflect the complicated real world. In this regard, we could not consider the trade relationship between Korea and the RoW. Additionally, we assumed Korea and the RoW always select the same policy option, which is not necessarily the case in the real world. Second, we considered that the RoW imposes a GHG emission tax. However, only 15 non-EU countries are operating explicit carbon pricing. Third, there was a limitation in obtaining the carbon intensity data of each specific product, so we used approximate numbers from each industry. Last, we included Norway, Liechtenstein, Iceland, and Switzerland in the RoW. However, these countries will get exemption from the CBAM obligations. Therefore, we expect further studies to analyze the impact of CBAM by reflecting more accurate data and assumptions.

The European Commission (2021) emphasized that what is good for the environment is also good for society and the economy. Europe's carbon emissions fell by 24% compared to 1990, but its economy grew by 62% during the same period. Besides, the Nobel Prize-winning economist Nordhaus stated in his book "The Spirit of Green" that advanced technologies can offset the negative externalities of a country if it makes wise choices and investments. The Korean economy is currently facing a massive change in the international trade environment. Making wise investments during the EU CBAM's transition period would enable Korea to become a low-carbon economy.

Appendix A. Calculation of GHG Emission Tax

A.1 Calculation of GHG Emission Tax without EU CBAM

Let us start from the eq. (18):

$$V_i'\left(e_i^d\right)\frac{\partial e_i^d}{\partial t_i}+T_i'\left(e_i^s\right)\cdot\frac{\partial e_i^s}{\partial t_i}+\frac{\partial p}{\partial t_i}\left(e_i^s-e_i^d\right)+p\left(\frac{\partial e_i^s}{\partial t_i}-\frac{\partial e_i^d}{\partial t_i}\right)-D_i'(E)\frac{\partial E}{\partial t_i}=0.$$

Using eqs. (1) and (2), we obtain

$$p\cdot\frac{\partial e_i^d}{\partial t_i}+(-p+t_i)\cdot\frac{\partial e_i^s}{\partial t_i}+\frac{\partial p}{\partial t_i}\cdot\left(e_i^s-e_i^d\right)+p\left(\frac{\partial e_i^s}{\partial t_i}-\frac{\partial e_i^d}{\partial t_i}\right)-\delta_i\cdot\frac{\partial E}{\partial t_i}=0. \quad \text{(A.1)}$$

We can simplify eq. (A.1) as follows:

$$t_i\cdot\frac{\partial e_i^s}{\partial t_i}+\frac{\partial p}{\partial t_i}\cdot\left(e_i^s-e_i^d\right)-\delta_i\cdot\frac{\partial E}{\partial t_i}=0, \quad \text{(A.2)}$$

where

$$\begin{aligned}
\frac{\partial e_i^s}{\partial t_i} &= \frac{\alpha_i\,(\alpha_i-A-B)}{A+B},\\
\frac{\partial p}{\partial t_i} &= \frac{\alpha_i}{A+B},\\
e_i^s-e_i^d &= \frac{(\alpha_i+b_i)\left(C+\sum_{j=1}^{3}\alpha_j t_j\right)-(A+B)(\alpha_i t_i+b_i a_i)}{A+B},\\
\frac{\partial E}{\partial t_i} &= -\frac{\alpha_i B}{A+B}.
\end{aligned} \quad \text{(A.3)}$$

Then, we insert eq. (A.3) into eq. (A.2) to obtain t_i for $i=2,3$:

$$t_i=\frac{(\alpha_i+b_i)\left(C+\sum_{j=1}^{3}\alpha_j t_j\right)+(A+B)(\delta_i B-b_i a_i)}{(A+B)^2}, \quad i=2,3. \quad \text{(A.4)}$$

To solve for t_2 and t_3 respectively, we simplify eq. (A.4) by supposing $\alpha_i+b_i=X_i$, $A+B=Y$ and $\delta_i B-b_i a_i=Z_i$ as follows:

$$t_2 = \frac{X_2\left(C + \sum_{j=1}^{3} \alpha_j t_j\right) + YZ_2}{Y^2}, \quad \text{(A.5)}$$

$$t_3 = \frac{X_3\left(C + \sum_{j=1}^{3} \alpha_j t_j\right) + YZ_3}{Y^2}. \quad \text{(A.6)}$$

Then, we obtain t_2 by inserting eq. (A.6) to eq. (A.5) and obtain t_3 vice versa:

$$t_2 = \frac{X_2 Y(C + \alpha_1 t_1) + X_2 \cdot \alpha_3 \cdot Z_3 + \left(Y^2 - X_3 \alpha_3\right) \cdot Z_2}{Y^3 - X_2 \alpha_2 Y - X_3 \alpha_3 Y}, \quad \text{(A.7)}$$

$$t_3 = \frac{X_3 Y(C + \alpha_1 t_1) + X_3 \cdot \alpha_2 \cdot Z_2 + \left(Y^2 - X_2 \alpha_2\right) \cdot Z_3}{Y^3 - X_2 \alpha_2 Y - X_3 \alpha_3 Y}, \quad \text{(A.8)}$$

where

$$\alpha_i + b_i = X_i,$$

$$A + B = Y,$$

$$\delta_i B - b_i a_i = Z_i.$$

This leads to eqs. (19) and (20).

A.2 Calculation of GHG Emission Tax with EU CBAM (policy option 1) for Korea and the RoW

Let us start from the eq. (41):

$$T_i'(e_i^s) \cdot \frac{\partial e_i^s}{\partial t_i} + \left(\frac{\partial e_i^s}{\partial t_i} - \frac{\partial e_i^d}{\partial t_i}\right) \cdot q + \left(e_i^s - e_i^d\right) \cdot \frac{\partial q}{\partial t_i} + V_i'\left(e_i^d\right)\frac{\partial e_i^d}{\partial t_i} - D_i'(E)\frac{\partial E}{\partial t_i} = 0,$$
$$i = 2, 3.$$

By inserting eqs. (1), (2), (24), and (25), we can obtain:

$$-q \cdot \frac{\partial e_i^s}{\partial t_i} + \left(\frac{\partial e_i^s}{\partial t_i} - \frac{\partial e_i^d}{\partial t_i}\right) \cdot q + \left(e_i^s - e_i^d\right) \cdot \frac{\partial q}{\partial t_i} + (q + t_i) \cdot \frac{\partial e_i^d}{\partial t_i} - \delta_i \cdot \frac{\partial E}{\partial t_i} = 0. \quad \text{(A.9)}$$

We can simplify eq. (A.9) as follows:

$$\left(e_i^s - e_i^d\right) \cdot \frac{\partial q}{\partial t_i} + t_i \cdot \frac{\partial e_i^d}{\partial t_i} - \delta_i \cdot \frac{\partial E}{\partial t_i} = 0, \quad i = 2, 3, \quad \text{(A.10)}$$

where

$$\frac{\partial q}{\partial t_i} = -\frac{b_i}{A+B},$$
$$\frac{\partial e_i^d}{\partial t_i} = \frac{b_i\,(b_i - A - B)}{A+B}, \quad \text{(A.11)}$$
$$\frac{\partial E}{\partial t_i} = -\frac{A b_i}{A+B}.$$

We insert eq. (A.11) into eq. (A.10):

$$(b_i - A - B)\cdot t_i = e_i^s - e_i^d - \delta_i A. \quad \text{(A.12)}$$

Then, we can insert eqs. (28) and (29) into e_1^s and e_1^d each:

$$(b_i - A - B)\cdot t_i = \alpha_i \cdot \left(\frac{C - \sum_{j=1}^{n} b_j t_j}{A+B}\right) - b_i a_i + b_i t_i + b_i \cdot \left(\frac{C - \sum_{j=1}^{n} b_j t_j}{A+B}\right) - \delta_i A. \quad \text{(A.13)}$$

From eq. (A.13), we can get $t_i \; for \; i = 2, 3$:

$$t_i = \frac{(A+B)(\delta_i A + b_i a_i) - (\alpha_i + b_i)(C - \sum_{j=1}^{n} b_j \hat{t}_j)}{(A+B)^2}, \quad i = 2, 3. \quad \text{(A.14)}$$

To solve for t_2 and t_3 respectively, we simplify eq. (A.14) by supposing $\alpha_i + b_i = X_i$, $A + B = Y$ and $\delta_i A + b_i a_i = Z_i$ as follows:

$$t_2 = \frac{Y Z_2 - X_2(C - b_1 t_1 - b_3 t_3)}{Y^2 - X_2 b_2}, \quad \text{(A.15)}$$

$$t_3 = \frac{Y Z_3 - X_3(C - b_1 t_1 - b_2 t_2)}{Y^2 - X_3 b_3}. \quad \text{(A.16)}$$

Then, we obtain t_2 by inserting eq. (A.16) to eq. (A.15) and obtain t_3 vice versa:

$$t_2 = \frac{Y^2 Z_2 - X_2 Y C + X_2 Z_3 b_3 - X_3 Z_2 b_3 + X_2 Y b_1 t_1}{Y(Y^2 - X_2 b_2 - X_3 b_3)}, \quad \text{(A.17)}$$

$$t_3 = \frac{Y^2 Z_3 - X_3 Y C + X_3 Z_2 b_2 - X_2 Z_3 b_2 + X_3 Y b_1 t_1}{Y(Y^2 - X_2 b_2 - X_3 b_3)}, \quad \text{(A.18)}$$

where

$$\alpha_i + b_i = X_i,$$

$$A + B = Y,$$

$$\delta_i A + b_i a_i = Z_i.$$

This leads to the eqs. (42) and (43).

A.3 Calculation of GHG Emission Tax with EU CBAM (policy option 2) for Korea and the RoW

Let us start from the eq. (57):

$$T_i'(e_i^s)\cdot\frac{\partial e_i^s}{\partial t_i}+\left(\frac{\partial e_i^s}{\partial t_i}-\frac{\partial e_i^d}{\partial t_i}\right)\cdot p_i+\left(e_i^s-e_i^d\right)\cdot\frac{\partial p_i}{\partial t_i}+V_i'\left(e_i^d\right)\frac{\partial e_i^d}{\partial t_i}-D_i'(E)\frac{\partial E}{\partial t_i}=0,\ \ i=2,3.$$

By inserting eqs. (1), (2), (24), and (25), we can obtain:

$$(-p_i+t_i)\cdot\frac{\partial e_i^s}{\partial t_i}+\left(\frac{\partial e_i^s}{\partial t_i}-\frac{\partial e_i^d}{\partial t_i}\right)\cdot p_i+\left(e_i^s-e_i^d\right)\cdot\frac{\partial p_i}{\partial t_i}+p_i\cdot\frac{\partial e_i^d}{\partial t_i}-\delta_i\cdot\frac{\partial E}{\partial t_i}=0. \quad \text{(A.19)}$$

We simplify eq. (A.19) as follows:

$$t_i\cdot\frac{\partial e_i^s}{\partial t_i}+\left(e_i^s-e_i^d\right)\cdot\frac{\partial p_i}{\partial t_i}-\delta_i\cdot\frac{\partial E}{\partial t_i}=0,\quad i=2,3, \quad \text{(A.20)}$$

where

$$\frac{\partial e_i^s}{\partial t_i}=-\frac{\alpha_i b_i}{A+B},$$
$$\frac{\partial p_i}{\partial t_i}=1-\frac{b_i}{A+B}, \quad \text{(A.21)}$$
$$\frac{\partial E}{\partial t_i}=-\frac{Ab_i}{A+B}.$$

We insert eq. (A.21) into eq. (A.20):

$$\alpha_i b_i\cdot t_i=(A+B-b_i)\cdot\left(e_i^s-e_i^d\right)+\delta_i Ab_i. \quad \text{(A.22)}$$

Then, we insert eqs. (28) and (29) into e_1^s and e_1^d each:

$$\alpha_i b_i\cdot t_i=(A+B-b_i)\cdot\left[\frac{\alpha_i(C-\sum_{j=1}^n b_j t_j)}{A+B}-b_i(a_i-t_i)+\frac{b_i(C-\sum_{j=1}^n b_j t_j)}{A+B}\right]+\delta_i\cdot Ab_i. \quad \text{(A.23)}$$

From eq. (A.23), we can get $t_i\ for\ i=2,3$:

$$t_i=\frac{(A+B-b_i)\left[(\alpha_i+b_i)\cdot(C-\sum_{j=1}^n b_j t_j)-a_i b_i(A+B)\right]+b_i\delta_i A(A+B)}{b_i(A+B)(\alpha_i+b_i-A-B)},\quad i=2,3. \quad \text{(A.24)}$$

To solve for t_2 and t_3 respectively, we first simplify eq. (A.24) by supposing $\alpha_i+b_i=X_i$ and $A+B=Y$ as follows:

$$t_2 = \frac{(Y-b_2)\left[X_2 \cdot (C-\sum_{j=1}^{n} b_j t_j) - a_2 b_2 Y\right] + b_2 \delta_2 A Y}{b_2 Y (X_2 - Y)}, \tag{A.25}$$

$$t_3 = \frac{(Y-b_3)\left[X_3 \cdot (C-\sum_{j=1}^{n} b_j t_j) - a_3 b_3 Y\right] + b_3 \delta_3 A Y}{b_3 Y (X_3 - Y)}. \tag{A.26}$$

Then, we obtain t_2 by inserting eq. (A.26) to eq. (A.25) and obtain t_3 vice versa:

$$\widehat{t_2} = \frac{(X_3-Y)(Y-b_2)[(C-b_1t_1)X_2-Ya_2b_2]-(Y-b_3)(Y-b_2)(X_3a_2b_2-X_2a_3b_3)+[(X_3-Y)Y+(Y-b_3)X_3]b_2\delta_2A-(Y-b_2)X_2b_3\delta_3A}{b_2[Y(X_3-Y)(X_2-Y)+(X_2-Y)(Y-b_3)X_3+(X_3-Y)(Y-b_2)X_2]}, \tag{A.27}$$

$$t_3 = \frac{(X_2-Y)(Y-b_3)[(C-b_1t_1)X_3-Ya_3b_3]-(Y-b_2)(Y-b_3)(X_2a_3b_3-X_3a_2b_2)+[(X_2-Y)Y+(Y-b_2)X_2]b_3\delta_3A-(Y-b_3)X_3b_2\delta_2A}{b_3[Y(X_2-Y)(X_3-Y)+(X_3-Y)(Y-b_2)X_2+(X_2-Y)(Y-b_3)X_3]}, \tag{A.28}$$

where

$$\alpha_i + b_i = X_i,$$

$$A + B = Y.$$

This leads to the eqs. (58) and (59).

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Declaration of Consent

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Title of the Thesis: EU Carbon Border Adjustment Mechanism - A Game-Theoretic Analysis of Impact on the Republic of Korea

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